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Ecological assessment of salmonid populations in a country undergoing rapid environmental and socioeconomic transitions (Mongolia)

DISSERTATION

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Declaration of Conformity

I, Andrew Kingsley Kaus, hereby confirm that this copy conforms with the original dissertation on the topic:

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Andrew Kingsley Kaus

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List of Abbreviations

%	Percentage
a.s.l.	Above sea level
As	Arsenic
Cd	Cadmium
cm	centimetres
CPUE	Catch per unit effort
Cr	Chromium
Cu	Copper
DNA	Deoxyribonucleic acid
DOWN	Downstream region
e.g.	*exempli gratia*
Eg	Egiin
ESU	Evolutionary Significant Units
FAO	Food and Agriculture Organization
FPA	Freshwater Protected Areas
GLM	Generalised linear model
H	haplotype
Hg	Mercury
i.e.	*id est*
I_R	Residency Index
KD	Kernel densities
Km	Kilometres
KRB	Kharaa River Basin
LHR	linear home range
m	meters
MID-DOWN	Mid-down river reaches
MID-UP	Mid-upper river reaches
n	sample size
Ni	Nickel
NIST	National Institute of Standards and Technology
NRC	National Research Council of Canada
P	*p* -value
Pb	Lead
PTWI	Provisional Tolerable Weekly Intake
s	seconds
SD	Standard Deviation
SE	Standard Error
TL	Total Length
UP	Upper River reaches (study's reference sites)
WHO	World Health Organization
WWF	World Wildlife Fund
WWTP	Waste Water Treatment Plants

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Summary

Mongolia is currently undergoing a rapid socioeconomic transition with extensive development driven by increased mineral resource extraction and large scale agriculture and pastoral expansion. There has also been unprecedented urbanisation and continued population growth that has placed added pressure on the ageing public infrastructure including power stations and waste water treatment plants. As a result, the country's pristine landscapes, including its vast freshwater ecosystems, are now facing widespread degradation, contamination and species losses in the most impacted regions. The proposed large-scale dams and imminent climate change effects will further damage these fragile ecosystems. With a number of rivers and lakes deteriorating, resident aquatic communities, including unique fish species, have suffered significant population declines. However, a more substantial threat currently facing these fish populations is the rapid and largely unregulated rise in fishing activities within an emerging recreational fishery. Although historically fish capture and consumption has not been a traditional part of the Mongolian diet or culture, this is changing rapidly. Therefore a comprehensive set of research projects were developed and implemented across Mongolia, to gather essential information on this new fishery, while also addressing existing knowledge gaps regarding the spatial ecology and genetic structure of the main target species. In addition, a potential human health risk was evident due to the increased consumption of locally caught fish species from a heavily impacted river basin, and thus this was also investigated. Overall, the collective aim of this fisheries research was to increase the scientific understanding and knowledge across a range of issues and ultimately advise authorities on improving current management regulations and conservation strategies. It is hoped that the recommendations can assist in safeguarding the future sustainability and resilience of the threatened fish populations and the emerging recreational fishery across Mongolia for the future.

A total of five fisheries related research projects were completed between 2011 and 2014, with the results from each used to formulate the conservation and management recommendations presented in this thesis. Due to the lack of knowledge regarding the emerging recreational fishery, roving creel surveys were conducted across three river basins and covered five key topics including angler demographics, fishing practices, current fishing trip data, fishing gear and costs, and angler knowledge and opinions. Fifty-eight fishing groups (n = 154 anglers) were interviewed and two angler types were identified: rural anglers with no or low incomes, who reside in the basin, fish alone or in smaller groups, fish frequently for shorter periods, and consumed fish more regularly; and

urban anglers who have medium to high incomes, live in larger cities, spent more money on fishing gear / trips and fished for multiple days at a time. *B. lenok* was identified as the most targeted and caught species in the fishery. The results of the creel surveys confirmed increased fish consumption in the Kharaa River basin, which was identified as a potential human health risk due to the widespread heavy metal contamination from both past and present mining activities. Thus heavy metal contaminates in river water, sediment and five consumed fish species were examined at 11 sites across the basin. Heavy metals were evident in all five sampled species, with maximum muscle contents of chromium (Cr), arsenic (As), mercury (Hg) and lead (Pb) detected in fish from the middle and lower reaches, while zinc (Zn) was highly elevated in *B. lenok* from the upper tributaries. Elevated median contents of Cr, copper (Cu), Hg and Pb increased with trophic level, with the bioaccumulation of Hg posing the greatest threat to human health with over 10 % of all fish sampled exceeded the internationally recommended threshold for Hg in consumable fish tissue (> 0.5 µg g^{-1} ww). This bioaccumulation in resident fish species could lead to chronic toxicity in people who consume them regularly and have additional exposure to other sources of contamination *e.g.* gold mining.

A further two projects were conducted that utilised passive acoustic telemetry to describe the spatial and temporal autecology, habitat use and behaviour of *B. lenok* in the Eroo River and *H. taimen* in the Onon/Balj rivers under Mongolia's extreme seasonal conditions. The maximum longitudinal movements (home ranges) detected were more extensive than previously reported for both species with 45.3 km for *B. lenok* and 126.1 km for *H. taimen*. Increased movements were recorded in spring and summer, with individuals entering surrounding tributaries and remaining there for between four and 85 days before returning to the main river channel. The results highlighted the importance of maintaining the integrity and connectivity of tributary habitats for spawning, feeding and overwintering, as well as hydrological and thermal refuges, which will be increasingly important for these species in the region with the pending impacts of climate change. This increased knowledge relating to the spatial ecology of these threatened species can guide the design and implementation of new protective measures such as the introduction of Freshwater Protected Areas (FPAs) across Mongolia. Further research was conducted to gain a broader, multigenerational understanding of the interconnectedness between conspecific populations of *H. taimen*, *B. lenok* and *T. baicalensis* across the major river basins. Both molecular and nuclear markers were used to demarcate the population's genetic structure and define Evolutionary Significant Units (ESUs) and priority populations for these species across their Mongolian distributions. Across all species, the most prominent pattern was a strong differentiation among major basins with low differentiation and weak patterns of isolation by distance within basins, which indicates high within-basin connectivity between populations, although exact patterns were not completely concordant among species.

The extensive results produced from the current scientific research has facilitated the development of a comprehensive set of key recommendations for implementing new, and enhancing existing, management and conservation measures relating to Mongolia's threatened salmonid species and its emerging recreational fishery. These recommendations include: 1. Establishing a series of Freshwater Protected Areas (FPAs) throughout Mongolia's major river basins, with their design and location based upon the spatial ecology and genetic population structure determined by the current research results; 2. Shifting the opening date of the fishing season to encompass the entire spawning period of *B. lenok* (the fishery's main target species), which appears to currently not be the case; 3. Adding the blunt-snouted lenok (*B*. sp.) to the prohibited species list, as it has been genetically proven to be an independent species and has a restricted distribution and low abundance in Mongolia; and 4. Introducing minimum (and potentially maximum) size limits for *B. lenok* and *T. baicalensis*, to better protect immature and pre-spawning individuals from being removed from the population. In addition, it is highly recommended to commence fisheries dependent and independent assessments in key river basins and conduct biomonitoring programs (using a bioindicator species) to track toxic heavy metal contamination and identify potential human health risks associated with consuming resident fish species from the more heavily impacted regions. The lack of knowledge of the current fishing regulations by anglers as well as the observed and reported widespread illegal fishing activities demands a wide-ranging angler education program to improve understanding and compliance within the fishery. The future survival of these threatened salmonids and the sustainability of the emerging recreational fishery in Mongolia currently hangs in the balance. However, if these scientifically based recommendations are implemented in full, and can be adequately enforced, then the responsible authorities can take a huge step forward towards reversing the current trends and preserving the country's imperilled freshwater fish populations and their valuable aquatic ecosystems. Mongolia can be a model for freshwater species conservation and management throughout the region and the world.

Summary in German / Zusammenfassung auf Deutsch

Die Mongolei befindet sich derzeit in einem rasanten sozioökonomischen Übergang mit tiefgreifenden Veränderungen, die v.a. durch eine Zunahme bergbaulicher Aktivitäten sowie einen Ausbau ackerbaulicher Nutzungen wie auch der Viehwirtschaft angetrieben werden. Derzeit vollzieht sich eine noch nie dagewesene Urbanisierung und ein weiteres Bevölkerungswachstum, das auf die alternde öffentliche Infrastruktur, einschließlich Kraftwerke und Abwasserbehandlungsanlagen, einen zusätzlichen Druck ausübt. Infolgedessen zeigen sich in den weitgehend unberührten Landschaften des Landes, einschließlich seiner riesigen Süßwasser-Ökosysteme, deutliche Anzeichen von Übernutzung natürlicher Ressourcen, Umweltverschmutzung und Artenverlusten. Zukünftig geplante große Staudämme werden neben den bevorstehenden Auswirkungen des Klimawandels die Hydrologie deutlich verändern. So sind bereits deutliche Beeinträchtigungen der Fluss-und See-Ökosysteme erkennbar, insbesondere in Hinblick auf ihre aquatischen Lebensgemeinschaften. Einige der weltweit einzigartigen Fischarten haben bereits erhebliche Bevölkerungsrückgänge erlitten. Eine weitere existenzielle Bedrohung für diese Fischpopulationen ist der rasche und weitgehend un-regulierte Anstieg der Fischereitätigkeiten aus einer aufstrebenden Freizeitfischerei. Obwohl Fischfang und -konsum keine traditionellen Elemente der mongolischen Ernährung oder Kultur darstellen, vollziehen sich diesbezüglich derzeit tiefgreifende Veränderungen. Daher wurden in der Mongolei umfangreiche Forschungsprojekte geplant und durchgeführt, um wesentliche Informationen über diese neue Art der Fischerei zu sammeln und gleichzeitig bestehende Wissenslücken in Bezug auf die räumliche Ökologie und die Metapopulationsstruktur der wichtigsten Zielarten zu schließen. Darüber hinaus zeigten Untersuchungen, dass sich aufgrund des erhöhten Konsums von lokal gefangenen Fischarten aus einem stark beeinträchtigten Einzugsgebiet ein potenzielles Risiko für die menschliche Gesundheit ergibt. Insgesamt ist das übergeordnete Ziel dieser Fischereiforschung, das wissenschaftliche Verständnis und Wissen zu erweitern und letztlich die derzeitigen Managementinstrumente zu verbessern und neue Erhaltungsmaßnahmen zu ergreifen, um die Nachhaltigkeit und Widerstandsfähigkeit der bedrohten Fischartenpopulationen und die aufkommende Erholung zu sichern. Insgesamt wurden zwischen 2011 und 2014 insgesamt fünf fischereibiologische Forschungsprojekte abgeschlossen, wobei die Ergebnisse dieser Arbeiten in Erhaltungs- und Managementempfehlungen münden. Wegen des Mangels an Wissen über die aufkommende Freizeitfischerei wurden Anglerbefragungen in drei Einzugsgebieten durchgeführt, welche fünf wichtige Themen wie Angler-Demographie, Fischereipraktiken,

Reisetätigkeiten, Fanggeräte und Kosten sowie Anglerwissen und Meinungen umfassten. Fünfundsechzig Angelgruppen (n = 154 Angler) wurden interviewt und zwei Anglertypen identifiziert: ländliche Angler ohne oder niedrige Einkommen, die in dem Becken wohnen, alleine oder in kleineren Gruppen fischen, häufig für kürzere Zeiten fischen und regelmäßig Fisch verzehren; und städtische Angler, die mittlere bis hohe Einkommen haben, in größeren Städten leben, mehr Geld für Fanggeräte / Ausflüge ausgegeben und typischerweise für mehrere Tage am Stück fischen. *B. lenok* wurde als die bevorzugte und am meisten gefangene Zielarten der Fischerei identifiziert. Die Ergebnisse der Anglerbefragungen bestätigten den erhöhten Fischkonsum im Kharaa-Einzugsgebiet, das aufgrund der weit verbreiteten Schwermetallverunreinigung aus der Vergangenheit und den gegenwärtigen Bergbauaktivitäten als potenzielles Risiko für die menschliche Gesundheit identifiziert wurde. So wurden Schwermetallverunreinigungen im Flusswasser, Sediment und fünf konsumierten Fischarten an 11 Standorten im Einzugsgebiet untersucht. Schwermetalle zeigten sich in allen fünf Stichprobenarten, wobei der maximale Muskelgehalt von Cr, As, Hg und Pb in Fischen aus dem Mittel- und Unterlauf festgestellt wurde, während Zn in *B. lenok* in den Oberlaufregionen stark erhöht war. Der erhöhte mediane Gehalt an Cr, Cu, Hg und Pb nahm mit trophischer Ebene zu, wobei die Bioakkumulation von Hg die größte Bedrohung für die menschliche Gesundheit darstellte, wobei über 10% aller Fischproben den international empfohlenen Schwellenwert für Hg im verzehrbaren Fischgewebe überstiegen (> 0,5 µg g-1 ww). Diese Bioakkumulation in residenten Fischarten könnte zu chronischen Intoxikationen bei Menschen führen, die sie regelmäßig konsumieren und zusätzliche Exposition gegenüber anderen Kontaminationsquellen haben, z.B. im Goldbergbau.

Es wurden weitere zwei Projekte durchgeführt, die eine passive akustische Telemetrie zur Beschreibung der räumlichen und zeitlichen Autökologie, des Lebensraumnutzens und des Verhaltens von *B. lenok* im Eroo River und *H. taimen* in den Flüssen Onon und Balj unter den extremen Klimabedingungen der Mongolei verwendeten. Die maximalen Längsbewegungen (Heimatbereiche) wurden -umfangreicher als bisher angenommen- für beide Arten wurden auf 45,3 km für *B. lenok* und 126,1 km für *H. taimen* ermittelt. Im Frühjahr und Sommer wurden erhöhte Bewegungen aufgezeichnet, wobei die Individuen in die umliegenden Nebenflüsse eintraten und dort zwischen 4 und 85 Tagen verblieben, bevor sie zum Hauptfluss des Flusses zurückkehrten. Die Ergebnisse zeigen die Bedeutung der Aufrechterhaltung der Integrität und der Konnektivität von Nebenflüssen für Laichen, Nahrungssuche und Überwinterung sowie hydrologische und thermische Schutzräume, die für diese Arten in der Region mit den anstehenden Auswirkungen des Klimawandels zunehmend an Bedeutung gewinnen werden. Die verbesserten Kenntnisse der räumlichen Ökologie dieser bedrohten Arten kann die Gestaltung und Umsetzung neuer Schutzmaßnahmen wie Süßwasser-Schutzgebiete in der Mongolei wissenschaftlich fundieren und leiten. Weitere Untersuchungen wurden durchgeführt, um ein breiteres, multigenerationales Verständnis der Zusammenhänge zwischen den konkreten Populationen von H. taimen, B. lenok und *T. baicalensis* über die großen Flusseinzugsgebiete zu gewinnen. Sowohl molekulare als auch nukleare Marker wurden verwendet, um die genetische Struktur abzugrenzen und definieren, so z.B. evolutionär signifikante Einheiten (ESUs) und eigenständige Populationen für diese Arten einschließlich ihrer räumlichen Verteilung in der Mongolei. Über alle Arten hinweg war das deutlichste Muster eine starke Differenzierung zwischen den großen Becken mit geringer Differenzierung. Dem gegenüber stehen schwache Muster der Isolation durch die Distanz in den Becken, die eine hohe einzugsgebietsinterne Konnektivität anzeigen, obwohl exakte Muster nicht vollständig unter allen Arten übereinstimmten. Die Prioritäten der Erhaltung müssen sich auf die Verbesserung des Schutzes der vorrangigen Bevölkerungsgruppen innerhalb jeder Art und ESU konzentrieren, um die begrenzten verfügbaren Ressourcen für die Arten- und Populations-Erhaltung und fischereiliche Bewirtschaftung in der Mongolei zu maximieren.

Die umfangreichen Ergebnisse aus der aktuellen wissenschaftlichen Forschung ermöglichten die Ableitung umfassender Empfehlungen für die Umsetzung neuer und die Verbesserung der bestehenden Management- und Erhaltungsmaßnahmen in Bezug auf die bedrohten Lachsarten der Mongolei und die aufkommende Freizeitfischerei. Diese Empfehlungen beinhalten 1.die Gründung einer Reihe von Süßwasser-Schutzgebieten (FPA) in den großen Flussgebieten der Mongolei auf der Grundlage der räumlichen Ökologie und der genetischen Bevölkerungsstruktur, die durch die aktuellen Forschungsergebnisse untermauert wird; 2. Eine Verschiebung des Eröffnungstermins der Fangsaison, welche im Gegensatz zur aktuellen Praxis die gesamte Laichzeit von *B. lenok* (die Hauptzielspezies der Fischerei); umfassen sollte; 3. Hinzufügen des Stumpfschnauzen-Lenok (B. sp.) zur Liste der besonders geschützten Arten, da er sich als eine genetisch unabhängige Spezies erwiesen hat, welche eine begrenzte räumliche Verteilung und geringe Populationsdichte in der Mongolei hat; und 4. Einführung von minimalen (und potentiell maximalen) Körpergrößenbeschränkungen für *B. lenok* und *T. baicalensis*, um die unreifen und heranwachsenden Individuen besser vor menschlichen Einflüssen zu schützen. Darüber hinaus empfiehlt es sich dringend, in den wichtigsten Flussgebieten fischereilich genutzte und nicht genutzte Fischpopulationen zu erfassen und Biomonitoring-Programme (unter Verwendung von Bioindikator-Spezies) zu implementieren, um toxische Schwermetallverunreinigungen zu verfolgen und potenzielle Risiken für die menschliche Gesundheit zu identifizieren, die mit dem Verzehr Fischen aus beeinträchtigten Regionen einhergehen. Schließlich verlangt das Fehlen von Kenntnissen über die derzeitigen Fischereiverordnungen durch Angler sowie die beobachteten und gemeldeten weitverbreiteten illegalen Fischereitätigkeiten ein weitreichendes Angler-Bildungsprogramm, um das Verständnis und die Einhaltung fischereilicher Regelungen zu verbessern. Das künftige Überleben der bedrohten Salmoniden und die Nachhaltigkeit der aufkommenden Freizeitfischerei in der Mongolei sind eng miteinander verbunden. Sofern die hier dargestellten wissenschaftlich fundierten Empfehlungen in vollem Umfang umgesetzt werden und hinreichend kontrolliert werden können, würden die zuständigen Behörden einen großen Schritt in Richtung der Umkehrung der aktuellen Trends machen und die gefährdeten Süßwasserfischpopulationen des Landes und ihre wertvollen aquatischen Ökosysteme bewahren. Die Mongolei könnte dann ein Modell für die Erhaltung und Bewirtschaftung von Süßwasserarten in der ganzen Region und der Welt werden.

Summary in Mongolian / Хураангуй

Монгол орон ашигт малтмалын олборлолт, хөдөө аж ахуй, бэлчээрийн газар нутгийн тэлэлтээр хязгаарлагдсан нийгэм-эдийн засгийн шилжилтийн үед оршин байгаа юм. Хотжилт төлөвлөлтгүй тэлж, хот суурин газрын хүн амын тоо байнгийн өсөн нэмэгдэж байгаа нөхцөл байдал нь хотын дэд бүтэц, тэр дундаа олон жил ашиглагдаж, шинэчлэлт, сэргээн засварлалт хараахан хийгдээгүй байгаа бохир ус цэвэрлэх байгууламжууд, цахилгаан станцуудын ачааллыг улам бүр нэмэгдүүлсээр байгаа бөгөөд үүний үр дүнд Монгол орны байгалийн унаган төрхөөрөө байгаа газар нутгууд, түүний дотор цэнгэг усны экосистемүүдэд экосистемийн доройтол, бохирдол, биологийн олон янзын байдлын хомсдол бий болох заналхийлэл тулгараад байна. Эдгээр заналхийлэлээс гадна уур амьсгалын өөрчлөлт, төлөвлөгдөж байгаа усан цахилгаан станцын томоохон төслүүд нь энэхүү эмзэг экосистемүүдэд аюулын харангыг улам бүр дэгдүүлж байна. Экосистемийн доройтолд өртсөн гол горхи, нуур мөрний тоо нэмэгдэх бүрт тухайн экосистемд тархах организмууд, загасны төрөл зүйл, тэдгээрийн популяцийн тоо толгой буурдаг. Ялангуяа загасны төрөл зүйлүүдийн популяийн тоо, толгойн бууралтад ямарваа нэг зохицуулалтгүй явагдаж байгаа загасчлах аялал, загас олборлолт нь ойрын үеийн томоохон аюулын нэг болоод байгаа юм. Хэдийгээр загас агнуур, загасыг хоол хүнсэндээ хэрэглэх байдал нь Монголын уламжлалт ан агнуур, хоол идээ биш боловч энэ төрлийн соёл, хэрэглээ улам бүр хурдацтай хөгжсөөр байна. Иймд Монгол орны агнуурын ач холбогдолтой цэнгэг усны загасны зарим зүйлүүдийн орон зайн экологи, генетикийн бүтцийн талаархи урьд өмнө хийгдэж байгаагүй судалгааны ажлыг гүйцэтгэх, бусад шаардлагатай мэдээлэл, мэдлэгийг бий болгох зорилтуудын хүрээнд томоохон судалгааны ажлуудын саналыг дэвшүүлж, хэрэгжүүлсэн юм. Түүнчлэн усан орчны бохирдлын нөлөөлөлд хүчтэй өртсөн голуудад тархсан загасыг хоол хүнсэндээ хэрэглэх байдалтай холбогдсон хүн амын эрүүл мэндийн эрсдлийн аюул ажиглагдах болсон тул энэ чиглэлд судалгааны ажлыг мөн гүйцэтгэсэн болно. Ерөнхийд нь дүгнэн үзвэл эдгээр судалгааны зорилго, зорилтуудыг Монгол орны загас хамгааллын өнөөгийн менежментийн арга хэмжээ, төлөвлөгөөг сайжруулахад тус дөхөм болох зөвлөмжийг боловсруулах, шинжлэх ухааны мэдлэг, мэдээллийг нэмэгдүүлэхэд зорьсон. Бидний дэвшүүлсэн менежментийн арга хэмжээний зөвлөмж нь хүрээгээ улам бүр тэлж буй загасчлалын аялал жуулчлалд зохицуулалт хийх, устаж, ховордож болзошгүй загасны төрөл зүйлүүдийн популяцийн тогтвортой байдлыг хангах, хамгаалахад чиглэгдсэн.

2011-2014 онуудад загасны чиглэлд судалгааны 5 дэд төслийг хэрэгжүүлсэн бөгөөд эдгээр төслүүдээс гарсан бүхий л үр дүнг загас хамгаалал, менемжментийн арга хэмжээний зөвлөмжид тусган

танилцуулсан. Эхний дэд төслийн хүрээнд загас агнуур, загасчлалын аялал жуулчлалтай холбоотойгоор социологийн буюу санал асуулгын судалгааг Монгол орны 3 голын сав газрын хэмжээнд хэрэгжүүлсэн. Санал асуулгаар (i) загасчидын хүн ам зүйн судалгаа, (ii) загасчлах чадвар туршлага, (iii) судалгааг авах үед барьсан загасны тоо хэмжээ, баригдсан загасны морфологийн мэдээлэл, (iv) загаслах хэрэгслийн төрөл, тэдгээрийн үнэ өртөг, (v) загасчидын загас хамгаалалын талаархи ерөнхий мэдлэг, санал бодолд чиглүүлэн асуултуудыг тодорхойлсон. Судалгаанд нийт 58 загасчдын бүлгийг (нийт 154 загасчид) хамруулж, санал асуулга явуулсанаас загасчидын эдгээр бүлгүүдийг үндсэн 2 төрөлд ангилж үзлээ: Нэгдүгээр бүлэгт орон нутгийн загасчид буюу өрхийн орлого бага, тухайн голын сав газарт амьдардаг, ганцаараа эсвэл цөөн хэдэн хүн нэгдэж богино хугацаагаар тогтмол загасчилдаг, загасыг тогтмол хүнсэндээ хэрэглэдэг хэсэг бүлэг багтах бол хоёрдугаар бүлэгт хот суурин газрын загасчид буюу өрхийн орлого дунджаас өндөрт хамаарах, хот суурин газарт оршин суудаг, загасчлах хэрэгсэл, загасчлах аялалд илүү их мөнгө зарцуулж, нэг удаадаа хэдэн хоногоор загасчилдаг хэсэг бүлэг хүмүүс хамаарч байв. Загасчид гол төлөв зэвэг загас (*B. Lenok*)-ыг агнадаг байна. Санал асуулгын судалгааны үр дүнгээс үзэхэд Хараа голын сав газарт загасыг хүнсэнд хэрэглэх байдал өссөн болох нь харагдаж байгаа бөгөөд хуучны болон одоогийн уул уурхайн үйл ажиллагаатай холбоотойгоор бий болсон хүнд металлын бохирдлын тархалтаас үүдэж болох хүн амын эрүүл мэндийн эрсдлийн асуудлыг тодорхойлж гаргасан. Иймд судалгааны удаах дэд төсөл нь Хараа голын сав газрын хэмжээнд мониторингийн 11 цэгт голын ус, хагшаас, 5 зүйлийн загасанд хүнд металлын бохирдлын судалгааг гүйцэтгэхэд чиглэгдсэн. Судалгаагаар тухайн 5 зүйл загасанд бүгдэд нь хүнд металл илэрсэн ба голын эхэн хэсгийн цутгал голуудад тархсан зэвэг загасанд цайр (Zn) харьцангуй өндөр хэмжээгээр агуулагдаж байсан голын дундаас адаг цэгүүдэд тархсан загасны булчин маханд хром (Cr), хүнцэл (As), мөнгөн ус (Hg), хар тугалга (Pb) илэрсэн юм. Идэш тэжээлийн түвшинд буюу загасны зүйлүүдэд хром (Cr), зэс (Cu), мөнгөн ус (Hg), хар тугалга (Pb) илэрч, нэмэгдсэн үзүүлэлттэй, ялангуяа судалгаанд хамрагдсан нийт загасны 10 гаруй хувьд мөнгөн усны агууламж загасны маханд агуулагдаж болох дээд хэмжээ (> 0.5 мкг/гр)- нээс давсан байгаагаас дүгнэн үзэхэд хүн амын эрүүл мэндэд зохих аюул нүүрлэсэн болохыг харуулж байгаа юм. Иймд уул уурхай зэргээс гаралтай хүнд металлын бохирдлын сөрөг үр дагавар нь хүнд металлын хуримтлал бүхий загасыг орон нутгийн иргэд хүнсэндээ тогтмол хэрэглэсэнээр ард иргэд хүнд металлын бохирдолоос үүдэлтэй өвчлөлд өртөх байдлаар илрэх боломжтой.

Дараагийн 2 дэд төслүүд нь Ерөө голд тархсан зэвэг (*B. lenok*), Онон, Балж голуудад тархсан тул (*H. taimen*) загасны орон зай, цаг хугацааны аутэкологи, амьдрах орчин, зан төрхийн судалгаанд чиглэгдсэн ба акустик телеметрийн аргыг (дохиолол) ашигласан юм. Өмнө хийгдсэн судалгааны үр дүнгүүдтэй харьцуулахад хоёр зүйл загасны аль алинд хамгийн урт шилжилт хөдөлгөөн (байршил нутаг)-ийг илрүүлсэн бөгөөд зэвэг загасны хувьд 45.3 км, тул загасны хувьд 126.1 км нүүдэллэж байгааг тогтоов. Ялангуяа хавар, зуны улиралд шилжилт хөдөлгөөн эрчимжиж, зарим бодгалиудын хувьд цутгал голууд руу нүүдэллэх, тухайн цутгал голууддаа 4-өөс 85 хүртэл хоногоор өнжсөний дараагаар голын үндсэн гулдралдаа шилжиж байгааг мөн илрүүлсэн. Эдгээр судалгааны үр дүнгүүдээс үзэхэд цутгал голууд нь загасны үржих, идэшлэх, өвөлжих амьдрах орчин болох төдийгүй уур амьсгалын өөрчлөлтөөс үүдэлтэй сөрөг нөлөөллөөс эдгээр зүйлүүдийг хамгаалах гидрологийн болоод дулааны хоргодох газар "refuge" болох чухал ач холбогдолтой болохыг тэмдэглэх нь зүйтэй. Эдгээр устаж болзошгүй 2 зүйл загасны орон зайн экологийн судалгааны үр дүнд бий болсон шинэ мэдлэг, мэдээлэл нь Цэнгэг Усны Тусгай Хамгаалалтай Газар Нутаг (ЦУТХГН) –ийг байгуулах гэх мэтчилэн хамгаалалын шинэ арга хэмжээг боловсруулах, хэрэгжүүлэхэд үндэслэл болж чадах юм.

Сүүлийн дэд төсөл буюу 5 дугаар дэд төсөл нь томоохон гурван голын сав газрын хэмжээнд хадран (*T. baicalensis*), зэвэг (*B. lenok*), тул (*H. taimen*) загасны зүйлүүдийн популяцуудын өөр хоорондын мульти генерацийн ойлголтыг нэмэгдүүлэхэд чиглэгдсэн. Бид молекул болон эсийн бөөмийн маркеруудыг ашиглан популяцийн генетик бүтцийг тогтоож, улмаар эдгээр зүйлүүдийн эволюцийн ач холбогдолтой нэгжүүд (ESUs), мөн нэн тэргүүнд хамгаалах шаардлага бүхий популяцийг Монгол орны тархац нутгийн хүрээнд тодорхойлсон. Сав газрын хэмжэээнд эдгээр гурван зүйл тус бүрийн популяцуудын генетик олон янз байдал бага байгаа нь популяци хоорондын шилжилт хөдөлгөөнийг илэрхийлж байна. Гэвч энэ нийтлэг үр дүн нь зүйл хооронд харилцан адилгүй.

Өргөн цар хүрээтэй хийгдсэн эдгээр судалгааны ажлуудын үр дүнд тулгуурлан Монгол орны загас, түүний дотор хулдын овгийн загасны төрөл зүйлийн талаарх одоогийн мөрдөн хэрэгжүүлж буй менежмент, хамгаалалын арга хэмжээг сайжруулах, шинээр хэрэгжүүлж болох арга хэмжээг багтаасан зөвлөмжийг боловсруулан гаргалаа. Үүнд: 1. Монгол орны томоохон сав газруудын хэмжээнд Цэнгэг Усны Тусгай Хамгаалалтай Газар Нутаг (ЦУТХГН) –ийг байгуулах. Газар нутгийн хэмжээ, байршилыг тухайн газар нутагт хийгдсэн орон зайн экологийн болоод популяцийн генетикийн бүтцийн судалгаанд үндэслэн тогтоох нь зүйтэй; 2. Загасчлах хорионы хугацаа дуусах өдрийн шинэчлэх. Ялангуяа загасчидын голлон агнадаг зэвэг загасны үржлийн нийт хугацаанд агнахыг хориглох. Одоогийн мөрдөгдөж байгаа загасчлах хорионы хугацаа дуусгавар болох хугацаа нь зэвэг загасны үржлийн хугацаатай давхацсан байгаа юм; 3. Морфологи болон генетикийн хувьд алслагдсан, тоо толгой нь хязгаарлагдмал монхор хошуут зэвэг (*B.* sp.) загасыг "Агнахыг хориглосон зүйлийн жагсаалт"-анд нэмэж оруулах; 4. Зэвэг (*B. lenok*) болон хадран (*T. baicalensis*) загасны агнаж болох хамгийн бага биеийн уртын хэмжээг тусгаж оруулах. Энэхүү санал болгож буй арга хэмжээний зорилго нь эдгээр загасны зүйлүүдийг үржлийн шат болоод үржлийн шатнаас өмнөх шатанд устах, тоо толгой нь хорогдохоос сэргийлж байгаа юм. Түүнчлэн томоохон голуудын сав газруудад загас агнуурын хараат болон хараат бус үнэлгээг өгөх, биомониторингийн хөтөлбөрийг (индикатор зүйлүүдийн хүрээнд) хэрэгжүүлэх, ялангуяа бохирдлын нөлөөлөлд хүчтэй өртсөн газар нутагт тархсан загасыг хүнсэнд хэрэглэхтэй холбогдсон, хүний эрүүл мэндэд эрсдэл учруулж болзошгүй хортой хүнд элементүүдийн бохирдлыг илрүүлэх хяналт шинжилгээг гүйцэтгэж байх шаардлагатай байна. Загасчидын загас агнуурын зохицуулалтын талаархи мэдлэг дутмаг байдал, хууль бус загас агнуурын өнөөгийн нөхцөл байдлаас дүгнэн үзэхэд загасчидын загас агнуур, түүний дагаж мөрдөх дүрэм журмын хүрээнд боловсролын хөтөлбөрийг боловсруулах, хэрэгжүүлэх нь зүйтэй. Иймд эрчимтэй хөгжиж буй загасчлах аялал болон устаж, ховордож буй хулдын овгийн зүйлүүдийн популяцийг ирээдүйд хадгалж үлдэх гэсэн хоёр үндсэн хэрэгцээ шаардлаганы тэнцвэрт байдлыг хангах асуудал чухал болоод байна. Гэвч шинжлэх ухаанд суурилсан зөвлөмжүүдийг бүгдийг тусгаж, тодорхой хэмжээнд албадан хэрэгжүүлж байж л өнөөгийн нөхцөл байдалд эрс өөрчлөлт хийх, Монгол орны цэнгэг усны загасны популяци болоод тэдний оршин амьдрах усан орчны экосистемийг хадгалж, хамгаалж чадна. Эцэст нь тэмдэглэхэд Монгол орон бол цэнгэг усны биологийн төрөл, зүйлийн хамгаалал, менежментийн арга хэмжээг бүс нутгийн болоод дэлхийн хэмжээнд авч хэрэгжүүлж чадах загвар бүс нутаг болж чадах юм.

INTRODUCTION

1 Research Objectives and Hypotheses

Freshwater ecosystems including rivers, lakes and wetlands not only contain vital water resources but provide many diverse goods and services of critical importance such as nutrient recycling, flood abatement and climate moderation to human societies everywhere (Postel & Carpenter, 1997; Wilson & Carpenter, 1999). Embedded within these ecosystems, which combined occupy only 0.8 % of the earth's surface, are more than 100 000 aquatic species, including 40 % of the total global diversity of fish species (Gleick, 1996; Lundberg et al., 2000; Malmqvist & Rundle, 2002). While these fish populations are an essential source of animal protein and micronutrients for millions of people in many developing countries around the world (FAO, 2016), they also support extensive commercial and recreational fisheries in almost all industrialized and advancing countries (Arlinghaus et al., 2002, 2010; Cowx et al., 2010; Welcomme et al., 2010; Youn et al., 2014). However, on a global scale, freshwater environments and their fisheries have been increasingly impacted by a plethora of anthropogenic forcings, which have included widespread pollution and contamination, habitat loss, fragmentation, flow modification, channelisation, water extraction, invasive species introductions, overexploitation and climate change (Gozlan et al., 2010; Welcomme et al., 2010; Cowx & Portocarrero, 2011). With the increased impact of these forcings compromising the integrity, resilience and sustainability of both the ecosystem and resident fish populations, their accumulative effect has meant that freshwater environments are now identified as the most threatened and degraded environments on the planet, having experienced declines in biodiversity far greater than those in the most impacted terrestrial ecosystems (Sala et al., 2000; Dudgeon et al., 2006; Ormerod et al., 2010; Vörösmarty et al., 2010).

Mongolia, in northern Asia, is one of the few countries in the world that are comprised of largely intact freshwater ecosystems and robust fish populations (Jensen et al., 2009; Hofmann et al., 2015; Karthe et al., 2015). The country's river and lake networks, especially in its more remote regions, have not suffered from widespread water pollution or habitat loss, there has been no major dams constructed or other large-scale modifications or diversions, and fish populations have generally resisted previous commercial fishing efforts that occurred in the 20th century (Dulmaa, 1999; Chandra et al., 2005; Kottelat, 2006). However, the current socioeconomic transition which is being driven by increased mineral resource exploitation and agriculture and pastoralism expansion, along with urbanisation and proposed hydroelectric dam construction, is now threatening the ecological status of the country's freshwater ecosystems and the aquatic fauna more than ever before (Hofmann et al., 2015; Malsy et al., 2016; Kasimov et al., 2017). Furthermore, there is an even greater threat also facing several of the larger-bodied fish populations, and that is their increased mortality from recreational fishing and poaching activities across the country. While more and more Mongolians are now picking up their rods and reels and are heading out to fish as part of an emerging recreational fishery, urgent action is required to improve conservation and management regulations before these fish population decline further. Anglers are known to target several species that have already suffered from widespread declines in abundance and distribution including the endangered Siberian taimen (*Hucho taimen*; Pallas 1773), the vulnerable sharp-snouted lenok (*Brachymystax lenok; B. lenok*; Pallas 1773), and the near threatened Baikal grayling (*Thymallus baicalensis*; Dybowski 1874; nominative species *T. arcticus*; Ocock et al., 2006).

The sustainable use of inland fisheries resources requires concerted actions that are adopted by individuals, stakeholder groups, non-governmental organisations, regional, state and national governments (Arlinghaus et al., 2002). These actions must be based on sound scientific knowledge regarding the fishery and its target species before adequate regulations can be developed and effective management strategies implemented. However, such detailed information is often difficult, time consuming and expensive to obtain, particularly in less developed nations or in countries with less advanced fisheries research and monitoring infrastructure (Cooke & Cowx, 2006). Additional challenges also exist when gathering information related to recreational fisheries that operate over an expansive area including in remote and isolated river reaches, contain an undetermined amount of illegal activities and / or involve rare and threatened species. Collecting data on Mongolia's emerging recreational fishery and its targeted fish populations encompasses each of these challenges, which has resulted in there being limited previous research undertaken on a range of related topics such as ecology, biology and genetic diversity of the exploited species, with only minimal information also available regarding basic fisheries parameters or potential biocontamination of consumed fish species. This situation has translated to a substantial gap in the understanding and knowledge concerning both the fishery and the fish species in Mongolia, and ultimately has limited the capacity of the responsible authorities to develop and implement sufficient and effective management strategies and prevent species losses. Therefore, the current thesis was undertaken with the aims to gain detailed information on five key research topics, which have their specific objectives and hypotheses described below:

i. An emerging recreational fishery in Mongolia's urbanising society: a threat to its pristine fish stocks?

In order to gain an overview of the expanding recreational fishing activities in Mongolia, roving creel surveys were conducted across three river basins known to be popular fishing destinations with anglers. These surveys aimed to significantly expand the knowledge and understanding of the fishery as very little information has been available for making informed management decisions in the past. There had only been preliminary interviews conducted previously with six fishing families in the Eroo River basin already reporting population declines of target species eight years earlier (Chandra et al., 2005). Therefore, comprehensive surveys were developed to gather a range of data regarding the demographics of the anglers, their fishing history and habits, trip frequency and duration, preferred fishing locations, targeted and regularly caught species, fish sizes caught, consumption rates, gear use, money spent, knowledge of current fishing regulations and opinions on threatened species and conservation. This research is critical and will not only provide a snapshot of the current situation in the fishery but also provide a baseline for comparable work in the future. The main hypotheses of the surveys included:

Hypothesis I: Fishing pressure is higher in the Kharaa River basin, which is closer to Mongolia's urbanising centers (Darkhan and Ulaanbaatar) compared to those that are more isolated (Eroo and Onon basins), and

Hypothesis II: Mongolian anglers are largely unaware of the current fishing regulations, which have led to widespread illegal fishing activities and fish population declines across the country.

ii. Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia)

With recreational fishing activities increasing across the country, potential human health implications associated with the regular consumption of locally caught fish species from heavily polluted river reaches has became evident and thus urgently needed to be addressed. The past and present mining operations have been identified as the source of significant contamination at a number of hotspot locations across the Kharaa River basins, a popular fishing location, with several toxic heavy metals detected previously in elevated concentrations in both the water and soil at those sites (Hofmann et al., 2010; Batbayar et al., 2017). With elevated contents of Hg already detected in Siberian dace (*Leuciscus baicalensis*, Dybowski, 1874) sampled from the Boroo tributary in the Kharaa River basin (Komov et al., 2014), the biocontamination and biomagnification of Hg, and the other toxic heavy metals, in the higher trophic level fish species that were being regularly consumed was completely unknown. Thus, Siberian dace and a further four fish species, including *B. lenok* and *T. baicalensis*, were selected to be sampled from 11 sites across the basin. Heavy metal contents were analyzed in the liver and muscle of collected individuals and were evaluated against the internationally recommended thresholds for each metal in fish tissue for human consumption. The main hypotheses of this important research included:

Hypothesis III: Toxic heavy metals have accumulated in the tissue of five consumed fish species across the Kharaa River basin, with elevated contents present in higher trophic level fish, and

Hypothesis IV: Biocontamination of Hg in consumed fish species from the Kharaa River basin currently present a risk to human health with their regular consumption.

iii. Movements and behaviour of an archaic trout, *Brachymystax lenok* (Pallas, 1773) under extreme environmental conditions in Mongolia

Understanding how fish move spatially within their habitats and temporally under changing seasonal conditions is essential for a science based approach to fisheries and threatened species management. *Brachymystax lenok* is listed as vulnerable in Mongolia, yet likely makes up a significant portion of the total harvest in the emerging recreational fishery, thus making it a species of high priority for management efforts. Although *B. lenok* has an extensive distribution throughout Eurasia, its autecology, and ecology in general, is largely understudied, with only one paper describing the restricted movements (max. 8.17 km) of a closely related species (*B. tsinlingensis*) in a heavily impacted Korean River (Yoon et al., 2015). Thus essential data is missing regarding the spatial ecology of *B. lenok*, with its movements and behaviours (depth and activity) having never before been documented in a highly-connected, free-flowing river system. Therefore, passive acoustic telemetry was selected as the method to obtain such detailed information from multiple individuals in the upper Eroo River over a 12 month period. This research aimed to address two main hypotheses:

Hypothesis V: The home range of *B. lenok* in an unfragmented river system is extensive (> 8.17 km), with significant movements upstream in spring and downstream in autumn, and

Hypothesis VI: *B. lenok* are more active during the day and less active at night, with depth occupancy not showing any diel variations.

iv. Seasonal home range shifts of the Siberian taimen (*Hucho taimen*, Pallas, 1773): Evidence from passive acoustic telemetry in the Onon River and Balj tributary (Amur River basin, Mongolia)

The Siberian taimen, *Hucho taimen*, is the largest salmonid in the world and thus a popular target for recreational anglers across Mongolia where it is listed as endangered on the country's Red List of Fishes. Although this species is now legally protected, there is an expected significant amount of poaching that still occurs and thus populations continue to decline (Ocock et al., 2006; Hogan & Jensen, 2013). Although previous research has reported extensive longitudinal movements of mature taimen of up to 93.2 km along a main river channel (Gilroy et al., 2010) a thorough understanding of this species' seasonal home range shifts into critical tributaries habitats has not been studied before. Therefore, from a management perspective, further detail relating to the spatial ecology of this imperiled, keystone species is essential for developing better conservation and species recovery strategies going forward. Passive acoustic telemetry was again chosen to tag and track the movements of individual *H. taimen* over a 12 month period between the Onon River and a major tributary (Balj) in the Amur River basin, eastern Mongolia. The hypotheses for this research included:

Hypothesis VII: *H. taimen* seasonal home ranges are more extensive in spring and autumn but are largely restricted during the summer and winter (ice coverage) months, and

Hypothesis VIII: All *H. taimen* descend tributaries (Balj tributary) in autumn after spawning / feeding to overwinter in deeper pools within the main river channel (Onon River).

v. Fish conservation in the land of steppe and sky: evolutionary significant units of threatened salmonid species in Mongolia mirror major river basins

In order to improve fisheries management outcomes, it is often necessary to demarcate the interconnectedness of conspecific populations within a river basin by conducting a metapopulation analysis that uses genetic markers to define and describe Evolutionary Significant Unit (ESUs) and priority populations. While ESUs represent a meaningful cluster of populations that maintain regular gene flow, and therefore represent genetically distinct and reproductively independent groups within a species distribution, the identification of priority populations based on elevated genetic diversity and differentiation provides for a clearer more targeted approach for implementing management strategies within the ESU. Thus, with a comprehensive understanding of the connectivity between threatened *H. taimen, B. lenok* and *T. baicalensis* populations throughout Mongolia, there is a greater chance to protect and conserve higher levels of genetic diversity and thus evolutionary potential within these species, which will improve their capacity to adapt to future environmental changes. In addition, the identification of priority populations is particularly important in regions where resources for conservation are limited such as in Mongolia. Therefore the main hypotheses for this genetic research were:

Hypothesis IX: Evolutionary Significant Units of Mongolia's threatened salmonid species mirror major river basins due to high within basin gene flow and connectivity, and

Hypothesis X: Larger bodied species such as *H. taimen* display increased genetic homogeneity over larger spatial scales compared to smaller bodied species such as *B. lenok* and *T. baicalensis*.

1.1 Overall Thesis Objectives

The overarching goals of the current fisheries related research conducted in data poor Mongolia (Karthe et al., 2015) is to not only advance the knowledge and understanding of several aspects related to the country's emerging recreational fishery and its main target species, but also, to collate the anticipated results and devise a list of key recommendations for improving the existing management and conservation strategies. In addition, methods for mitigating the impact on these threatened fish populations from current anthropogenic forcings and substantial imminent threats are discussed along with possible ways to improve angler compliance.

2 Mongolia's Natural Environment

2.1 Geographic Ecoregions

Mongolia is located in northern Asia, on the central Asian plateau, between the Russia Federation and the People's Republic of China (latitudes 41˚ and 52˚ N and longitudes 87˚ and 102˚ E). It is the second largest land locked country in the world and the 19th largest overall with a total land area covering 1 564 116 km^2 (Galdan et al., 2010). Mongolia's average elevation is 1580 m above sea level (a.s.l.), with the country's highest point, Khuiten Peak (4374 m), located in the Tavan bogd massif within the Altai Mountains in the far western provinces. Along with the Altai, there are also the Khangai Mountains running through the center of the country and the Khan Khentii Mountains in northern Mongolia. The country's lowest point is Hoh Nuur at 518 m a.s.l. in the eastern plains. Mongolia's unique location places it in an ecological transition zone between the Mongolian-Manchurian steppe, the Siberian taiga forest and the Gobi desert. The steppe ecoregion consists of temperate grass and shrub lands that covers 887 300 km^2 and forms a crescent around the Gobi desert. Deciduous forests of birch (*Betula platphylla*), Siberian larch (*Larix sibirica*) and several pine species (*Pinus sibirica*, *P. silvestis*, *P. obovarta*), make up between 8 and 10 % of the total area of Mongolia, mostly in the mountainous northern regions. The Gobi desert in the south, Asia's largest desert, occupies 1 295 000 km^2 in Mongolia and northern China and consists mostly of bare rock and small regions of sand.

2.2 Climatic Conditions

The continental climate in Mongolia produces extremely cold and dry winters that last from November until March each year when average air temperatures remain below freezing (-35°C to -15°C) and there is minimal precipitation (Batima et al., 2005). However, in certain years blizzards or *dzuds* bring extreme cold and freezing rain to large regions of the country causing significant losses of human life and livestock (Nandintsetseg et al., 2007). The most recent of these occurred in the winters 2011 when 16 000 livestock died as a result of particularly harsh, sub-zero conditions. In contrast, Mongolian summers are short and hot with maximum temperatures reaching 38°C in the Gobi desert and 33°C in the capital, Ulaanbaatar. The northern regions receive the highest annual rainfall in the country with 300 – 400 mm, typically falling in the warmest months between April and September, which generates periodic flooding events (Batima et al., 2005). The southern regions, including the Gobi desert, generally receive no rainfall in most years.

2.3 Hydrological Networks

Despite Mongolia's dry, semi-arid landscape there are extensive rivers and lake systems which are mostly located in the northern half of the country (Figure 1). These freshwater ecosystems form three distinct hydrological basins that make up only 0.7 % of the total land area in the country. The largest of these in terms of area is the Central Asian Basin, which covers 65 % of Mongolia's most western and southern regions (Dulmaa, 1999). This basin is endorheic and is thus made up of internal draining watersheds including the Great Lakes Depression, the Valley of Lakes and the lowlands of the Gobi Desert. Within this region there are six major lakes, both saline and freshwater (Baatar et al., 2017), several major rivers including the Khovd, Zavkhan and Tesiin, and important wetlands that support a number of threatened migratory bird species.

The Selenge River basin in the central north of the country is the largest external discharging river system in Mongolia, making up over 90 % of the total Arctic Ocean drainage watershed in Mongolia (447 000 km^2). The Selenge River is also the main inflow (60 %) for the world's largest and deepest freshwater lake, Lake Baikal in Siberian Russia (Stubblefield et al., 2005; Tornqvist et al., 2014; Kasimov et al., 2017). Mongolia's two largest cities, Ulaanbaatar and Darkhan, are situated within the Selenge River basin on the Tuul and Kharaa rivers respectively. Lake Hovsgol, Mongolia's largest lake by volume drains into the Eg River, a major northern tributary of the Selenge. This ultra-oligotrophic lake is 136 km long, 36.5 km wide and has a maximum depth of 267 m. It holds 70 % of the country's freshwater and 0.4 % of all the freshwater in the world. Despite its very remote location, Lake Hovsgol has recently come under an increasing pollution pressure (Free et al., 2016). The remaining 10 % of the Arctic Ocean drainage consists of the very upper reaches of the Yenisei River, with the Shishged being the major river in this separate watershed in the Darkhad Depression, a small region located west of Lake Hovsgol in the country's far north-central region.

The other large river basin in Mongolia includes the upper tributaries of the Pacific Ocean draining Amur River in the north east of the country (Figure 1). The Amur River is the 10th longest river in the world and one of the last free-flowing rivers of its size. Three tributaries are located in Mongolian territory including the Onon River, which flows north-east from the Khan Khentii Mountains 818 km (298 km in Mongolia), the Kherlen River, the most southern tributary within the Mongolian Amur catchment, which flows over 1250 km from the Khan Khentii Mountains east before entering Hulun Lake in China, and the Khalkhin tributary that runs through far eastern Mongolia, close to the Chinese border. This river is 233 km long and flows first into Buir Lake and then also on to Hulun Lake in China.

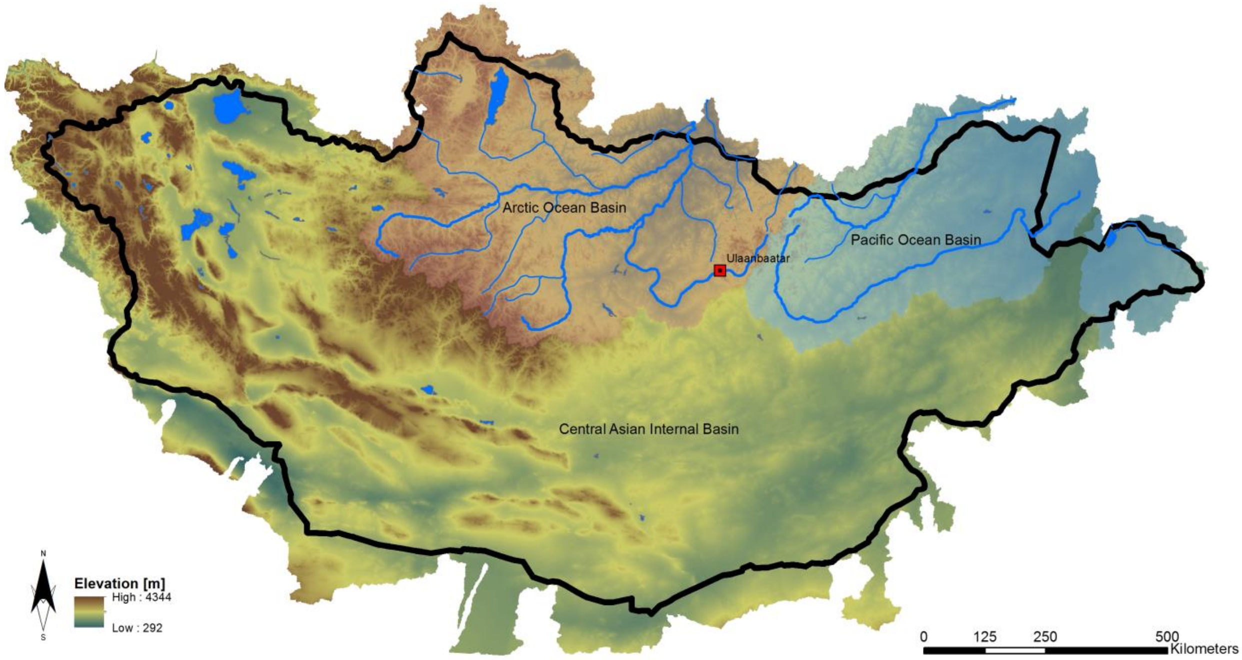

Figure 1. Elevation map of Mongolia. Elevation map of Mongolia showing the Arctic Ocean Basin, the Pacific Ocean Basin and the Central Asian Internal Basin.

2.4 Freshwater Fish Fauna

Within Mongolia's freshwater ecosystems there resides a unique fish assemblage made up of approximately 76 native and two introduced species (with established populations) from 14 families (Kollelat, 2006). However, it is expected that this number will continue to increase with additional research as confusion remains surrounding the taxonomy of several species (Kollelat, 2006). The highest species diversity is recorded from the Amur River basin (~ 44 species), while the Selenge River basin is reported to have only half of that with ~ 24 species. The Central Asia basin has the lowest species diversity with only eight species (Dulmaa, 1999). The cyprinids (Family Cyprinidae), which includes the carps and minnows, are the most abundant and diverse fish family in Mongolia with 41 confirmed species. This is followed by the Family Nemacheilidae with eight species including several stone loaches from the genus *Barbatula*, and the Family Thymallidae with five grayling species (*Thymallus* species). The remaining 11 fish families have only three or less species currently recognised in Mongolia. Four of Mongolia's endemic fish are found in the Central Asian Basin including the Mongolian grayling (*Thymallus brevirostris*), lake Osman (*Oreoleuciscus angusticephalus*), Dzungarian dace (*Leuciscus dzungaricus*) and the Gobi loach (*Barbatula dgebuadzei*).

The status of many of Mongolia's fish species have been assessed where possible and included on to the country's Red List of Fishes in 2006 (Ocock et al., 2006). This document considered only 64 native species of which 48 were classified into conservation categories according to the guidelines and criteria of the IUCN Red List (IUCN, 2001). Sixteen species of were not assessed due to their unconfirmed presence in Mongolia, while 22 (46 %) species were listed as data deficient (DD) due to insufficient information on basic population biology, distribution and abundance. The resulting status of the remaining species highlighted significant declining trends and threats to many Mongolian fish species. While only one species, the Siberian sturgeon (*Acipenser baerii*) was listed as Critically Endangered, six species were assigned endangered status (*Hucho taimen, Thymallus grubii, T. nigrescens, Coregonus pidschian, Leuciscus dzungaricus* and *Barbatula dgebuadzei*), four species were listed as vulnerable (*Brachymystax lenok, Orecleuciscus angusticephalus, O. humilis,* and *T. brevirostris*) and three species as Near Threatened (*Acheilognathus asmussi, Leuciscus idus and T. arcticus* – re-described as *T. baicalensis*) (Ocock et al. 2006).

3 Anthropogenic Forcings

3.1 Current Socioeconomic Transitions

Mongolia, one of the least densely populated countries in the world (< 2 people / km^2), is currently experiencing a significant socioeconomic shift (World Bank, 2017; Fan et al., 2016). The vast steppe landscapes that have supported the traditional nomadic and semi-nomadic herding lifestyles for millennia are increasingly being abandoned as Mongolians, particularly the younger generations, move in large numbers to the urban centres in search of better jobs prospects, education opportunities and health care (Fan et al., 2016; Long, 2017). As a result, over one third of the 3.027 million people (2016) now live in the capital Ulaanbaatar, with over 60 % of the city's residents living in sprawling, unplanned "ger" (Mongolian tents) settlements on the outskirts of the city (Long, 2017). This urbanisation, along with the country's significant economic growth, which has been driven by the expansion in the mining sector and increases of large-scale, commercial agriculture and livestock production, has helped to generate a growing middle and upper class. Mongolia is now classified as a lower-middle income country by the World Bank, even though 21.6 % of Mongolia's population in 2017 are still living in poverty (Asian Development Bank, 2017). However, this rapid transition that has continued across the country since the political changes in the early 1990s from a one party socialist system to a multi-party, open market democracy has also come at a significant environmental cost. Environmental protection laws and regulations have not existed, been inadequate to address the changing conditions or have been intentionally set aside in the name of progress. The major anthropogenic forcings that have impacted on Mongolia's freshwater ecosystems and have thus contributed the most to the decline of Mongolia's threatened fish populations are discussed below.

3.2 Intensifying Fishing Activities

The capture and consumption of fish in Mongolia was first documented in the 13th century, with mention of hooks and nets made of horse hair harvesting local fish populations to be preserved for winter (Dulmaa, 1999). Then approximately 250 years ago, fish stocks began to be commercially exploited by Russian merchants who caught fish in Mongolia and transported them to Siberia for sale (Dulmaa, 1999). By the beginning of the 20th century, commercial fishing was fully operational across the country with fish from more than 20 species being harvested from both rivers and lakes (Dulmaa, 1999). According to the Food and Agriculture Organization (FAO), Mongolia's annual harvest between 1975 and 2008 was highly variable, with maximum catches obtained in 1979 and 1999 of more than 500 t, and minimum catches recorded in 1991 and 2008 of 100 t or less (FAO, 2017). Since 2008, the annual reported harvest has been 100 t or lower, with the lowest ever recorded catch in 2014 of 49 t (FAO, 2017). Although there has been a general decline in Mongolia's annual commercial harvest over recent years, there is also believed to be an unknown level of illegal commercial fishing occurring across the country with reports that it is significant and driven by the demand for Mongolian fish in both Chinese and Russian black markets (Ocock et al., 2006; Hogan & Jensen, 2013).

While Mongolia's commercial harvests have been steadily declining, fish capture and consumption within the country's recreational fishing communities have been growing rapidly due to rising economic wealth, widespread availability of cheap, imported fishing gear and influence from foreign fishing techniques and practices (Chandra et al., 2005). Although there is currently very little data available on this emerging recreational fishery, it is expected to consist of a growing proportion of Mongolia's new middle and upper classes who now have the resources to travel extensively to the country's pristine rivers and lakes to spend their leisure time fishing and camping. There is also thought to be a small number of subsistent anglers who rely on local catches to supplement both their diet and income, but this is yet to be fully determined. Although, fishing laws including licensing and seasonal closures are in place, fishing activities are largely unregulated and as such there is an expected significant amount of illegal fishing taking place across the country (Ocock et al., 2006, Jensen et al., 2009; Hogan & Jensen, 2013). While compliance and enforcement of the fishing regulations is undoubtedly a major issue for authorities, the regulations themselves also need to be updated and expanded in order to better protect the threatened fish populations and their critical habitats going forward. For a more detailed description of the current Mongolian fishing laws refer to Appendix 1. In addition, there is also a growing number of local and foreign fishing outfitters that conduct *H. taimen* fishing expeditions during summer and autumn each year, with most companies operating in the more remote river basins including the Egiin (Eg), Delgermoron, Shishged and Onon. While some locally run, budget companies have been accused of operating without proper licensing and are rumored to not always adhere to strict catch and release fishing practices, the international operators have invested heavily in conserving *H. taimen* populations and their habitats, as the conservation of this species is essential to the success of their businesses.

3.3 Contamination of Aquatic Ecosystems

Mongolia's freshwater ecosystems have suffered a progressive degradation in recent years due to a myriad of reasons related to growing urbanisation, mining, industrialisation and shifting land use practices (Onda et al., 2007; Priess et al., 2011; Hartwig et al., 2016). This degradation now poses serious challenges for Mongolia, as water quality and quantity have been significantly affected along with the ecological services that the rivers and lakes provide. In many regions, related public infrastructure such as waste water treatment plants (WWTPs) has not kept pace with contemporary changes and thus a large number of “gers” and newly built households in smaller towns are not connected to the region’s outdated WWTPs. As a result high amounts of poorly treated wastewater have entered the adjacent waterways (Hofmann et al., 2010; Karthe et al., 2015). This increased discharge of nutrients and other contaminates has led to serious implications for water quality and the potential for significant eutrophication issues in many regions across Mongolia including the lower Kharaa River basin (Hofmann et al., 2011). In addition, the massive expansion and intensification of the agriculture sector, has also seen an increase in the application of mineral fertilizers and manure to cultivated land, which has additionally influenced river water quality due to run-off related impacts (Hofmann et al., 2010; Karthe et al., 2015).

Following the socio-economic and political changes in Mongolia in the early 1990’s, the national herd consisting of goats, sheep, horses, cattle, camels and reindeer was left largely unregulated and thus has grown dramatically, currently standing at over 61.5 million animals (National Statistics Office of Mongolia, 2017). As a result of this expansion, there has been widespread overgrazing of the steppe, including the adjoining riparian vegetation in many river basins, which together with the excessive trampling from livestock, has dramatically reduced the riverbank stability and led to increased erosion and fine sediment input into the river channel (Hartwig et al., 2016). The subsequent effects within these aquatic ecosystems have included increased turbidity and sedimentation, which has been reported to have impacted the hyporheic zone dimensions and functioning through restricted spatial extent, lowered hydraulic connectivity, lower metabolism and ecological critical quality of pore water, with the most prominent ecological response related to decreased biomass of benthic algae and altered macroinvertebrate community metrics (Hartwig et al., 2016). Although the resident fish communities were not extensively investigated in this regard, high turbidity and sedimentation is known to negatively affect most fish species, especially salmonids, by reducing visibility and thus successful prey capture (de Robertis et al., 2003), increased physiological stress (*e.g.* gills trauma) and ultimately reduced survival rates (Bash et al., 2001). Sedimentation can also prevent eggs in redds from receiving oxygen and inhibiting removal of waste products as well as entrapping larvae in the substrate (Everest et al., 1987). At this point, it is unclear if Mongolian fish communities in the impacted regions are being negatively affected under the current conditions.

Over the past 50 years, the mining industry in Mongolia has been experiencing a rapid expansion with extensive mineral deposits of copper, coal, molybdenum, tin, tungsten and gold being increasingly discovered, extracted and exported (Dallas, 1999). At its height, mining was responsible for more than 80 % of the country’s trade and

21.8 % of the national gross domestic product, with further growth predicted in the near future as continued foreign investment and new large-scale mines come online such as Tavan Tolgoi, which contains the world's largest untapped coal deposits (Mongolian Statistical Information Services, 2015).

In many cases mining activities have also been largely unregulated or illegal and were regularly conducted using inefficient and out of date extraction methods. Although legislation was passed in 2012 prohibiting all forms of mining activities from being conducted close to a river, stream or lake, many mining operations have continued unopposed in impunity, while others have left a lasting legacy of significant environmental damage and contamination of air, soil and water at numerous abandoned mining sites around Mongolia (Choi et al., 2004; Hofmann et al., 2010; Sorokina et al., 2013; Batbayar et al., 2015; Thorslund et al., 2016). Already in 2003, a state inventory for surface water in Mongolia identified 23 rivers in eight provinces as being morphologically altered and / or polluted due to mining activities, with several tributaries of the Selenge River including the Tuul and Kharaa included on this list (Batsukh et al., 2008). While some commercial companies were involved in large scale strip-mining of tributaries, others have used draglines from placer dredges to remove large amounts of topsoil, vegetation, and up to 10 m of overlying layers of alluvium so it could be sluiced for gold and later deposited into dredge pits (Stubblefeld et al., 2005). With these extensive operations, over 4000 m^3 of gravel and sand were processed in a day, with several km of floodplain extracted in a year (Stubblefeld et al., 2005). This surfacing mining has caused severe disturbances of both the terrestrial and aquatic environment (Choi et al., 2004).

Along with increased turbidity and total phosphorus from mining alluvial soils in Mongolia (Stubblefield et al., 2005; Chalov et al., 2015), one of the biggest environmental issues associated with mineral extraction, particularly gold, has been the influx of heavy metals into the surrounding environment due to the natural weathering of newly exposed and overburdened soil and rocks *e.g.* As, as well as the past and present use of illegal mining techniques *e.g.* Hg to extract gold (Grayson et al., 2004; Steckling et al., 2011; Pfeiffer et al., 2015; Batsaikhan et al., 2017). These toxic heavy metals have been detected in elevated concentrations in certain hotspot regions where mining activities have, or are still occurring (Hofmann et al., 2010). However, the extent that these heavy metals have been incorporated into the resident fish species remains relatively unknown, with preliminary research on the topic having solely investigated the bioaccumulation of Hg in Siberian dace (*Leuciscus baicalensis*) from the Boroo Gol, a tributary of the Kharaa River that has been highly impacted by mining activities in the past (Hofmann et al., 2010; Komov et al., 2014; Pfeiffer et al., 2015). Thus, the level of this Hg contamination along the aquatic food chain and the subsequent risk to human health from consuming

Siberian dace and other higher trophic level species has not yet been determined. Likewise the contamination level of other toxic heavy metals, which have also been detected at elevated concentrations in the Kharaa River basin (water and sediment) including As, Pb, Cadmium (Cd), Cr, Cu, nickel (Ni) and Zn have also not been addressed by the scientific community or health / environmental authorities previously. Therefore, heavy metal contamination of consumed fish species in the Kharaa River presents an unevaluated risk to human health as the capture and consumption of local species continues to grow across the basin. Urgent investigations are required in order to fully describe the content of these toxic heavy metals in consumed fish tissue from the Kharaa River basin, one of the more popular fishing locations in Mongolia.

3.4 Imminent Threats

As well as the mounting threats that are currently applying pressure to Mongolia's freshwater ecosystems and their resident fish populations, there are two additional major anthropogenic forces that are expected to induce significant habitat modifications and fundamentally alter the boreal aquatic environment going forward. These include the construction of several, large-scale hydroelectric dams and the imminent effects of climate change.

The desired expansion of Mongolia's energy production via hydroelectric power, along with the need to create a secure water supply to develop new mining and refining operations in the Gobi Desert, looks set to transform several major river systems in both the Selenge and Amur River basins in the near future. Mongolia's rapid urbanisation and development has meant the nation's energy provisions are under pressure and thus the Ministry of Energy is attempting to diversify the county's power supply to ultimately become self-sufficient (Kohn, 2015). Although hydropower was introduced to Mongolia as early as the 1950's, with technical and economic assistance from the Soviet Union, only 10 small plants and an additional two larger stations at Dorgon (12 MW) and Taishir (11 MW) in western Mongolia are currently operational (WWF Mongolia, 2017; Hydroelectric Plants in Mongolia, 2013). However, there are now several major proposals throughout Mongolia that are either in the early stages of planning and development or construction including a 300 MW Shuren hydroelectric project on the Selenge River main channel and a 315 MW hydroelectric project on the Eg River, as well as a dam (with hydroelectric capabilities) and reservoir with substantial water diversion schemes planned for both the Orkhon and Kherlen rivers (HydroWorld, 2013; Simonov & Wickel, 2015). While these projects have the potential to meet Mongolia's growing power requirements and reduce the reliance on the heavily polluting coal fired power stations, there is also a river basin scale environmental impact expected with significant consequences for the aquatic ecosystem both above and below the planned dam walls. These major effects are well known and generally include large scale habitat transformations where lotic species are lost from the newly formed lentic environment, habitat fragmentation with the movement of species, nutrient and sediments being partially or completely blocked. There is also a dramatic alteration of the natural flow regimes and at certain times of the year potential sharp declines in water quantity and quality downstream from the dam (Dynesius et al., 1994; Nilsson et al., 2005). The damming of the Selenge River and its tributaries will, in addition, impact the world's largest freshwater lake (by volume), Lake Baikal in Siberia, as the Selenge provides over 50 % of the main water inflow (Leermakers et al., 1996).

Climate change is another major factor that threatens the freshwater environments and fish communities in Mongolia, even though the continental climate is already categorized as extreme with long, cold winters; short, hot summers and low annual precipitation (Karthe et al., 2015). While Mongolia has already experienced an increase in the mean air temperature of 1.8˚C since the 1940's, with all seasons becoming warmer (Batimaa, 2006), computer models are predicting a further rise of between 2.6 and 5.1˚C before the end of the century (Karthe et al., 2014). Precipitation trends have also shown high spatial and temporal fluctuations throughout the country (Liu et al., 2013), with high evapotranspiration in many regions (Priess et al., 2011). Future predictions suggest that the mean annual precipitation will increase by 20 to 86 mm per year (Karthe et al., 2014), with others indicating there will be a significant decrease (Sato et al., 2007). In any case, increased temperatures and variability in precipitation are likely to have various direct and indirect effects on regional hydrology, vegetation growth, permafrost persistence and snow coverage (Liu et al., 2013; Karthe et al., 2014). For the fish fauna, this could potentially mean a shift to more frequent and extreme high water temperatures, low water levels, unseasonal flood events, prolonged extreme winter temperatures and expanded ice coverage, which can all have a significant impact on the survival of many of the already threatened fish species (Ocock et al., 2006).

RESEARCH CHAPTERS

4 An emerging recreational fishery in Mongolia's urbanising society: a threat to its pristine fish stocks?

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4.1 Abstract

Mongolia's freshwater fish populations have persisted in a near natural state for centuries. However, over the last 25 years this has changed substantially as the country has undergone a rapid socioeconomic change following the shift in 1990 from a socialist economy to a market based economy. Over the same period, recreational fishing has increased in popularity to the point where it is considered to be the primary threat to several targeted fish species. Despite this, minimal data is available for management purposes as the fishery has remained poorly studied. Therefore creel surveys were conducted across three river basins in 2012, which aimed to provide the first overview of the fishery as it relates to five key topics (angler demographics, fishing practices, current fishing trip data, fishing gear and costs and angler knowledge and opinions). Anglers could be separated into two main types: rural anglers that have no or low incomes, reside in the basin, fished alone or in smaller groups, fished more frequently but for shorter periods and consumed fish more regularly; and urban anglers who have medium to high incomes, live in the capital city Ulaanbaatar, spent more money on fishing gear and trips and fished more intensely for multiple days at a time. *B. lenok* was targeted and captured most often (63 % of total catch) by both angler types. Total catch per unit effort (CPUE) was highest in the Onon River and lowest in the Kharaa River. However in all three catchments both legal and illegal fishing was reported to be common, which sums up to a significant threat for native fish stocks. Thus authorities need to improve current management approaches by implementing scientifically sound strategies in addition to more effective enforcement measures and widespread angler education programs.

4.2 Introduction

The human exploitation of freshwater fish stocks from inland waters is virtually ubiquitous on earth (Allan et al., 2005; Arlinghaus, 2005). While communities in many poor and rural regions, particularly in the developing world rely heavily on subsistent harvests as an irreplaceable source of dietary protein, micronutrients and income (FAO, 2016; Youn et al., 2014), in economically advancing countries, freshwater catches are increasingly dominated by community based recreational fishing (Welcomme, 2001; Arlinghaus et al., 2002). It is the recent expansion of these recreational fisheries that has now made them the principal exploiter, and thus the primary causal agent in the decline of numerous inland fish stocks within the rivers and lakes where they operate (Post et al., 2002; Cooke & Cowx, 2006; Lewin et al., 2006). It is therefore imperative that such emerging recreational fisheries are not simply disregarded by authorities as having a negligible impact on resident fish stocks, but are monitored and managed carefully to ensure their sustainability and prevent their over exploitation. While scientifically sound recreational fishery management strategies demand detailed knowledge relating to various biological and ecological components of the target species and system, it is also essential to consider the actions, characteristics and behaviours of participating angler groups (Arlinghaus & Mehner, 2004), as recreational fisheries management, is in essence, people management (Arlinghaus et al., 2002).

The challenge to successfully manage exploited fish stocks in countries and regions where resources are often limited and fisheries data is typically minimal or completely missing is difficult (Arce-Ibarra et al., 2008; Bentley, 2015). Thus this makes the application of common management techniques such as maximum sustainable yields or safe biological limits problematic as these tools rely not only on estimates of biological parameters such as natural mortality rates and age at first maturity, but also fisheries parameters including total harvest levels and fishing effort as well as relevant spatio-temporal patterns of fishing pressure. For recreational fisheries, this essential data is often collected from creel surveys where anglers are interviewed and their catches measured and recorded over a specific period of time or location (Ellender et al., 2010; Veiga et al., 2010). Inter-annual creel surveys can also be used to identify long-term fishing trends and related impacts on fish communities such as shifts in target species, reductions in population biomass and losses of biodiversity as well as the possibility to assess the effectiveness of various management strategies (Dunlop et al., 2012; Wise et al., 2012). For an emerging recreational fishery, such as the one in Mongolia, conducting comprehensive creel surveys is an essential first step in providing this preliminary data in order for establishing a reference point to monitor the development of the fishery and its impact on the targeted fish populations as it continues to develop.

Mongolia has experienced a comprehensive socioeconomic shift over the past three decades following the political transition in the country when high unemployment rates, mass livestock mortalities, inflated food prices and increased availability of cheap fishing gear all likely contributed to an increased fishing effort (Dulmaa, 1999; Chandra et al., 2005). While initially the capture of fish was likely a low cost way to supplement protein in regional diets, in more recent years, it has been assumed that fishing has gained popularity due to substantial lifestyle changes that include higher incomes and increased leisure time (FAO, 2012). As a result, there is now widespread concern that these recreational anglers pose an existential threat to the local fish populations that have until recently persisted in a relatively pristine state. Until now, they have never been harvested intensely, nor widely impacted by stocking programs or species introductions, nor fragmented by major dams or suffered from substantial habitat loss and pollution (Dulmaa, 1999; Kottelat, 2006; Karthe et al., 2017). However, as the rapid growth of recreational fishing in Mongolia has been largely unregulated and included a significant amount of illegal harvesting, there has also been a corresponding decline in the distribution and abundance of several of the main target species including *Hucho taimen* (Pallas, 1773), *Brachymystax lenok* (Pallas, 1773) and *Thymallus baicalensis* (Dybowski, 1874) (Ocock et al., 2006; Hogan & Jensen, 2013). Thus, the increased fishing pressure has reduced the status of these species to *endangered*, *vulnerable* and *near threatened* (nominative species listed as *T. arcticus*) respectively on the Mongolian Red List of Fishes 2006 (Ocock et al., 2006).

To date, very little information is available on Mongolia's emerging recreational fishery as there has been no previous detailed assessment undertaken across the country. Only Chandra et al. (2005) has conducted preliminary interviews with six local families in the Eroo River who reported that there had already been a decline in *H. taimen* (size and abundance) and sturgeon (*Acipenser baerii*, Brandt 1869) catches, particularly below intensive mining locations. Therefore the current research objectives were to obtain a broader scale understanding and insight into Mongolia's emerging recreational fishery in order to provide information for improving national management strategies and promoting sustainability of resident fish stocks. Comprehensive creel surveys were conducted across three river basins that are popular fishing locations in Mongolia during the open fishing season between mid-June and October 2012. The basins were chosen due to their variation in regards to the number of residents, access, fishing potential (*id est* (*i.e.)* target species abundance) and past observed fishing effort. The surveys consisted of five sections including S1: Angler Demographics, S2: Fishing Practices, S3: Current Fishing Trip Data, S4: Fishing Gear and Costs, and S5: Angler Knowledge and Opinions.

4.3 Materials and Methods

Study Basins

The Kharaa River (362 km) is located in northern Mongolia within the Selenge River basin (Arctic Ocean drainage, Figure 2). It is a third order stream with an average annual discharge of 8.3 $m^3 s^{-1}$, although during the survey period in 2012, river discharge was significantly below the long-term average (Karthe et al., 2014). The 14 534 km^2 basin is one of the most densely populated in Mongolia containing approximately 147 000 inhabitants in three main centers, including the country's second largest city Darkhan (74 000 residents). There is substantial agriculture, grazing and mining operations in the middle and lower reaches, which has led to increased nutrient input, erosion and heavy metal contamination of surface, sediment and fish fauna (Hofmann et al., 2010; Hartwig et al., 2016; Kaus et al., 2016; Batbayar et al., 2017), while the upper reaches are characterized by only limited anthropogenic impacts (Kopp et al., 2014; Hofmann et al., 2015). Mongolia's capital Ulaanbaatar, with 1.2 million residents, is also in close proximity to the south-east of the basin with easy access by both sealed road and railway. The Kharaa River fish fauna consists of 16 species, with eight being caught by anglers including *Brachymystax lenok, Thymallus baicalensis, Leuciscus baicalensis* (Dybowski, 1874), *Esox lucius* (Linnaeus 1758) , *Perca flavescens* (Mitchill, 1814), *Silurus asotus* (Linnaeus 1758), *Lota lota* (Linnaeus 1758), and *Cyprinus carpio* (Linnaeus 1758). *H. taimen* are rarely caught in the basin and are expected to only exist

The adjacent Eroo River basin is located to the north–east of the Kharaa basin but due to the absence of intensive land use, mining operations and major settlements in its upper and middle regions, the Eroo River is one of the least polluted in northern Mongolia (Batbayar et al., 2017; Karthe et al., 2017). Khonin Nuga is located in its upper reaches and is only accessible by 4WD along an 80 km dirt road from Zuunkharaa (Kharaa basin). The ranger and his family are sole permanent residents throughout the year, with forestry workers frequenting the area regularly during the survey period. The region is mountainous with large areas of taiga forest and narrow river valley sections that are only accessible by inflatable boat. Officially since 2013 the region surrounding Khonin Nuga has been included in the extension of the Khan Khentii Strictly Protected Area, although recreational fishing has not yet been prohibited. Until recently the resident fish fauna, which is similar to that found in the Kharaa basin, had not been heavily fished due to its isolation. Thus larger, mature *H. taimen* (~ 1m) are still present, while *B. lenok* and *T. baicalensis* are relatively abundant in extremely low numbers or enter as migrants.

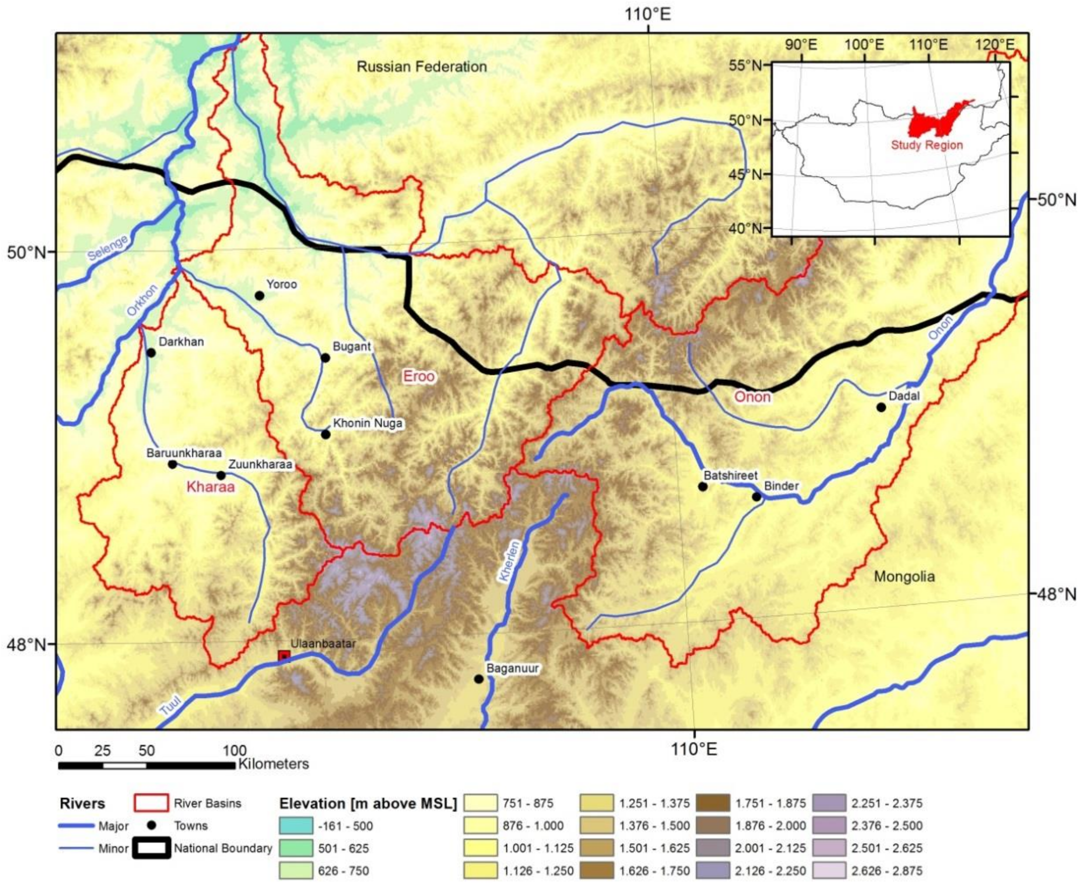

Figure 2. River basins in Mongolia. Map showing the three river basins including the Kharaa, Eroo and Onon (outlined in red) in northern Mongolia where creel surveys were conducted between June and October 2012.

The Onon River (94 010 km^2) is a third order tributary of the Amur River (Pacific Ocean drainage) and is located in north-eastern Mongolia, where it flows 298 km until the Russian border (Figure 2). The middle and lower reaches of the Mongolian section meanders through rocky outcrops and steppe landscape with patches of taiga forest. Several small towns are in close proximity to the Onon River including Batshireet, Binder and Dadal (total residence 1000 – 3000), which make the river readily accessible to local residents. A sealed road part of the way from Ulaanbaatar also allows city travelers to visit the area relatively easily. The Onon River basin contains one of the last robust *H. taimen* populations in Mongolia, two *Brachymystax* species including the sharp-snouted (*B. lenok*) and blunt-snouted (*B. sp.*) lenoks, which are commonly misidentified by anglers, *Thymallus grubii* (Dybowski, 1869) and *Esox reichertii* (Dybowski, 1869).

Creel surveys

Creel surveys were translated into Mongolian language and distributed to all anglers and fishing groups that were encountered in the river basins between June 15th and October 1st 2012. Although there was not a constant effort to search for anglers over this time, there were 28 days in total where surveys were conducted, particularly on the weekends when fishing effort increased. The survey consisted of a total of 40 questions across five sections S1: angler demographics, S2: fishing practices, S3: current fishing trip data, S4: fishing gear and costs and S5: angler knowledge and opinions. One survey was completed per fishing group with the explanation to provide specific individual details where appropriate *e.g.* number of fish caught per person. Not all questions were answered by all anglers; but all legitimate responses were considered and included in the summary tables and analyses. Where an amount range was given *e.g.* fishing trips or money spent, a mean was taken and used in the overall calculations. With respect to the estimated money spent on going fishing over a year, the money spent on the current trip was multiplied by the estimated number of trips for 2012. All CPUE estimates were minimum values as most surveys were conducted in the middle of each fishing trip, which is why CPUE was calculated per hour as well as per day. Data was analysed using Kruskal-Wallis Test and Tukey HSD post-hoc test and was visualized in R (R Development Core Team 2010, version 1.0.44) using the package ggplot2.

4.4 Results

A total of 58 fishing groups (n = 154 anglers) were surveyed from the three river basins: 17 fishing groups (n = 27 anglers) from the Kharaa, 18 groups (n = 59 anglers) from the Eroo and 23 groups (n = 68 anglers) from the Onon. There were between one and nine anglers per group with a significantly lower number of anglers per fishing group in the Kharaa compared to the other two basins ($p < 0.05$;

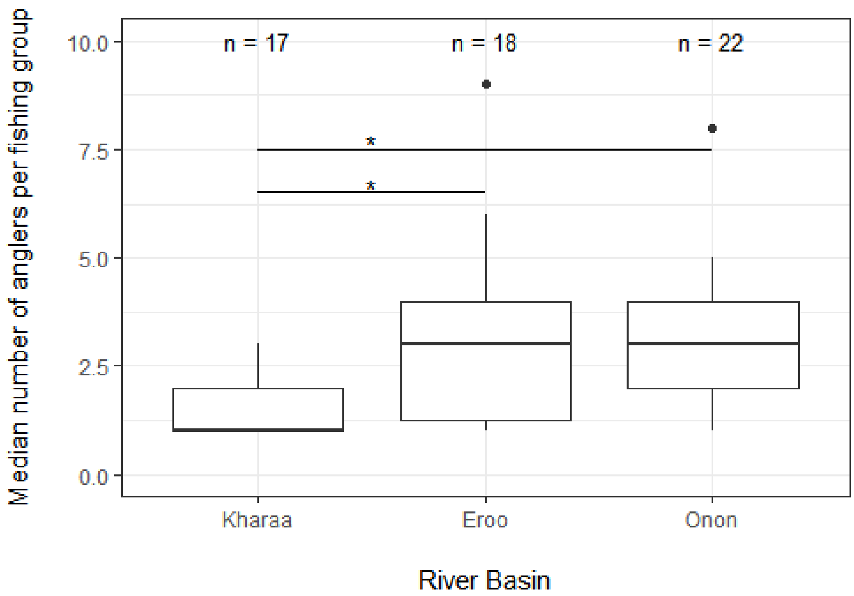

Figure 3). The following results are a summary of the responses from the 58 fishing groups to the five survey sections.

Recreational Fisher Demographics

All anglers interviewed were male (100 %), with 98 % Mongolian (Table A2- 1). Angler age ranged from 16 to 71 years old with a mean of 38.2 ± 12 years across all basins. The majority of groups in the Kharaa (63 %) and Onon (83 %) resided within these basins, with the next largest groups of anglers coming from Ulaanbaatar (26 – 16 % respectively). In the Eroo, most fishing groups were from Ulaanbaatar (59 %), while four were from the adjacent Kharaa basin. 73 % of anglers surveyed were employed, 14 % were retired or unemployed, 9 % were students and 3 % herders. All anglers travelled by 4WD to the Eroo, 77 % used a car in the Onon and 65 % were on foot or came by public transport in the Kharaa. Surveyed anglers first went fishing in the mid 1990's, between 22 and 26 years old, with 64 % responding that neither their fathers nor grandfathers had previously fished before them.

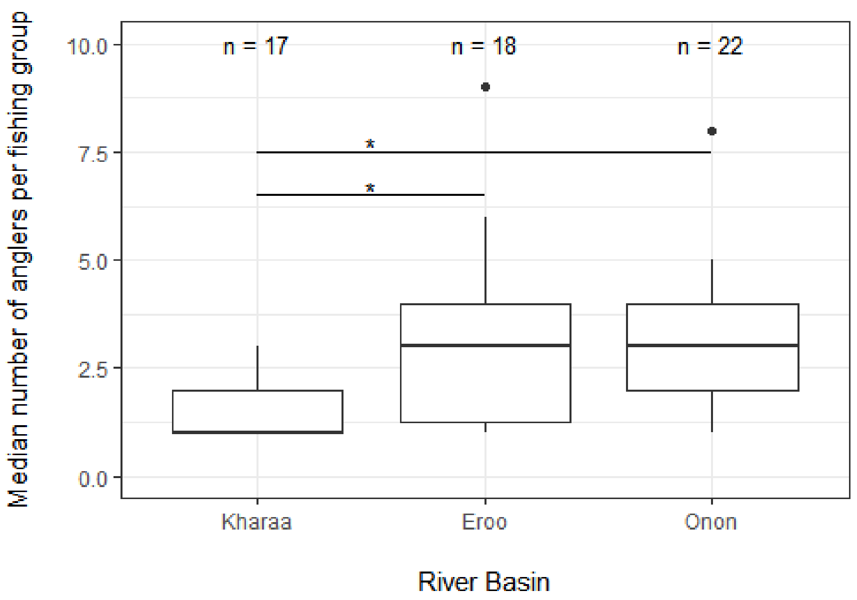

Figure 3. Boxplot showing the median number of anglers per fishing party in the Kharaa, Eroo and Onon basins surveyed in northern Mongolia between June and October 2012. Boxes indicate the median (black line) and 10/90 percentile, whiskers 2 x percentile range. Solid black dots indicated data outliers. Asterisks (*, $p < 0.05$) indicate significant differences between two river basins (separated by a horizontal black line). The n values above each box illustrate the total number of fishing groups used in the analysis.

Fishing Practices

Thirty-eight fishing groups (70 %) indicated that they went fishing at least once a year (Table A2- 2). The median (± SE) number of fishing trips undertaken by Kharaa anglers was significantly higher than anglers in the Eroo ($p < 0.01$) and Onon ($p < 0.05$) in 2011 (Figure 4). However, the median number of fishing days per angler was not significantly different between basins ($p > 0.05$; Figure 5). Kharaa anglers fished most frequently (> 10 trips; n = 7), most Onon anglers fished occasionally (4 – 9 trips; n = 12) and Eroo anglers fished rarely (0 – 3 times) in 2011. Most fishing trips in 2011 occurred in summer (n = 50), with autumn the next most popular time (n = 25). Three groups fished in spring and none in winter. The mean (± SE) fishing hours per day was not significantly different between basins ($p > 0.05$). Most anglers in the Eroo and Onon fished in other rivers, while less than half of the Kharaa anglers fished in another river (44 %). 77 % of all anglers kept their catch, 15 % (n = 10) released it and only 7 % (n = 5) gave it away or sold it. Fish consumption among anglers was rare with 71 % eating fish 0 - 3 times a month (n = 36). Only eight anglers ate fish frequently or more than 10 times a month (16 %), with seven of these in the Kharaa basin.

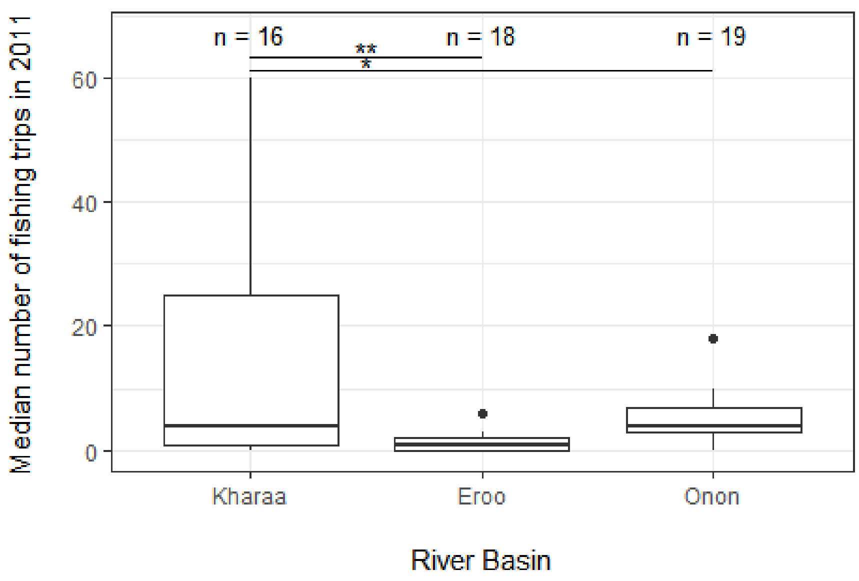

Figure 4. Boxplot displaying the median number of fishing trips per fishing group across the three river basins in Mongolia in 2011. Boxes indicate the median (black line) and 10/90 percentile, whiskers 2 x percentile range. Solid black dots indicated data outliers. As asterisk (** = $p < 0.01$; * = $p < 0.05$) indicates a significant different between river basins (separated by a horizontal black line). The n values above each box illustrate the total number of fishing groups used in the analysis.

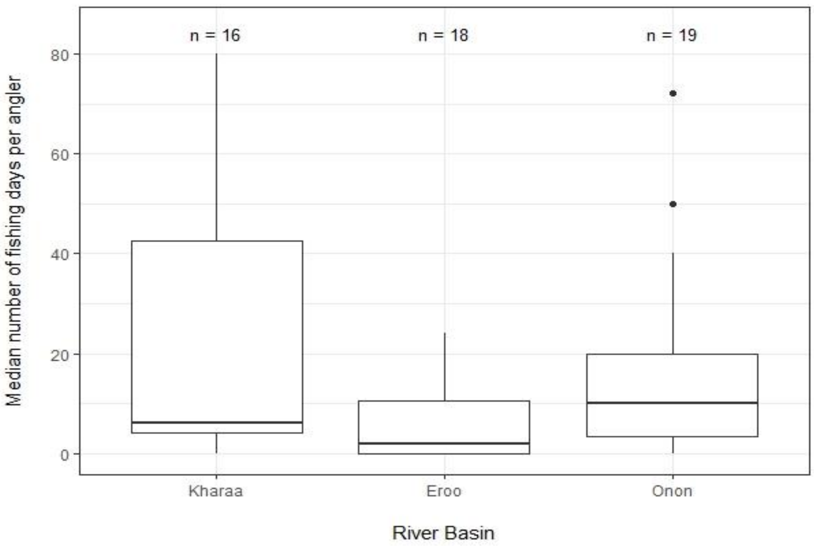

Figure 5. Boxplot displaying the median number of fishing days per angler across the three river basins in Mongolia in 2011. Boxes indicate the median (middle line) and 10/90 percentile, whiskers 2 x percentile range. Solid black dots indicated data outliers. No significant differences were identified between the basins. The n values above each box illustrate the total number of fishing groups used in the analysis.

Current Fishing Trip

Only 54 % (n = 30) of anglers surveyed had purchased a fishing permit for the current trip, 7 % (n = 4) did not, and 39 % (n = 22) had never bought one to go fishing before (Table A2- 3). The mean (± SE) length of the current trip was significantly longer for Eroo anglers (3.06 ± 0.36 days, $p < 0.001$) compared to the Kharaa (1.29 ± 0.14 days) and Onon anglers (1.48 ± 0.16 days). *B. lenok* was identified as the most targeted species (n = 32), followed by *H. taimen*, *T. baicalensis* and '*no matter'* which each had all 14 positive responses. 20 % of anglers wanted to catch 10 or more fish during a trip, 34 % between four and nine fish and 38 % wanted to catch three or less fish.

B. lenok made up 63 % of the total recorded catch, with 34 individuals retained in the Eroo (32.3 ± 7.9 cm total length (TL)), 30 (36.5 ± 7.5 cm TL) in the Onon (*B. lenok* and potentially some blunt-snouted individuals - *B.* sp.) and 12 in the Kharaa (34.5 ± 4.7 cm TL; Figure 6 & Figure 7). No significant difference ($p > 0.05$) was detected for *B. lenok* lengths between basins ($p > 0.05$). *T. baicalensis* was the second most caught species making up 27 % of the total catch with 31 individuals from the Eroo (21.4 ± 5.3 cm TL) and one individual from both the Onon (27 cm TL - *T. grubii*) and Kharaa (32 cm TL; Figure 6 & Figure 7). Eight *H. taimen* were caught, representing 7 % of the total catch (seven in the Onon; 71.7 ± 2.9 cm TL and one in the Eroo; 60 cm TL; Figure 6 & Figure 7), along with four *Leuciscus spp.* (3 %, 20 ± 3.8 cm TL) in the Kharaa. The mean (± SE) CPUE for each angler per day of fishing was highest in the Onon followed by the Eroo and Kharaa, but there was no significant difference ($p > 0.05$; Figure 8). The mean (± SE) CPUE for each angler per hour of fishing was again highest in the Onon and relatively even in the Kharaa and Eroo, with no significant difference detected between basins ($p > 0.05$; Figure 8).

Fishing Gear and Costs

All fishing groups used rods and reels, with one angler also using a net in the Kharaa (Table A2- 4). Artificial lures were used by 64 % of anglers, followed by "*everything*" (14 %), grasshoppers (10 %), rain worms (5 %) and live fish (3 %). Two fishing groups were fly fishing (3 %). 45 % of the fishing gear used was purchased at black markets in Ulaanbaatar and Darkhan, with 38 % of sales from Ulaanbaatar fishing tackle shops. Six fishers bought equipment from overseas. The median money spent on fishing gear so far in 2012 was 89 600 ₮ ($37.20 ± 5.6 USD) per person. Anglers in the Eroo spent significantly more per person ($p < 0.05$; 158 462 ₮ / $65.78 ± 16.4 USD) than anglers in the Onon (68 000 ₮ / $28.23 ± 6.2 USD) and Kharaa (61 000 ₮ / $25.32 ± 5.7 USD) (exchange rate of $1 USD to 2409 ₮ MNT; Figure 9 – dark grey bars). The estimated expenditure (median ± SE) in 2012 for anglers on fishing trips was 90 000 ₮ or $37.36 ± 9.22 USD (Figure 9 – light grey bars). Eroo anglers spent significantly more in 2012 with a total of 300 000 ₮ ($p < 0.001$; $124.57 ± 22.32 USD) per person in comparison to anglers in the Onon and Kharaa who spent 120 000 ₮ ($49.82 ± 4.15 USD) and 17 500 ₮ ($7.27 ± 9.21 USD) per person respectively.

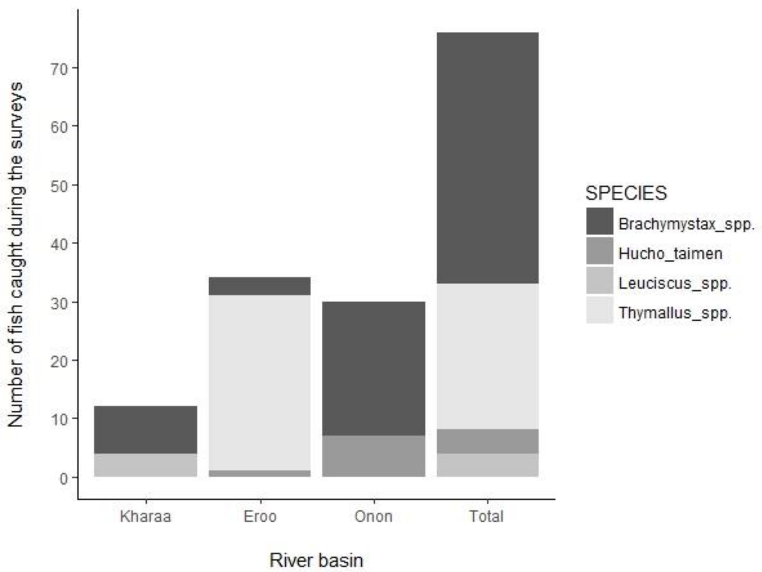

Figure 6. Stacked bar plot displaying the catch composition for each river basin recorded during the creel surveys conducted between June and October 2012. The total catch (sum of all three basins) per species is also shown to demonstrate the potential overall catch composition in the fishery.

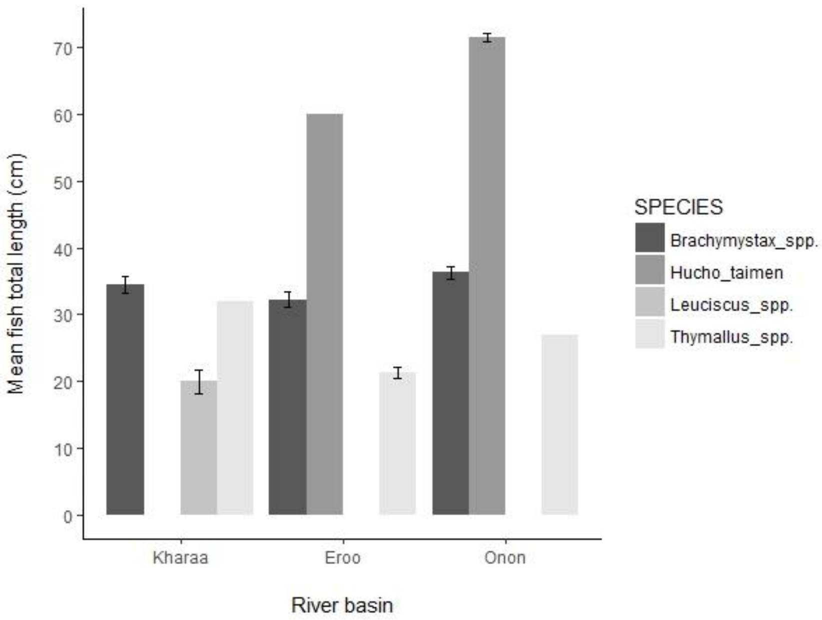

Figure 7. Grouped bar plot displaying the mean fish total length (± SE) per species and river basins that were captured during the surveyed fishing trips between June and October 2012. No significant difference ($p > 0.05$) was detected for *B. lenok* lengths caught between river basins. No other species lengths were compared due to low numbers in one or two other basins.

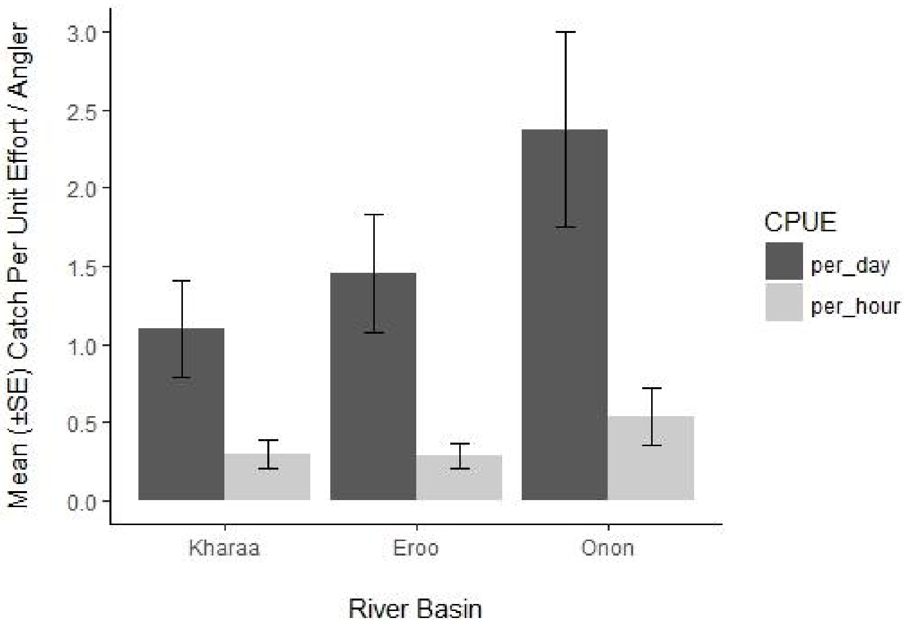

Figure 8. Paired bar plot displaying the mean Catch per Unit Effort (± SE) per angler per day and per hour in the three river basins between June and October 2012. No significant differences were detected between basins for either CPUE per day or CPUE per hour.

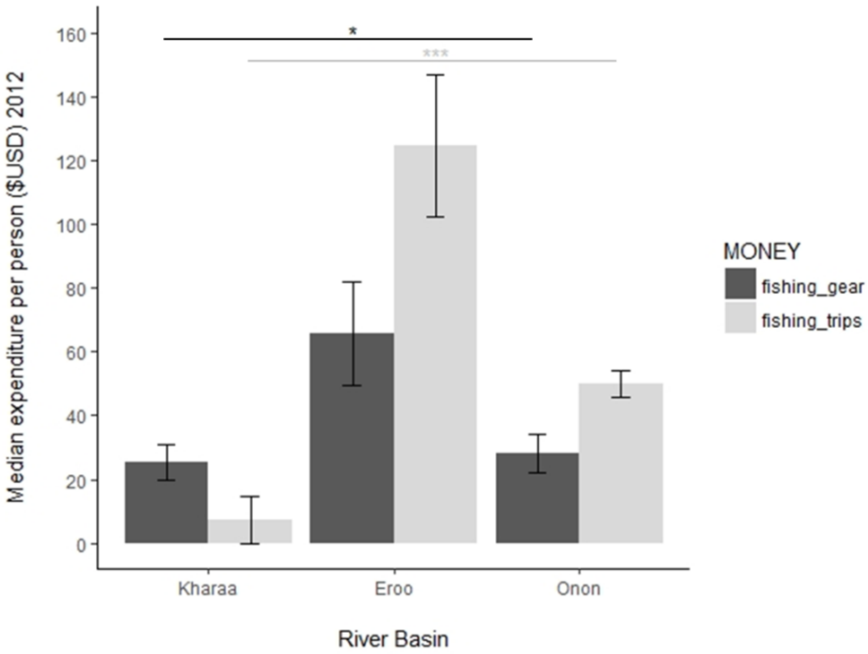

Figure 9. Paired bar plot displaying the median (± SE) expenditure per person ($USD) in 2012 on fishing gear (dark grey bars) and fishing trips (light grey bars) in the three river basins between June and October 2012. The asterisk (** = $p < 0.01$; * = $p < 0.05$) above the bars indicates significant differences between basins.

Fisher Knowledge and Opinions

62 % of all anglers indicated that they thought fishing was getting worse, while 27 % thought fishing had not changed, and 2 % said it had improved (Table A2- 5). Anglers responded that overfishing (57 %), pollution (19 %) and a decrease in water levels (19 %) were responsible for the decline. Illegal fishing had been witnessed by over half the fishers (56 %, n = 29) with netting having being seen in all three basins, dynamiting observed in the Kharaa and motor boat use in the Onon. In the Kharaa, 71 % of anglers did not know or were unsure of the fishing regulations, while this trend was reversed in the Eroo and Onon basins with 80 % and 70 % answering that they knew the regulations respectively. Almost all anglers knew *H. taimen* were under threat and in danger of becoming extinct (93 %; n = 52). Most fishing groups said that they released fish alive (97 %; n = 56) because they were too small (69 %; n = 22) or for conservation reasons (31 %; n = 10). Across the surveyed river basins, 60 % of all responses indicated that they would support new fishing laws to improve sustainability and conservation of local fish populations, while the remaining 40 % were against additional regulations or were unsure.

4.5 Discussion

The current creel surveys represent the most comprehensive investigation to have focused on Mongolia's emerging recreational fishery. The data gathered from these three river basins indicates that there are similarities in angler demographics and target species across basins, while fishing group size, number of fishing trips and economic outlay showed significant differences. These results can provide a reference point for future research to identify longer term trends, quantify growing effort in the fishery and improve management decisions in order to achieve sustainability.

Angler Demographics and Fishing Practices

This emerging recreational fishery is dominated by Mongolian men below 40 years of age (> 70 %), although Russian, Chinese and Kazakh immigrants and some western visitors (not with a tour company) are also known to be active in the fishery (Chandra et al., 2005; Ocock et al., 2006; Hogan and Jensen, 2013). Most anglers began fishing in the mid to late 1990's and are thus the ones responsible for the rapid increase in fishing effort observed across the country, especially as over 60 % of these anglers responded that neither their fathers nor grandfathers had been fishing before them. In Mongolia, like in other developing countries such as India, the rapid increase in the number of recreational anglers has been attributed to the improved economic wealth of its citizens, which has allowed surplus time and money to be spent on leisure activities such as fishing (FAO, 2012; Gupta et al., 2012). As a result, angler income along with place of residence has subsequently defined two angler types: the *rural angler* who was dominant in the Kharaa and Onon basins where they resided in close proximity to the river and typically had lower paying jobs or were unemployed, retired, were students or herders; and the *urban angler* who were prominent in the Eroo basin where many had travelled from Ulaanbaatar and worked medium to high income jobs and were engineers, bankers, government workers or private business owners. The identification of these different angler groups is important for management purposes as each appears to be responsible for impacting fish populations to varying degrees and in different regions.

The Kharaa River flows through one of the more densely populated basins in Mongolia and is thus likely one of the most heavily fished regions in the country as there was a significantly higher mean number of fishing trips undertaken in 2011 in the Kharaa compared to the other river basins surveyed, although as these trips were significantly shorter in length, the median number of fishing days per angler remained comparable across basins. The prolonged, elevated fishing pressure over the last 20 – 30 years has no doubt been a major factor in the local expiration of *H. taimen* in the Kharaa basin. This expiration of the largest predatory fish species indicates a potential sequential decline in the captured species within the fishery (Allan et al., 2005). Kharaa *H. taimen* populations have disappeared faster than those in several Russian rivers where trophy-sized individuals of 1 m or more have gone in less than 20 years from exploited rivers in which they were formally abundant (Matveyev et al., 1998). While it is clear that *H. taimen* have been overexploited, *B. lenok* populations may be more resilient to the fishing pressure, as they appear to have not been impacted to the same degree. This was evident in the mean total lengths of individuals, which were not significantly different compared to those in the Eroo and Onon river basins. However, in contrast, the Kharaa CPUE was the lowest of the three basins, again indicating that the local fish populations have been impacted compared to the Onon and Eroo. The fishing pressure in the Kharaa River is likely to be one of the highest in Mongolia; the future widespread fishing pressure is expected to have substantial impacts on the remaining resident fish community.

Although rural anglers in the Onon also live within the river basin and work lower income jobs, they reportedly fished less frequently but in larger groups compared to anglers in the Kharaa. Onon anglers tended to travel by car to fish with bigger groups in more isolated reaches along the river where they could obtain the highest CPUE. This difference may be attributed to the more robust fish populations present, including *H. taimen*, which have survived in the Onon due to the historically low human population densities and intact river integrity. Even though Onon anglers tended to go fishing only occasionally, the combination of the high CPUE and the larger group sizes indicates that the total annual harvest across the basin may be considerable. It appears that the Onon is in a much earlier stage of exploitation compared to the Kharaa, but this is likely to change in the near future as fishing pressure continues largely unchecked. In addition, illegal catches of *H. taimen* and the misidentification of the *B*. sp. as the sharp-snouted lenok (*B. lenok*) that is also caught and retained, will adversely impact on the rare and fragmented populations of these threatened species across the Onon basin.

The wealthier urban anglers such as those identified in the Eroo River basin represent a new threat to the Mongolian fish populations. While these anglers tended to go fishing only rarely (0 – 3 times per year), they went in large groups and for longer periods at a time and thus there was no statistical difference between the median number of fishing days per angler across the three basins. This result highlights the fact that urban anglers are also responsible for a considerable amount of fishing pressure across the country, although they tend to be focused on the more remote rivers that still hold robust fish populations. Thus, this new threat means that even those rivers that have been protected by their isolation in the past are now the target of increased fishing pressure from urban anglers as they have the resources to travel to these locations where fish are currently more abundant for multiple days at a time. Although, the CPUE results suggest that these urban anglers are less efficient compared to the rural anglers in the Onon, this is likely to change rapidly in the coming years as experience and skills improve amongst this group and they capture more fish.

Target Species

Like many fish species that inhabit boreal rivers, Mongolia's fish populations are especially vulnerable to overfishing due to their sporadic recruitment, slow growth rates, low natural mortalities, small population sizes and longevity (Schindler et al., 1993; Allan et al., 2005; Vander Zanden et al., 2007). *B. lenok* was repeatedly listed as the intended target species across the three river basins and as a result made up 63 % of the total reported catch during the surveys. This level of exploitation represents a considerable threat for this already vulnerable species throughout Mongolia, which was previously expected to experience a population decrease of at least 30 % over 15 years or three generations from 2006 (Ocock et al., 2006). Thus going forward, management measures need to pay particular attention to *B. lenok* catches in order to avoid future widespread overexploitation and possible expiration in the more heavily fished regions. In addition, the targeting of *H. taimen* was also reported in the Eroo and Onon basins (7 % of the reported catch), which is also a potential concern for the conservation of this endangered species even though it is legal to catch during the open fishing season. While the intentional killing of *H. taimen* was prohibited in 2012, enforcement is minimal in Mongolia (Jensen et al., 2007) and most anglers do not use the recommended single, barbless hooks, which is aimed to reduce hooking injuries and post release mortalities. Instead, local anglers typically use two or three large treble hooks per lure or spinning bait with these having the potential to severely damage individuals especially if they are incidentally hooked deeply in the throat, eye or gill causing severe injuries that have been shown to increase post-release mortalities by up to 71 % for some salmonids (Siewert & Cave, 1990; High & Meyer, 2014). In one previous study, it was found that hooking mortality in brook trout (*Salvelinus fontinalis*) increased with fish size due to the likelihood of larger fish being hooked in critical locations more often when the fish were caught with treble hooks compared to single hooks (Nuhfer & Alexander, 1992), while an another study suggested smaller individuals in a targeted rainbow trout population were more vulnerable to injury and mortality from hooking related incidences (Meka, 2004). Further concerns also surround the post capture handling of *H. taimen* due to the large body size and aggressive nature of mature individuals that makes them difficult to land, extract the hooks and handle out of water for photo opportunities. All of these tasks increase the exposure of fish to air which can considerably reduce survival and physical damage as has been shown in other trout species (Meka, 2004). However, the overarching question remains of what proportion of caught *H. taimen* are released unharmed in the absence of widespread education and enforcement programs, considering there are minimal punitive ramifications for such an incident. On numerous occasions *H. taimen* have been observed being captured and killed across multiple years in the Eroo River, which is one location that actually has a permanent ranger on site.

Fish Lengths and Overfishing

While no size limit regulations for target species currently exist within the Mongolian fishing laws, information regarding the size range of these species along with biological data such as age or length at first maturity, can help to determine if individuals are being caught before they have had a chance to reproduce. If this is the case, then fish populations may decline at a faster rate than expected, as there are fewer individuals available for spawning. It is expected that age at first maturity is generally between 3 to 6 years for *Thymallus* and *Brachymystax* and 4 to 8 years for *Hucho* (Holčík et al., 1998; Matveyev et al., 1998; Froufe et al., 2003), however, the estimated size ranges at these ages have a wide variation between 20 and 34 cm for *T. baicalensis*, 18 and 54 cm for *B. lenok* and 38 and 97 cm for *H. taimen* (Holčík et al., 1998; Matveyev et al., 1998; Jensen et al., 2007; Tsogtsaikhan et al., 2017). While these estimated size ranges are large, and more age at maturity data is urgently required, there is an indication that some of the currently caught individuals are still immature *e.g. T. baicalensis* in the Eroo basin. In any case, this fish length data can be used as a baseline for future studies to compare catches and identify long-term trends in the fishery. Clear signs of overfishing will be apparent if mean fish lengths become smaller and smaller, as a result of the larger individuals are captured and removed from the population at a high rate (Allan et al., 2005).

Fish Consumption

Although the majority of recreational anglers in the current study reported that they kept the fish they caught (77 %), with very few selling their catch, the level of fish consumption was generally low with 70 % of all anglers indicating that they consumed fish rarely (0 - 3 times per month). However, seven rural anglers from the Kharaa River basin indicated that they did catch and consume fish frequently (> 10 per month), with the highest consumption rate reported as '*almost daily'* by a retired husband and wife. Such a high frequency of fish consumption was unexpected in this fishery and indicates that there is a partial subsistence or reliance on local fish populations by a small number of people to supplement their diets for several months each year. This is critical information and something that should not be neglected by authorities, especially in the Kharaa basin, where there has been heavy metal contamination detected in the ground and surface water, river sediment and fish fauna from several sites, a result of both past and present mining activities (Hofmann et al., 2010; Kaus et al., 2016). A recent study identified elevated levels of Hg in certain consumed fish species, which could potentially pose a danger to the more sensitive community members including pregnant women and young children if those species were consumed more regularly (*e.g. Lota lota*) or people had already been exposed to additional sources of heavy metals *e.g.* mine workers (Kaus et al., 2016). Monitoring levels of Hg and other toxic contaminants such as Pb, Cd and Cr within the Kharaa River fish fauna is vital to prevent future health risks.

Economic Evaluation

Recreational fishing is a major economic contributor worth billions of dollars in many developed countries around the world (Hickley, 1998). Although an overall economic estimate of the Mongolian recreational fishery is not possible to calculate from these results, Hickley (1998) has suggested that an estimated 10 % of the population in developed countries is engaged in recreational fishing. If this were the case in Mongolia with a population of 2.754 million, then 275 540 people could spend up to $10.6 million USD (26.2 billion ₮) every year on fishing gear, food and fuel to go fishing (based on average spending per angler). However, the actual number of Mongolian anglers, for the moment, is likely to be substantially lower than 10 % and potentially somewhere between 1 % (27 540 people) and 0.1 % (2 754 people) of the total Mongolian population. Therefore an estimate of the economic value of Mongolia's emerging recreational fishery with these participation levels is likely to be somewhere between $1.06 million USD (2.62 billion ₮) and $106 827 USD (262 million ₮) per year.

Although a fishing permit is required by law to be purchased per angler for each trip of up to three days (Article 10 of the Mongolian Law on Hunting, Compendium of Environmental Law and Practice in Mongolia 2000), 46 % of anglers surveyed had not bought a fishing permit for their current trip, with 85 % of this group saying they had never bought a permit to go fishing previously. Thus almost every second angler group was fishing illegally under Mongolian law and is liable for a fine of 10 000 – 25 000 ₮ per person as per Article 16.1.6. This is a substantial loss of revenue for the local authorities, revenue that could be used to fund improved enforcement and conservation efforts in each specific region. The Kharaa River rural anglers were the least likely to have ever purchased a fishing permit, while in the other basins, the number of fishers without a permit was approximately a third. If fishing permits and fines were better enforced across Mongolia, which could be achieved through the employment of more officers, then the overall value of this emerging recreational fishery would be considerably more.

Angler Knowledge and Opinion

Illegal fishing contributes to the overexploitation of fish stocks making it one of the major limiting factors in preventing desired management and conservation outcomes (Agnew et al., 2009). In Mongolia, illegal and unregulated fishing activities are reportedly widespread, although few details are available (Ocock et al., 2006; Hogan & Jensen, 2013). It is expected that the combined effect of a lack of knowledge or disregard for the fishing regulations by anglers, the limited government resources for adequate enforcement over vast regions and the absence of substantial fines or punishment, have all combined to minimise compliance and embolden poachers. In the current surveys, the majority of anglers in the Kharaa and Onon basins reported that they had witnessed illegal fishing, with only three groups having observed it in the Eroo. Netting was the most common activity reported, while the use of dynamite was also seen in the Kharaa. However, the facts that there were no reports of illegal fishing in the closed spawning season (1 April to 15 June) or the killing of the protected *H. taimen* (officially prohibited in 2012), both of which have been regularly observed by the authors, indicates a lack of knowledge of these more basic fishing regulations within the recreational fishing community. Thus it was no surprise that 40 % of all fishing groups responded that they were '*not sure*' or '*do not know*' the current Mongolian fishing regulations, with over 70 % of all anglers responding this way in the Kharaa. These figures highlight a clear need for improved enforcement along with an expansive educational program implemented across Mongolia, including Ulaanbaatar, to expand the understanding and ultimately compliance of the fishery regulations. At the time of the survey, there was one such program in place in the Onon River basin, which involved an NGO working with local anglers to form clubs, which would provide information on the regulations and best practices of fish handling, while helping to install a sense of responsibility for the local fish stocks. This program appeared to have already made a positive impact with increased awareness and conservation tendencies showing through in the survey for Onon River anglers.

Conclusions

The information gathered from the creel surveys provides a first insight into Mongolia's emerging recreational fishery. This information can help authorities to evaluate and improve the existing fishery management strategies in order to safeguard the sustainable use of targeted populations and better protect threatened species in the future. If these fish stocks continue to be undermanaged, then the potential impacts posed by this growing fishing pressure may become irreversible with continued population declines and local extinctions. With additional threats to water quantity and quality as well as aquatic habitat integrity and connectivity in many parts of Mongolia including threats from urbanisation, industrialisation, agricultural expansion and climate change, the implementation of new management tools such as FPAs is strongly advised. A series of spatially meaningful FPAs, where fishing is prohibited, can conserve critical habitats such as spawning grounds and overwintering pools, while also preserving critical genetic diversity if valuable priority populations can be identified across the distribution of each species. This action would allow the limited resources currently afforded to fisheries protection in Mongolia to be more effectively distributed. It is also recommended that future creel surveys be conducted within the Kharaa, Eroo and Onon basins, as well as other heavily fished rivers, to monitor growth and identify negative trends within the fishery. This should be coupled with a broader recreational angler education program or fishing licence course to increase awareness of the regulations and improve the handling practices of these endangered species.

5 Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia)

Kaus, A., Schäffer, M., Karthe, D., Büttner, O., von Tümpling, W., Borchardt, D. (2016). Regional Environmental Change, 16(4). doi: 10.1007/s10113-016-0969-4

5.1 Abstract

Past and present gold mining operations scattered throughout the Kharaa River basin, Mongolia, have been identified as a major source of heavy metal and metalloid contamination. However, the potential accumulation of toxic contaminates including Cr, Zn, As, Cd, Hg, Cu, Ni and Pb in the resident fish fauna and the subsequent human health risks associated with their consumption, have previously not been quantified. In the current study, contaminates in water, sediment and five consumed fish species (*Leuciscus baicalensis*, *Thymallus baicalensis*, *Brachymystax lenok*, *Lota lota* and *Silurus asotus*) were examined. The results indicated that concentrations of As and Hg exceeded the national permissible limits for drinking water in the Gatsuurt tributary of 10 $\mu g\ L^{-1}$ and 0.05 $\mu g\ L^{-1}$ respectively, while Hg contents detected in the sediment of the Boroo tributary were highly elevated (0.78 $\mu g\ g^{-1}$). Heavy metal and arsenic accumulation was evident in all five fish species sampled across the basin, with maximum muscle contents of Cr, As, Hg and Pb detected in several species caught in the middle and lower river reaches, while Zn was highly elevated in *B. lenok* collected in the upper tributaries. Elevated median contents of Cr, Cu, Hg and Pb increased with trophic level, with Hg accumulation posing the greatest threat to humans as 10.7 % of all fish sampled in the study exceeded the internationally recommended threshold for Hg in consumable fish tissue. Although recreational fishing is rapidly growing throughout Mongolia, the overall level of fish capture and consumption remains relatively low. However, increasing pollution and accumulation in resident fish species could lead to chronic heavy metal toxicity in people who consume them regularly from the most polluted regions of the basin, while additionally being exposed to other sources of contamination.

5.2 Introduction

Globally, heavy metals and metalloids have been increasingly released into the environment as a result of a plethora of anthropogenic activities (von Tümpling et al., 1995; Durrieu et al., 2005; Dhanakumar et al., 2015; Pfeiffer et al., 2015). Upon release, these toxic pollutants are often transported to, and concentrated in, nearby rivers and lakes where they contaminate the water and sediment, and are ultimately incorporated into the aquatic biota (Dušek et al., 2005; Lu¨ et al., 2011; Nyirenda et al., 2012). While trace amounts of Cr, Cu, Ni and Zn are biologically essential for normal growth and functioning of organisms, they are damaging in high concentrations, whereas As, Cd, Pb and Hg are all nonessential and highly toxic even at low levels (Shukla et al., 2007). Certain elements can also potentially accumulate and magnify along the food chain amassing hazardous concentrations in higher trophic level species such as fish. If these fish are then regularly consumed by people, potential serious health implications can occur including neurochemical and cardiovascular damage, cancers, restrictive lung disease, renal and gastrointestinal problems and prenatal abnormalities or death (Weil et al., 2005; Morea et al., 2007). The risk is amplified if people are simultaneously exposed to elevated levels of heavy metals in drinking water, other foods and / or their domestic or occupational environments (Järup, 2003; Tchounwou et al., 2012).

In order to gain a complete overview of the heavy metal contamination within an ecosystem, including the potential threat to human health, it is necessary to not only identify the source and extent of the pollution through sampling water and sediment, but to also evaluate the magnitude of the bioaccumulation in the consumed fish species (Pérez-Cid et al., 2001). Numerous studies have identified elevated concentrations of one or more heavy metals in locally consumed freshwater fish, including multiple instances where national and international thresholds established for their safe consumption have been exceeded. These studies have also identified both biotic (*e.g.* fish length or age) and abiotic factors (*e.g.* water or sediment contents) which have influenced the heavy metal concentrations in resident fish species. For example, in the Puyango River basin of southern Ecuador and the Petit-Saut hydroelectric reservoir in French Guiana, Hg contamination from small-scale gold mining has made local piscivorous fish species a potential risk for human consumption (Tarras-Wahlberg et al., 2001; Durrieu et al., 2005). Tarras-Wahlberg et al., (2001) reported that bottom dwelling species were more likely to accumulate higher contents of Hg due to the ingestion of contaminated sediments from the river substrate compared to other species. In addition, in Lake Titicaca, pollution from intensive mining activities and urban sewage discharge had, elevated levels of Cu, Zn, Cd and Hg in four fish species, prompting recommendations by the authors to limit fish consumption in certain heavily polluted parts of the lake (Monroy et al., 2014). It was reported that metal bioaccumulation in fish was only weakly related to metal concentrations in the environment (water and sediment), although nonessential elements (Cd, Hg, Pb) were generally more consistent with environmental peaks than biologically essential ones, with the exception of Cu (Monroy et al., 2014). Additionally in France, 60 % of brown trout (*Salmo trutta fario*) sampled from an historical mining region in the Cévennes National Park exceeded the maximum allowed concentrations for human consumption of Pb and Cd in fish tissue (Monna et al. 2011). The heavy metals detected in trout from this study reflected the high content in the river sediment, although age-related effects were also identified as an influential factor determining contamination in fish (Monna et al., 2011). These results highlight the capacity of various heavy metals originating from mining operations to contaminate locally consumed freshwater fish stocks to the point where they potentially pose a health risk to people consuming them, even if the contamination occurred in the past.

In Mongolia, gold mining is currently a driving force in the national economy, with substantial operations located in the country's northern regions including the Boroo and Gatsuurt tributaries of the Kharaa River Basin (KRB) (Sandmann, 2012; Karthe et al., 2015a). However, recent reports indicate that these mining activities are often major sources of heavy metal and As pollution in both river water and sediment (Hofmann et al., 2010; Enkhdul et al., 2010; Oyuntsetseg et al., 2012; Brumbaugh et al., 2013; Pfeiffer et al., 2015). Hg is known to have been used extensively in the Boroo River sub catchment by the thousands of illegal small-scale, artisanal miners who have used and released Hg into the environment during the gold amalgamation process (Grayson et al., 2004; Steckling et al., 2011). This source of Hg has added to the existing pollution that has resulted from a factory accident in 1956 where a substantial amount of this highly toxic and persistent element escaped into the nearby Boroo River (Tumenbayar et al., 2000). Further upstream in the Gatsuurt tributary, the expanding open-cut gold mining operations have also been correlated with the release of As from the surrounding soil and rocks (Tsetsegmaa et al., 2009), elevating As concentrations in the tributary's water and sediments (Enkhdul et al., 2010; Pfeiffer et al., 2015). In addition, the Kharaa River upstream from Darkhan city at Khongor sum has been the location of a second industrial accident that occurred at a mining ore post processing plant in 2007, which saw both Hg and cyanide escaping in large quantities (Hofmann, 2008). As a result of these past and present gold mining operations and accidents, several locations across the KRB have been identified as pollution hotspots as they are known to have elevated concentrations of toxic heavy metals in the water and sediment (Hofmann et al., 2010; Batbayar et al., 2015; Kosheleva et al., 2015). This high level of pollution in certain regions is a cause for concern, as it is also a likely source of contamination for the resident fish species including those that are increasingly being captured and consumed by the basin's small, but growing, recreational fishing community. Traditionally, in Mongolia there has been little cultural connection to fishing or consuming fish, although in recent decades this has changed rapidly (Chandra et al., 2005; Jensen et al., 2009). Seventeen fish species in habitat the KRB including the Siberian sturgeon (*Acipenser baerii*) and Siberian taimen (*Hucho taimen*) that are listed as critically endangered and endangered, respectively, in the Mongolian Red Book of Fishes. However, over recent years both have become extremely rare due to overfishing and are now likely locally extinct. Up to eight species of fish are regularly caught by the recreational fishers in the KRB, which fish year round but are mostly concentrated in the summer and autumn months between June and November. Fishers typically target two salmonid species including the sharp snout lenok (*Brachymystax lenok*) and the Baikal grayling (*Thymallus baicalensis*), but also consume incidentally caught fish including the Siberian dace (*Leuciscus baicalensis*), burbot (*Lota lota*) and the introduced Amur catfish (*Silurus asotus*), among others (Kaus pers. obs.). The catch is mostly consumed by the fisher, their family and friends, or sometimes sold to the public in roadside stands or in city markets. To date, the human health risks associated with the consumption of these potentially contaminated fish species remains unknown, but needs to be urgently determined. This study aimed to quantify the existing contents of four nonessential and highly toxic elements (As, Cd, Pb and Hg) and four biologically important, but potentially contaminating heavy metals (Cr, Zn, Ni and Cu) in the muscle and liver of five consumed fish species, surface water and river sediment from across the KRB. Additionally, the study aimed to identify in which species and regions the heavy metal bioaccumulation in fish exceeded the internationally recommended thresholds for human consumption of fish tissue and thus evaluate, whether, health warnings are warranted considering the current level of fish capture.

5.3 Materials and Methods

Study site

The Kharaa River Basin (14,534 km^2) is located in northern Mongolia within the Selenga River catchment. The main river channel is 362 km long from its source in the Khan Khentii Mountains (2668 m a.s.l.) to its confluence with the Orkhon River (654 m a.s.l.). Annual air temperatures fluctuate between -40˚C in winter and 40˚C in summer, while the average annual rainfall varies between 250 and 350 mm (Karthe et al., 2015a). The population in the basin is approximately 147,000 with over half residing in the city of Darkhan. Gold mining remains an important industry and key source of income for thousands of people in the basin. Hofmann et al.,

(2010) has identified nine gold mines in operation, four abandoned gold mines, six main centres of small gold mining activities and nine potentially contaminated regions including areas in the Boroo, Gatsuurt and Zagdalin tributaries and both upstream and downstream from Darkhan city (**Figure 10**).

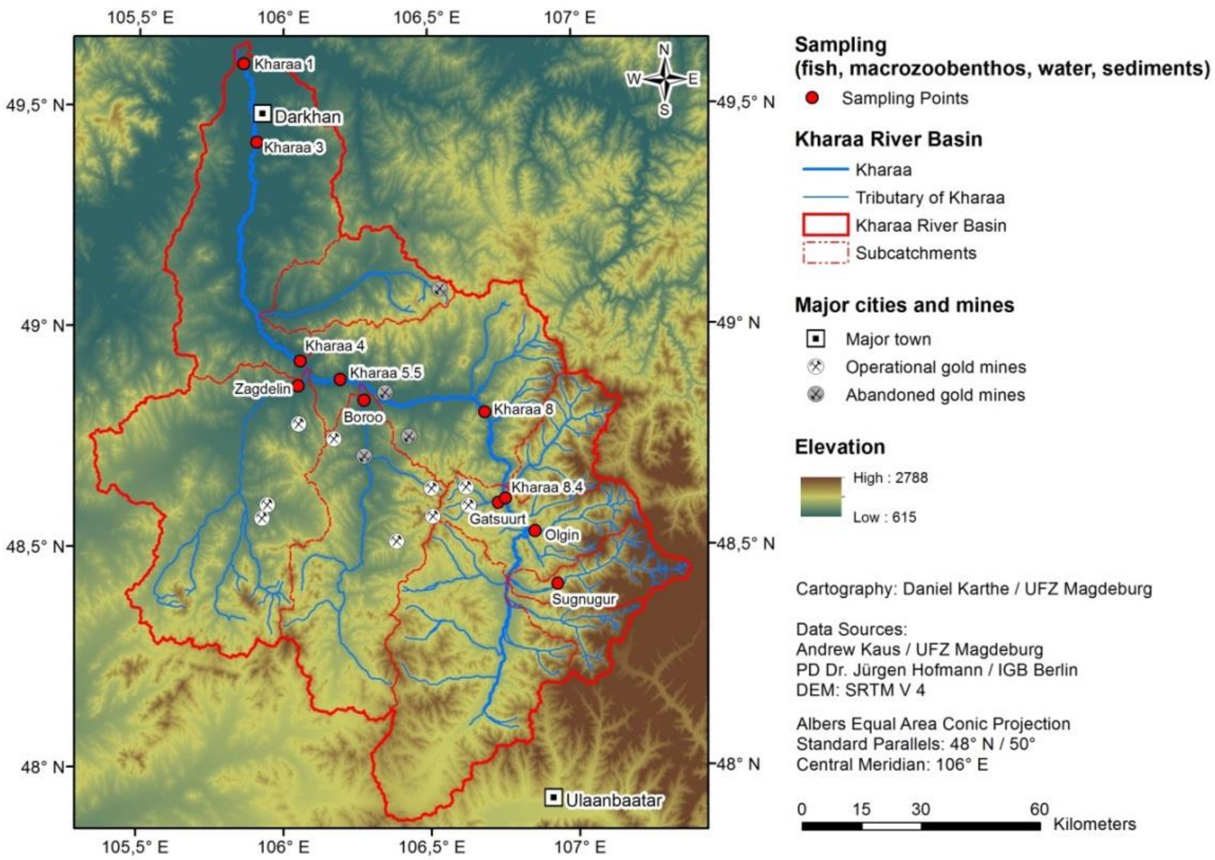

Figure 10. Kharaa River basin in northern Mongolia including the 11 sample sites marked with a red circle. UP stream reference sites: Sugnugr and Olgin. MID-UP sites: Gatsuurt, Kharaa 8.4 and Kharaa 8. MID sites: Boroo and Kharaa 5.5. MID-DOWN sites: Zagdalin and Kharaa 4, and DOWN stream sites: Kharaa 3 and Kharaa 1.

Field sampling

Surface water, river sediment and fish were collected from 11 sites across the KRB in June 2011 (see **Figure 10**). In the upstream region, which is largely undisturbed and mountainous (Hofmann et al., 2015a) two tributaries were sampled, Sugnugr and Olgin, which were selected as the study's reference sites (UP). In the mid-upper region (MID-UP), three sites were sampled including the Gatsuurt tributary, a small stream flowing directly through the Gatsuurt mining area; Kharaa 8.4, the most upstream main channel site, located approximately 1 km downstream from the Gatsuurt tributary and the Kharaa River confluence; and Kharaa 8, another main channel sampling location, which is a popular fishing spot in a lower impacted area of the basin.

The middle region (MID) has two sampling sites including the Boroo River, a heavily polluted tributary draining a sub catchment with a high concentration of illegal small-scale mining activities as well as a large open cut mine; and Kharaa 5.5, a main channel site located several kilometres downstream from the Boroo and Kharaa River confluence. The mid-down region (MID-DOWN) also consists of two sites including the Zagdalin River, another tributary with mining and agriculture dominating the sub catchment; and Kharaa 4, a main channel site located 2.6 km downstream from the Zagdalin and Kharaa River confluence. Finally, in the downstream region (DOWN), sites Kharaa 3 and Kharaa 1 were sampled. Both are main channel sites located either side of Darkhan city and are characteristically slow flowing, meandering river reaches with little riparian vegetation and high levels of bank erosion (Hofmann et al., 2015a).

Surface water samples were each collected with a new plastic syringe that had been triple-rinsed and strained through a single-use 0.45 µm membrane filter. One sample was collected at each site for the Hg analysis in an acid washed glass bottle and acidified with hydrochloric acid, while a second sample was taken for analysis of the other considered heavy metals (Cr, Zn, As, Cd, Ni, Cu and Pb) in new polyethylene vials and acidified with redistilled nitric acid. Water samples were kept chilled during transportation and storage until final analysis at the Helmholtz Centre for Environmental Research analytical laboratory in Magdeburg, Germany. Fine surface sediment samples were collected from the river's edge and small backwaters where sediment had accumulated as a result of the natural flow regime. A single sediment sample of approximately 0.3 – 0.5 kg was taken with a Teflon scoop and kept in plastic containers for transportation back to the laboratory. Fish were captured using two backpack electrofishing machines (Hans Grassl GmbH, Germany; Type ELT 60) or obtained via angling and sampling catches of local fishers. Total lengths (cm) and weights (gr) were measured, and otoliths were taken for ageing purposes. A sample of muscle from the left dorsal fillet and the liver was removed from each fish for analysis. In order to avoid cross-contamination, all dissections were conducted using ceramic scalpels and pincers on a Teflon cutting board that was cleaned thoroughly between each fish.

Laboratory analysis

Heavy metal concentrations were obtained from the filtered and acidified water samples prepared in the field without alteration. Concentrations of Cd, Cr, As, Zn, Cu, Ni and Pb were analysed with the ICP-MS, while total Hg concentrations were determined using the Mercury Analyser (Jena, Germany). Sediment samples were freeze-dried at -51˚C for 48 h (Christ Alpha 1–2 lyophiliser, B. Braun Biotech International, Melsungen, Germany) (Margetínová et al., 2008) and sieved to obtain a < 63 µm homogenised fine sediment sample. From this sample, a 0.5 g subsample was extracted and digested overnight in acid-washed teflon containers in a combined 10 ml mixture of HCL and HNO_3 (Aqua Regia) at room temperature. To ensure complete digestion of the sediment, the samples were then microwaved on a 40 minute cycle and after diluted with Milli-Q water to obtain a standard volume of 20 ml for the final analysis.

Fish tissue samples were cleaned of all remaining skin, scales, bone and blood and a 1.00 g of muscle and 0.50 g of liver were subsampled and digested overnight in 2 ml of H_2O_2 and 8 ml of HNO_3 (69 %) at room temperature. The acidified samples were further digested in a 40 min microwave cycle of heat and pressure before being transferred to new polyethylene vials where Milli-Q water was added to standardise the sample volume to 20 ml. Heavy metal analysis was conducted using the ICP-MS and the Mercury Analyser as per the water and sediment samples. Due to the small size of *L. baicalensis*, it was necessary to combine muscle and liver samples from two individuals captured at the same site and of similar sizes into a single sample to meet the required minimum analytical amount of 0.5 g. The tissues from both individuals were combined at a ratio of 50:50 where possible. Thus, as a result, 37 of the 46 *L. baicalensis* final samples contained two combined individuals. No aggregations of tissues were necessary for the other species. *L. baicalensis* individual ages were estimated using length and age data reported for Siberian populations by Loboń-Cerviá et al., (1996). For the remaining species, fish ages were obtained by counting annual growth rings of whole otoliths under a stereomicroscope with translucent light by two independent readers conducting two blind reads each.

Quality assurance

For every ten water, sediment or fish tissue samples, one blank and one standard sample was also analysed. The analysis of blanks was undertaken to determine potential contamination during the analysis, while the assessment of standard reference material was conducted to test the accuracy and precision of the analytical method and identify drifting errors. The standard reference materials used were from the National Institute of Standards and Technology (NIST) and the National Research Council of Canada (NRC). For sediment samples NIST 2704 was used, for fish muscle NRC Dorm-2 was used and for fish liver NBS DOLT was used.

Data analysis

Dissolved water (µg L^{-1}) and fine sediment (µg g^{-1}) results are presented as unaltered analytical values for each KRB sample site. Only water concentrations for Ni were taken from a similar 2007 sampling campaign (Ibisch unpublished). Heavy metal content data from fish tissue samples were tested for normality and homogeneity of variance using both Shapiro–Wilk and Levene's tests. Significant differences within and between species muscle and liver heavy metal contents were calculated using the non-parametric Mann–Whitney U test due to the non-normal distribution of the data. In order to investigate the relative influence of different biotic and abiotic variables on the heavy metal accumulation patterns detected in KRB fish species, a generalised linear model (GLM) with a Gaussian distribution was fitted to log-transformed heavy metal data. Included as explanatory variables for all elements were fish tissue, fish length, fish age and site sediment contents from the location where the fish were caught. Site water concentrations from the fish sampling locations were added for As and Hg only, as all other heavy metals considered were below detection limits. Site sediment content and water (for As and Hg) concentrations were used to indicate the contamination level of each sampling locations and determine whether fish heavy metal content reflected site contamination. Fish length was also included over the highly correlated ($R^2 = 0.98$) fish weight measurements to reflect fish size. Multiple GLMs were completed per species and heavy metal, and the best model was selected by first using the automatic '*step*' function in R which removes non-significant elements from full models containing full fixed factors and interactions, then using the manual backwards stepwise deletion method of remaining non-significant variables. All figures and statistics were produced using R (R Development Core Team 2010, version 3.1.3) or STASTICA 12 (STATSOFT 2013).

5.4 Results

Water Concentrations (filtered to <0.45 µm)

Dissolved water concentrations (µg L^{-1}) of Cr (< 0.5), Ni (< 0.5), Zn (< 5), Cd (< 0.2), Cu (< 0.5) and Pb (< 0.5) in the water samples were all below the analytical detection limits (see **Table 1**). As was detected at every site in the basin, with an overall mean concentration of 3.4 ± 4.29 µg L^{-1} (mean ± SD). The highest concentrations were recorded in the Gatsuurt (15.3 µg L^{-1}) and Boroo (6.9 µg L^{-1}) tributaries, while the lowest concentrations were detected in the Sugnugr (0.6 µg L^{-1}) and Olgin (1.0 µg L^{-1}) tributaries. Total dissolved Hg was at or below the detection limit of 0.008 µg L^{-1} in the surface water at Sugnugr, Zagdalin and Kharaa 1, with the highest concentrations in the basin detected at Gatsuurt (0.066 µg L^{-1}), followed by Kharaa 3 (0.031 µg L^{-1}) and Kharaa 8.4 (0.03 µg L^{-1}). Hg concentrations in the Boroo tributary were 0.025 µg L^{-1}. The mean total dissolved Hg concentration for the Kharaa River basin surface water was 0.022 ± 0.02 µg L^{-1} (mean ± SD).

River Sediment Contents (sieved to < 63 µm)

All heavy metals and As were detected in the fine river sediment across the basin (see **Table 1**). Only Hg was at or below the detection limit (< 0.05 µg g^{-1}) in eight of the 11 sites. The maximum total Hg content was in the Boroo River sediment (0.78 µg g^{-1}), followed by Kharaa 4 (0.08 µg g^{-1}) and Kharaa 5.5 (0.06 µg g^{-1}). The Boroo River sediment also contained the highest content of Pb (17.6 µg g^{-1}), Ni (23.6 µg g^{-1}), Cu (21.7 µg g^{-1}) and Cr (44.5 µg g^{-1}), with the Gatsuurt tributary recording the next highest measurements for these four metals. The maximum total As content was detected in the Gatsuurt tributary sediment (30.8 µg g^{-1}), followed by the Boroo tributary sediment (14.5 µg g^{-1}). Sugnugr had the highest content of both Zn (112 µg g^{-1}) and Cd (0.55 µg g^{-1}), with Boroo (c_{Zn} = 102 µg g^{-1}) and Kharaa 4 (c_{Cd} = 0.46 µg g^{-1}), recording the next highest contents in the basin for these heavy metals, respectively.

Table 1. Dissolved surface water concentrations (< 0.45 µg L^{-1}) and river sediment contents (< 63 µg g^{-1}) of Cr, Zn, As, Cd, Hg, Pb, Cu and Ni per region and sampling site in June 2011.

Region	Site	Cr	Zn	As	Cd	Hg	Pb	Cu	Ni[1]
		Surface water concentration [µg L^{-1}]							
UP	***Sugnugr***	< 0.5	< 5	0.6	< 0.2	< 0.008	< 0.5	< 0.5	< 0.5
UP	***Olgin***	< 0.5	< 5	1.0	< 0.2	0.009	< 0.5	< 0.5	< 0.5
MID-UP	***Gatsuurt***	< 0.5	< 5	15.3	< 0.2	0.066	< 0.5	< 0.5	< 0.5
MID-UP	***Kharaa 8.4***	< 0.5	< 5	2.0	< 0.2	0.030	< 0.5	< 0.5	< 0.5
MID-UP	***Kharaa 8***	< 0.5	< 5	1.7	< 0.2	0.024	< 0.5	< 0.5	< 0.5
MID	***Boroo***	< 0.5	< 5	6.9	< 0.2	0.025	< 0.5	< 0.5	< 0.5
MID	***Kharaa 5.5***	< 0.5	< 5	1.6	< 0.2	0.009	< 0.5	< 0.5	< 0.5
MID-DOWN	***Zagdalin***	< 0.5	< 5	2.0	< 0.2	0.008	< 0.5	< 0.5	< 0.5
MID-DOWN	***Kharaa 4***	< 0.5	< 5	2.2	< 0.2	0.019	< 0.5	< 0.5	< 0.5
DOWN	***Kharaa 3***	< 0.5	< 5	2.1	< 0.2	0.031	< 0.5	< 0.5	< 0.5
DOWN	***Kharaa 1***	< 0.5	< 5	1.5	< 0.2	0.008	< 0.5	< 0.5	< 0.5
		River sediment content [µg g^{-1}]							
UP	***Sugnugr***	23.8	112.0	13.2	0.55	< 0.05	13.7	12.3	11.4
UP	***Olgin***	28.7	77.7	13.0	0.38	0.05	13.4	15.3	14.7
MID-UP	***Gatsuurt***	40.9	99.2	30.8	0.45	< 0.05	15.9	18.8	19.2
MID-UP	***Kharaa 8.4***	33.1	79.1	10.5	0.45	< 0.05	14.1	15.1	15.9
MID-UP	***Kharaa 8***	30.3	78.1	8.2	0.44	< 0.05	12.2	13.0	13.7
MID	***Boroo***	44.5	102.0	14.5	0.45	0.78	17.6	21.7	23.6
MID	***Kharaa 5.5***	27.9	67.6	6.1	0.45	0.06	11.6	11.5	11.7
MID-DOWN	***Zagdalin***	37.7	78.3	4.8	0.42	< 0.05	12.0	12.1	15.5
MID-DOWN	***Kharaa 4***	39.0	91.1	8.0	0.46	0.08	15.9	19.3	20.5
DOWN	***Kharaa 3***	30.6	74.6	4.3	0.39	< 0.05	10.9	11.3	13.0
DOWN	***Kharaa 1***	31.4	77.2	4.4	0.42	< 0.05	11.1	11.1	12.8

[1] Ni water samples are from a June 2007 sampling campaign

Fish Muscle and Liver Contents

A total of 119 muscle samples and 74 liver samples were analysed for their heavy metal and metalloid contents from the five fish species captured across the KRB (**Table 2**). The basin-wide accumulation of heavy metals in fish tissue indicated Cr, Hg and Pb were typically present in higher amounts in fish muscle, while As, Zn, Cd and Cu were associated with fish liver (**Figure 11**). Significant differences ($p < 0.05$) between heavy metal muscle and liver contents were identified for Cr, Zn, As, Cd, Ni, Cu and Hg in *L. baicalensis*, for Cr, As, Zn, Cd and Cu in *T. baicalensis*, for Cr, As, Hg, Zn, Cu and Pb in *B. lenok* and for all elements in *L. lota*, but no elements in *S. asotus*, most likely as a result of the small sample size. Median muscle contents of Cr, Hg and Pb generally increased from the lower trophic level species to the higher trophic level species (*L. baicalensis* < *T. baicalensis* < *B. lenok* < *L. lota* < *S. asotus*), while liver contents of these heavy metals remained lower than the levels in the muscle. Extremely elevated ($p < 0.05$) median liver contents were observed for As in *L. lota*, Cd in *S. asotus* and Zn in *B. lenok*, while liver contents of individual *B. lenok* had the maximum amounts of Ni (0.82 µg g^{-1}) and Cu (33.8 µg g^{-1}) detected in the study. In fish muscle, several individuals exceeded the maximal permissible limits for human consumption for Zn, Hg and Pb. Four *B. lenok* (53.2 – 109 µg g^{-1}) had Zn contents in their muscle above the 40 µg g^{-1} threshold. For Hg, six *L. baicalensis* (0.52 – 1.85 µg g^{-1}), one *B. lenok* (0.58 µg g^{-1}), five *L. lota* (0.50 – 0.72 µg g^{-1}) and two *S. asotus* (0.65 – 0.88 µg g^{-1}) had contents in their muscle above the 0.5 µg g^{-1} threshold, and for Pb two *B. lenok* (0.59 and 0.73 µg g^{-1}) and two *L. lota* (0.32 and 0.34 µg g^{-1}) had contents in their muscle above the 0.3 µg g^{-1} threshold.

Generalised linear model (GLM)

The GLM determined the influence of five variables in explaining the observed heavy metal patterns detected in the sampled fish species (Table A3- 1). The most important explanatory variables across species and heavy metals were fish age and length / tissue interactions, followed closely by fish tissue, fish length and site sediment contents. Site water concentrations for As and Hg were significant ($p < 0.05$) for all species except *S. asotus* for Hg. For *L. baicalensis*, length / tissue interactions were the most important explanatory variable being significant for all heavy metals, while for *T. baicalensis* and *B. lenok* fish age was the only variable significant for each heavy metal and arsenic. Fish length, fish tissue and length / age interactions were all significant for *L. lota* and *S. asotus*, while fish tissue and fish age were both significant for all but one heavy metal (Pb and Cr), respectively.

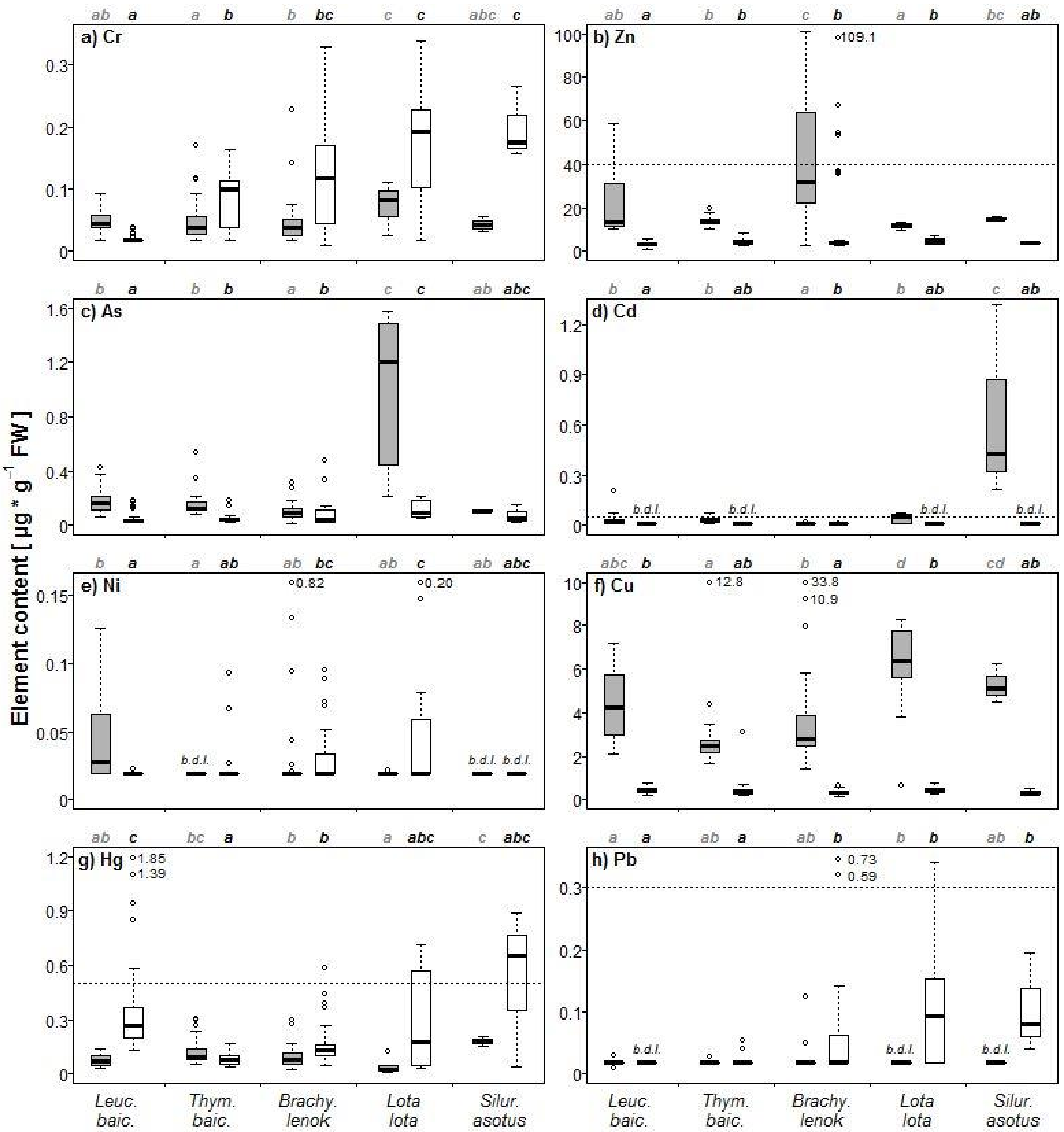

Figure 11. Heavy metal contents (Cr, Zn, As, Cd, Ni, Cu, Hg and Pb) in liver (grey boxes) and muscle (white boxes) of five consumed fish species in the Kharaa River basin (L. baicalensis n = 14 liver samples / 46 muscle samples, T. baicalensis n = 23 / 24, B. lenok n = 34 / 35, L. lota n = 10 / 11 and S. asotus n = 3 / 3) collected in June 2011. Letters (a, b, c, d) above each plot indicate significant differences between species groups—grey letters relate to liver, and black letters relate to muscle. Boxes indicate the median and 10 / 90 percentile, whiskers 2 9 percentile range, open dots are outliers; b.d.l. indicates values are below detection limits. Dotted lines indicate international recommended thresholds for human consumption of fish tissue where applicable.

Regional Patterns of Heavy Metal Bioaccumulation in Fish Muscle

The regional differences between the median heavy metal muscle contents of sampled fish species were considerable (**Figure 12**). The median Cr contents were generally low and well below the internationally recommended threshold of 1 µg $g^{-1}$for this heavy metal in consumed fish muscle. For Zn, only *B. lenok* in the UP region had elevated contents close to the 40 µg g^{-1} threshold, while for all other species and regions Zn accumulation remained low (< 10 µg g^{-1}). The highest As median muscle contents were detected in *L. lota* sampled from the DOWN region, although As was also elevated in *S. asotus* (DOWN) and *B. lenok* (UP). The median As contents in the muscle of all other fish species and regions was below 1 µg g^{-1}, however, no threshold has been given for As in consumed fish, as the principle form in fish tissue is organic As (arsenobetaine) and thus nontoxic to humans (FAO/WHO 2011). Cd was below the analytical detection limits in all species and regions except for *B. lenok* in the upper tributaries (UP), although median muscle contents were still well below the recommended threshold of 0.05 µg g^{-1} for fish tissue. Median muscle contents of Ni and Cu were negligible in all fish species and regions sampled in the KRB. Hg detected in fish muscle exceeded the international recommended threshold of 0.5 µg g^{-1} in three different species and two regions: *L. baicalensis* in the MID region and *L. lota* and *S. asotus* in the MID-DOWN region. *S. asotus* in the DOWN region also recorded an elevated median muscle Hg content of 0.46 µg g^{-1}. Pb was very low or below the detection limit for *L. baicalensis*, *T. baicalensis* and *B. lenok* in the UP, MID-UP and MID regions. Elevated median Pb contents were detected in four fish species (TB, BL, LL, SA) in the MID-DOWN region, although the 0.3 µg g^{-1} threshold was not exceeded.

Table 2. Summary table of sampled species displaying sample size (n), mean total length (TL) in cm (± SD), mean total weight (TW) in grams (± SD) and the number of individuals in different age classes (years).

Species	n	TL (mean ± SD)	TW (mean ± SD)	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9
L. baicalensis	46	18.16 (± 1.61)	56.33 (± 19.10)	0	0	0	3	17	15	8	3
T. baicalensis	24	22.73 (± 4.08)	117.75 (± 59.34)	6	3	11	4	0	0	0	0
B. lenok	35	32.35 (± 8.03)	376.61 (± 334.83)	0	3	12	11	6	2	1	0
L. lota	11	37.54 (± 24.0)	801.73 (± 975.40)	6	1	0	0	1	1	2	0
P. asotus	3	52.87 (± 7.04)	949.9 (± 424.44)	0	0	0	0	1	1	0	1

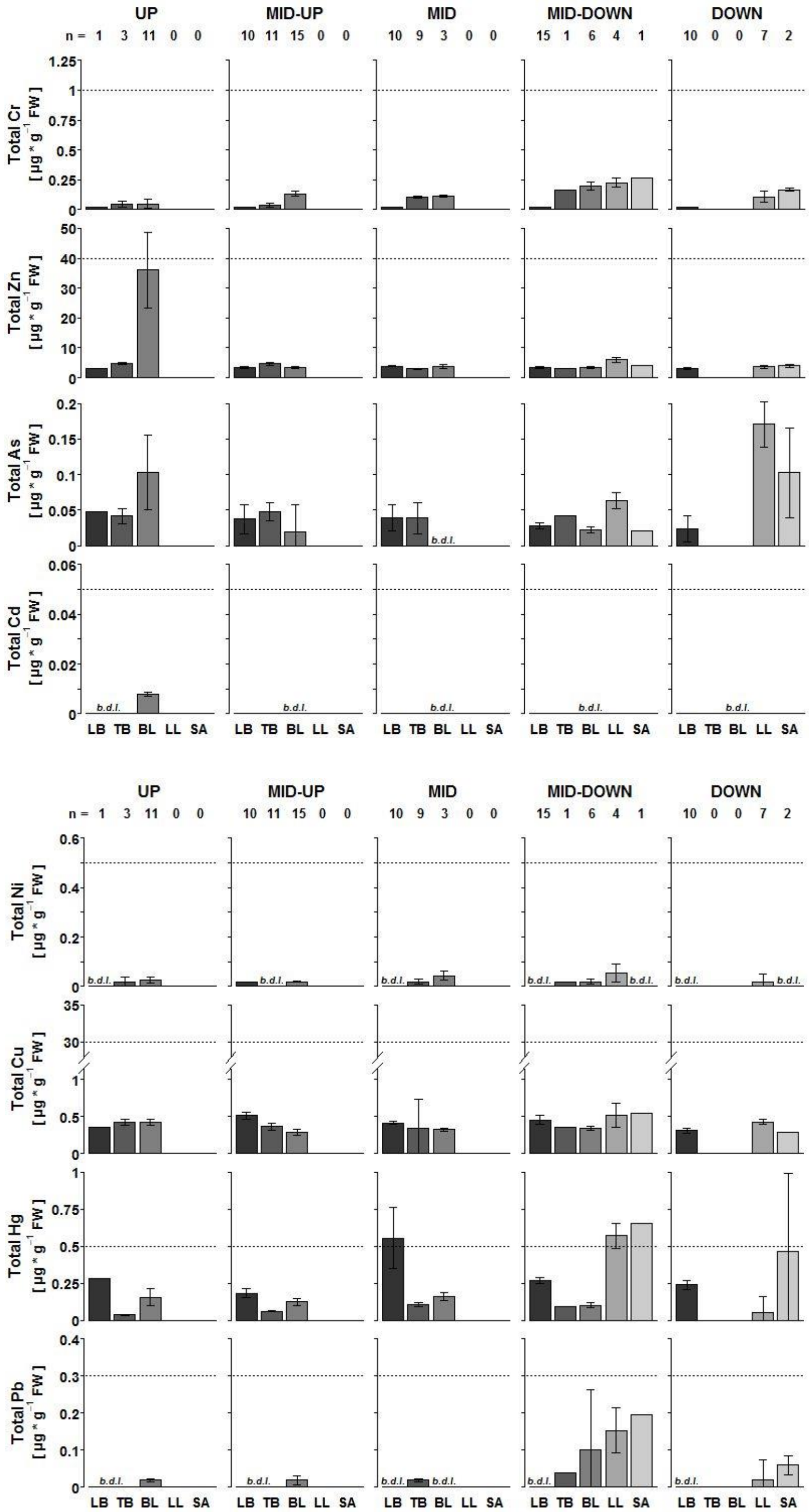

Figure 12. Median heavy metal contents with standard error in the muscle of five fish species (L. baicalensis, LB; T. baicalensis, TB; B. lenok, BL; L. lota, LL and S. asotus, SA) grouped into five regions across the KRB; UP stream (Sugnugr and Olgin), MID UP (Gatsuurt, Kharaa 8.4 and Kharaa 8), MID (Boroo and Kharaa 5.5), MIDDOWN (Zagdalin and Kharaa 4) and DOWN stream (Kharaa 1 and Kharaa 3). The dotted lines indicate the international recommended thresholds for human consumption of fish tissue. The line of numeric values above the bars represents the number of samples included in each region (n).

5.5 Discussion

Several studies of surface water, groundwater and river sediment in the KRB have highlighted the localised heavy metal and As pollution associated with gold mining activities (Hofmann et al., 2010, 2015b; Inam et al., 2011; Pfeiffer et al., 2015; Batbayar et al., 2015). In the current study, maximum surface water concentrations for both c_{As} = 15.3 µg L^{-1} and c_{Hg} = 0.066 µg L^{-1} were detected in the Gatsuurt tributary downstream from the mine site, where these elements were more than double any other concentration detected in the KRB during the study, but less than half that of previously reported maximum concentrations for As (30.1 µg L^{-1}) and Hg (2.0 µg L^{-1}) (Hofmann et al., 2010; Pfeiffer et al., 2015). However, the 2011 concentrations still exceeded the Mongolian drinking water thresholds of 10 µg L^{-1} for As and 0.05 µg L^{-1} for Hg, indicating a significant health risk for the local residents, their livestock and wildlife who rely on this tributary for their drinking water. The As content detected in the Gatsuurt tributary sediment was also the highest in the basin at 30.8 µg g^{-1}, although well below the previously reported level of c_{As} = 136 µg g^{-1}sampled from closer to the mine site (Enkhdul et al., 2010), and still below the recommended threshold for As (c_{As} B 40 µg g^{-1}) in river sediment recommended for German Rivers (Schneider et al., 2003). In contrast to the elevated Hg in river water, Hg in Gatsuurt sediment was beneath the analytical detection limit, suggesting a more recent source of Hg pollution is contaminating the river water, but had not yet accumulated in the sediment. In any case, the Gatsuurt tributary is one of the most polluted in the KRB and considering the future expansion of the mining operations, the potential increased pollution could have significant impacts on the usability of the river water for downstream residents as well. Mitigating measures should be urgently implemented to minimise As leaching from the overburdened soil and rocks during the open-cut mining operations, while attempts should be made to identify the source of the high Hg concentration in the tributary water. Current residents must be made fully aware of the hazards of drinking the water from the Gatsuurt tributary, as prolonged exposure to even low concentrations of these toxic elements can induce serious health problems (Pfeiffer et al., 2015; Steckling et al., 2011).

A second polluted site identified in the KRB was the Boroo tributary. While water concentrations for As and Hg were elevated above reference levels, they did not surpass Mongolian drinking water thresholds even with the very high content of c_{Hg} = 0.78 µg L^{-1} in the sediment. The Boroo River Hg sediment contamination can be characterised as a moderately polluted ecosystem (c_{Hg} - < 0.8 µg g^{-1}), according to the German Chemical Classifications (LAWA, 1997a), and recorded the same maximum Hg content as Lake Titicaca sediment (c_{Hg} = 0.78 µg g^{-1}; Monroy et al., 2014), but a lower maximum content compared to the Puyango River in

Ecuador (c_{Hg} = 0.99 µg g^{-1}; Tarras-Wahlberg et al., 2001), both regions that reported hazardous Hg contamination in resident fish tissue. Elevated contents of Cr, Zn, Pb, Cu and Ni were also detected in the Boroo tributary sediment; however, all heavy metals there and elsewhere in the KRB were below the German Chemical Classifications for river sediment Class I thresholds as related to an aquatic ecosystem without any anthropogenic interference (c_{Cr} – B 80 µg g^{-1}, c_{Ni} B 30 µg g^{-1} and c_{Pb} B 25 µg g^{-1}), or below the Class I–II thresholds indicating levels of very low pollution (c_{Zn} B 150 µg g^{-1}, c_{Cu} B 20 µg g^{-1}and c_{Cd} B 0.6 µg g^{-1}; LAWA, 1997a). Thus, the Boroo tributary was confirmed as a key source of Hg pollution in the KRB owing to the contamination related to artisanal, small-scale mining as well as the 1956 Hg industrial accident (Hofmann et al., 2010; Tumenbayar et al., 2000). Although the use of liquid Hg to amalgamate gold in Mongolia's small-scale mining operations was prohibited in 2008, strict enforcement is lacking and so its use likely continues, potentially adding to the already high Hg levels in this sub catchment.

During high rainfall and snow melt events, contaminates are either washed or leached from mining sites into nearby streams and tributaries or are infiltrated into groundwater bodies (Chalov et al., 2015; Hofmann et al., 2015b), where they are influenced by processes including dispersion, sorption, dissolution—precipitation and different chemical reactions that ultimately bind them to sediments and suspended loads (Thorslund et al., 2012; Chalov & Romanchenko, 2015). As a result, heavy metal concentrations in surface waters fluctuate greatly, making a single water sample capable of only providing an approximation of the local contamination at a specific point in time, whereas the analysis of the heavy metal sediment content can offer a more robust assessment of the long-term pollution status of a local area. Therefore, future water and sediment monitoring programmes in the KRB should have an increased temporal sampling regime in order to accurately follow the contamination levels stemming from the expanding open cut and illegal, placer mining operations.

Palaearctic riverine fish communities are naturally separated into upstream salmonid-dominated and downstream cyprinid-dominated communities due to the species' ecological and biological preferences for specific habitat conditions. Mature individuals of many fish, including the sampled species, typically have extended home ranges which include spawning, feeding and winter refuge pools in river reaches separated by up to 100 km. Particularly, in the harsh conditions of the prolonged Mongolian winter, individuals are forced to exit the smaller tributaries before they freeze solid forcing fish to return to the main river channel and accumulate in the deeper pools under the river ice, only re-entering those tributaries in spring to access more optimal spawning and feeding sites. It is expected that for at least *B. lenok* and *T. baicalensis*, individuals have likely travelled between multiple sampling sites and potentially across adjacent regions during extended seasonal migrations (> 45 km) as has been indicated by acoustic telemetry tagging and population genetics studies of these species in Mongolia (Research Projects 6). Thus, individuals have potentially been exposed to different levels of heavy metal contamination, and therefore, in order to gain a complete understanding of the accumulation pattern of KRB fish, it was necessary and reasonable to evaluate fish both at a basin-wide scale by grouping individuals by species, as well as at a regional scale by dividing fish into sampling regions.

The heavy metal accumulation observed in KRB fish species was highly variable depending on the contaminate and the main depository tissue. *S. asotus*, like other catfish, are opportunistic predators that feed on most other fish species in their habitat (Stolyarov, 1985). Thus, they are at the top of the aquatic food chain, where they tend to accumulate elevated contents of heavy metals such as Hg due to biomagnification processes (Paterson et al., 2009). This has evidently happened with regard to the high *S. asotus* Hg content in the KRB, and has likewise occurred in the lower Selenga River basin near Lake Baikal, where *S. asotus* accumulated the highest Hg muscle content of the 13 fish species investigated there. *S. asotus* recorded a mean Hg muscle content of ~ 0.216 µg g^{-1} wet weight (ww) (1.08 µg g^{-1}dry weight, dw; Komov et al., 2014; Haines et al., 1992), which was 2.4 times lower than KRB *S. asotus* (mean = 0.52 ± 0.43 µg g^{-1} ww, median = 0.65 µg g^{-1} ww, n = 3). In addition, a related catfish species (*Silurus glanis*) in the Danube River, Serbia, also accumulated the highest Hg content of the four fish species investigated in that study, recording a mean Hg muscle content of ~ 0.326 µg g^{-1} ww (Subotić et al., 2013), although this was also less than the Hg detected in KRB *S. asotus*. The GLM results indicated fish length, fish tissue, fish age and site sediment all significantly contributed to the Hg accumulation in *S. asotus*, suggesting that older, larger fish accumulate more Hg in their muscle tissue and that this species close affinity to the river substrate has also played a substantial role. The elevated Cd observed in the liver of KRB *S. asotus*, compared to muscle, was related to biotic factors only (*e.g.* fish length and age), as site sediment was not significant. Danube catfish also showed higher mean contents of Cd in their liver (~ 0.004 µg g^{-1} ww) compared to muscle (~ 0.002 µg g^{-1} ww) (Subotić et al., 2013), although at far lower levels in relation to KRB *S.asotus'* liver contents (mean = 0.655 ± 0.58 µg g^{-1} ww, median = 0.426 µg g^{1} ww, n = 3). Therefore, in comparison with the lower Selenga basin and Danube River catfish, the Kharaa River *S. asotus* had accumulated considerably higher heavy metal contents in the muscle for Hg, Pb, As, Cr and Cd but lower contents of Zn and Cu thus highlighting the hazardous heavy metal contamination of this consumed Kharaa River species.

Lota lota are also close to the top of the aquatic food chain as they are a predatory species that consumes mainly fish, but also invertebrates at smaller sizes (Pääkkönen & Marjomäki, 2000). *L. lota* have accumulated a median Hg muscle content of 0.178 µg g^{-1} ww (mean = 0.306 ± 0.28 µg g^{-1} ww, n = 11), with four individuals exceeding 0.5 µg g^{-1} ww. However, this was in contrast to *L. lota* sampled from the Taimyr Peninsula in northern Russia, which recorded a mean Hg muscle content of ~ 0.494 µg g^{-1} ww (Allen-Gil et al. 2003), or considerably above KRB *L. lota* levels. Although, in the Lena and Mezen rivers, also in Russia, mean Hg muscle contents of *L. lota* were lower with ~ 0.05 and ~ 0.15 µg g^{-1} ww, respectively (Castello et al., 2014), or well below KRB *L. lota* contents. The GLM results indicated a complex process of Hg accumulation in *L. lota*, with fish age appearing to play the most significant role. For Cr, *L. lota* accumulated the highest median muscle content of all KRB species with a content of 0.193 µg g^{-1} ww (mean = 0.171 ± 0.1 µg g^{-1} ww, n = 11), which was elevated compared to Danube River *L. lota* with ~ 0.008 µg g^{-1} ww (Subotić et al., 2013). Fish length, fish tissue and site sediment along with the interactions of these variables have influenced Cr contents in *L. lota* muscle as determined by the GLM. Arsenic was found to be extremely elevated in the liver of *L. lota* compared to the other species investigated, which was also the case for *L. lota* in the Danube River, Serbia (Subotić et al., 2013), and from the Taimyr Peninsula in Russia (Allen-Gil et al., 2003). KRB *L. lota* As liver contents (median = 1.2 µg g^{-1} ww, mean = 0.99 ± 0.56 µg g^{-1} ww, n = 11) were 4.6 and 3.5 times higher than the mean As liver contents from this species in the Danube River (~ 0.212 µg g^{-1} ww) and the Taimyr Peninsula (~ 0.28 µg g^{-1} ww), respectively, once dry weights were adjusted to wet weights (see Komov et al., 2014; Haines et al., 1992). According to the modelling results, As accumulation in *L. lota* was complex, with all variables and interactions significant, except for tissue / age. Previous studies have suggested that elevated As contents in fish can be explained by the geomorphological substratum (Rowland et al., 2011), but this does not appear to be the case in the KRB with low As sediment contents and water concentrations compared to reference sites detected in the lower basin (Kharaa 1 and Kharaa 4) where *L. lota* with the highest As contents were captured.

B. lenok and *T. baicalensis* are both benthopelagic species that prefer clearer, faster flowing and well-oxygenated waters of the middle and upper KRB basin. The diet of these salmonids includes zoobenthos, macroinvertebrates, fish and terrestrial rodents (Chandra et al., 2005), which has, along with their upstream habitat preferences, likely contributed to their low heavy metal contents detected in most of the KRB individuals. These species typically recorded lower median heavy metal contents in comparison with *L. lota* and *P. asotus* for all elements, except Zn in *B. lenok* sampled from the UP region. The reason behind the high Zn content in *B.*

lenok in the upper reference tributaries was undetermined, although elevated levels were generally found in individuals sampled from the Olgin tributary site. This site, whilst itself did not have elevated Zn in the water or sediment (77.7 μg g^{-1}), is located in the same upstream region as the Sugnugr tributary where the highest Zn sediment contents were detected in the KRB (112 μg g^{-1}). This contamination supports the idea that individuals of this species undertake extended seasonal movements between the main channel and various spawning and feeding tributaries, which was also observed in acoustic telemetry tagging studies (Chapter 6). In other regions that have examined heavy metal accumulation in *B. lenok*, including the Genhe and Ussuri rivers in north eastern China, heavy metal contents in the muscle were also very low, being below KRB levels for Cr, Cd, Zn, Ni and Pb in both rivers, and for Cu in the Ussuri River (Wang & Mou, 2011). While for *T. baicalensis* sampled in Lake Baikal at the mouth of the Selenga River (0.076 μg g^{-1} ww– 0.38 μg g^{-1} dw; Komov et al., 2014), mean Hg muscle contents were comparably low compared with the KRB individuals (mean = 0.084 ± 0.03 μg g^{-1} ww, median = 0.086 μg g^{-1} ww, n = 24), while further downstream in the Yenisei River near Krasnoyarsk City, Russia, the heavy metal burden was investigated in *Thymallus arcticus* and was again found to have a similar low muscle content of Pb, Zn, Ni and Cd, but elevated Cr contents compared to KRB grayling (Anishchenko et al., 2009).

L. baicalensis is a small bodied cyprinid that consumes periphyton, zoobenthos and terrestrial insects (Chandra et al., 2005) and thus occupies the bottom tier of the KRB food web. However, the elevated contents detected in this species are likely due to its benthic feeding behaviour, where it incidentally ingests contaminated fine sediments and suspended organic matter, which can increase its uptake of heavy metals, than what would generally be the case for a lower trophic level species. This has been previously described in other regions and species, where sediment contaminated with heavy metals has posed a direct risk to benthic feeding fish (Köse et al., 2015; Monroy et al., 2014). Although the GLM results determined site sediment as a significant factor influencing the accumulation of most heavy metals in *L. baicalensis*, it also identified water concentrations for As and Hg, fish length, fish age, fish tissue and multiply interactions of these variables as also being significant, thus suggesting that heavy metal accumulation in *L. baicalensis* in the KRB is more complex than just considering heavy metal contamination in the river sediment. In similar studies, *L. baicalensis* sampled in the Russian section of the lower Selenga River basin and nearby lakes were reported as having mean Hg muscle contents between ~ 0.136 (0.68 μg g^{-1} dw) and ~0.054 μg g^{-1} ww (0.27 μg g^{-1} dw) (Komov et al., 2014), which is substantially lower than in the KRB where the mean muscle Hg content was 0.362 μg g^{-1} ww (median = 0.254 ± 0.32 µg g^{-1} ww, n = 45). In the Pechora River, northern Russia, *Leuciscus idus* also had lower muscle contents for Cd and Pb, but higher contents for Cu and Zn (Allen-Gil & Martynov, 1995), further illustrating the increased bioavailability of contaminating heavy metals in the KRB compared to other similar rivers and species.

Regional patterns of heavy metal bioaccumulation in the KRB fish fauna was evident for Cr, Zn, As, Hg and Pb, while Cd, Ni and Cu accumulation showed no obvious regional differences in fish muscle content. In the unimpacted reference sites (UP region), *B. lenok* had still accumulated elevated Zn and As due to the increased background levels in the sediments. In the upper basin, *B. lenok* is the largest species and also likely moves substantial distances from deeper overwintering pools into smaller tributaries to spawn and feed in spring. Thus, the bigger *B. lenok* sampled in this region has likely been exposed over multiple years to these elevated heavy metals during their extensive seasonal movements and through the ingestion of their contaminated prey items. In both the MID-UP and MID regions, where only *L. baicalensis, T. baicalensis* and *B. lenok* were collected, contamination levels were comparable to the upstream reference region, except for Zn and As in *B. lenok* and the elevated Hg levels detected in *L. baicalensis* in the MID region. As *L. baicalensis* was the only species collected in the heavily polluted Boroo tributary, it was not unexpected that the Hg contamination from the sediment was reflected in these individuals. There was also no apparent contamination in the MID-UP region fish fauna from the expanding mining operations in Gatsuurt, even with the hazardous As and Hg concentrations detected in the tributary's water. Heavy metal and metalloid contamination was most apparent in the MID-DOWN and DOWN regions of the KRB, particularly as the larger trophic species were collected there. Both *L. lota* and *S. asotus* recorded Hg contents above international thresholds (0.5 µg g^{-1}) in the MID-DOWN region, although the number of individuals sampled was very low. As Hg in the sediment was below the detection limits in the Zagdalin tributary, it is expected that the Hg recorded in the main channel site (Kharaa 4) had been transported downstream from its source in the Boroo tributary and thus the persistent and accumulative capability of Hg in the environment has likely contaminated these fish species in the neighbouring MID-DOWN region as well. Pb, and to a small degree Cr, contamination was limited somewhat to the MIDDOWN region even though the maximum contents in the river sediment was also detected in the Boroo tributary. It is likely that both of these heavy metals (Pb and Cr) have also been transported downstream, increasing sediment contents in the adjacent MID-DOWN region main channel site and further exposing the higher trophic level species to this contamination, which has subsequently accumulated in the individuals that were captured there. However, why

T. baicalensis and *B. lenok*, which were sampled in both regions showed increased Pb and Cr accumulation in the MID-DOWN compared to the more polluted MID region is unclear. In the DOWN region, elevated As in *L. lota* and *S. asotus* was also unexpected as there was low As in both water and sediment sampled in this region. Individuals with the higher As contents were also generally smaller (< 20 cm TL; n = 6), as was the case concerning *L. lota*, potentially indicating that a specific nursery area, that was not sampled, contains a higher As content than the main river sites sampled in the DOWN region. Only one *S. asotus* sampled in the DOWN region had a high Hg muscle content of 0.88 µg g^{-1}, while a second individual recorded 0.04 µg g^{-1}. Both fish were also similar lengths of 49 and 48.6 cm TL respectively. The reason for this elevated Hg content in a single individual in the DOWN region is unclear, but it is likely related to either the fish's own movements or movements of its prey items potentially having been exposed to Hg contamination elsewhere. Considering the sediment contents were similar for Hg both above and below Darkhan (Kharaa 3 and Kharaa 1), it appears that neither Darkhan city nor the 2007 Hg spill has had a major influence on fish contamination in the region, although the Hg concentration in the water closest to the spill location remained elevated above references levels (0.031 µg L^{-1}).

The Kharaa River basin fish fauna has been exposed to and accumulated elevated contents of several toxic heavy metals in their edible muscle tissue, with Hg posing the greatest threat to human health if fish are consumed frequently. Even though, in 2011 only 10.7 % of the total fish sampled from the five species had accumulated Hg above the internationally recommended threshold of 0.5 µg g^{-1} ww, this low level of contamination should still be considered carefully in relation to the amount, frequency and sensitivity of the people consuming fish from the KRB. Therefore, information obtained from a recreational fishing survey conducted during the summer of 2012 (Chapter 4) indicated that while fish consumption was generally low for most fishers, it varied considerably from once or twice a year to almost every day in the summer and autumn months for unemployed and retired residents. The most common species and mean size caught was *B. lenok* of 34 cm (25 – 40 cm), which had a median Hg muscle content of 0.14 – 0.16 µg g^{-1} ww. So considering the average consumption rate of KRB recreational fishers was approximately one *B. lenok* per week during the fishing period, then the Provisional Tolerable Weekly Intake (PTWI), as related to the safe human consumption of methyl Hg (~ 80 % of total Hg) in fish muscle, these fishers are ingesting between 21 – 24 % of the recommended weekly intake by the WHO (MeHg 1.6 µg kg^{-1} body $weight^{-1}$ $week^{-1}$). With this weekly threshold potentially being exceeded at the maximum consumption rate reported in the survey (5 – 7 fish $week^{-1}$) or if a highly contaminated *L. lota* or *S. asotus* is consumed. These potential health risks also need to be seen in the context of other sources of heavy metal exposure, of which several are relevant in Mongolia. If the human body burden for Hg or other heavy metals is already elevated due to occupational exposure (*e.g.* artisanal gold miners) (Steckling et al., 2011), ingestion of contaminated water (*e.g.* Gatsuurt tributary), consumption of other contaminated foods (plant products grown on soils enriched in heavy metals; Kasimov et al., 2011), or exposure to significant air pollution (locally elevated levels of several heavy metals; Sorokina et al., 2013), then frequently eating contaminated fish species will serve to intensify the chronic absorption levels in a person. This is concerning considering the most sensitive community members, including pregnant women and young children, may already be facing potential serious health implications from other sources of heavy metal contamination as well (Steckling et al., 2011).

Conclusions

Although the demand for direct intervention (*e.g.* restrictions of fish consumption) is not immediately warranted, it is advisable to implement an investigative monitoring programme in order to quantify pollution levels and determine trends of heavy metal contamination within the KRB fish fauna. A meaningful set-up with regard to spatial sampling strategies, analytical methods and potential biological indicator species may be derived from the results of the current study. In a broader context, the data presented here has filled an important knowledge gap for integrative water resource management planning, which in the case of the KRB, has typically been impeded by poor data availability (Karthe et al., 2015b). For the first time in the KRB or anywhere in Mongolia, it has been shown that heavy metal emissions related to gold mining activities are not only theoretical risks, but that accumulation from the environment into consumed fish species is evident and has reached concerning levels in the worst affected regions *e.g.* in the middle and lower river reaches. The described findings from the KRB, as a model study area, are also important to better understand mining-related risks across the vast Selenga-Baikal basin, which is characterised by a similar natural environment and comparable anthropogenic pressures (Karthe et al., 2015).

6 Movements and behaviour of an archaic trout, *Brachymystax lenok* (Pallas, 1773) under extreme environmental conditions in Mongolia

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6.1 Abstract

Knowledge of a species' spatial and temporal movements along with the way these shift under extreme seasonal conditions is vital for understanding its autecology and developing scientifically sound conservation and management strategies. The aim of this research was to describe and quantify the diel and seasonal movement, acceleration and depth of *Brachymystax lenok*, a threatened, potadromous salmonid that inhabits the boreal river basins of northern Asia and Siberia. Twenty-one mature individuals were implanted with an acoustic transmitter and monitored over a 15 month period in the upper Eroo River, Northern Mongolia. Mean (± SD) *B. lenok* home ranges were 19.1 ± 15.1 km, with maximum longitudinal movements detected of up to 45.3 km. Two periods of increased longitudinal movements were identified; the first in late summer / early autumn when 10 *B. lenok* moved downstream to deeper, overwintering pools, with the second period occurring in late spring and early summer when nine *B. lenok* were recorded entering surrounding tributaries. Diel activity and depth typically increased during daylight followed by decreased activity or resting periods in shallower river sections at night. These results highlight the need to maintain a high level of river connectivity by implementing and enforcing an expansive spatial management plan to better protect and recover the threatened Eroo River basin lenok populations, which can be transferred to similar regions across Mongolia and throughout the species' declining distribution.

6.2 Introduction

In subarctic regions of the world, pronounced seasonal weather fluctuations can create extreme environmental conditions that shape riverine habitats and regulate aquatic communities (Weber et al., 2013; Resh et al., 1988). In order to prevail in such ecosystems, boreal fish species must endure high-intensity disturbances including prolonged minimal water temperatures, extended low river discharge, complete river ice coverage and break up, reduced light and food availability and major flood events (Prowse, 2001). While such volatilities ultimately increase the susceptibility and mortality of individuals (Power et al., 1993; Brown et al., 2011), resident fish populations display specific movement patterns and behaviours in order to survive and reproduce in these harsh environments, if migrating away from them is not an option. Thus, acquiring a detailed knowledge of these movements and the way they shift under fluctuating conditions is essential for not only understanding a species' autecology, but for developing and implementing scientifically sound conservation and management regimes such as spatial and temporal protected areas and periods, river restoration measures and environmental flows regimes. In addition, this information is critical in light of the exacerbating climate change effects that are already impacting on the world's most sensitive ecoregions and species, including high latitude and altitude ecosystems inhabited by the world's archaic salmonid genra, such as those found in Mongolia (Shed'ko et al., 1996; Deng et al., 2015; Malsy et al., 2015; Hartman et al., 2017).

The possibility to quantify free-swimming fish movements and behaviours has progressed significantly in recent years with rapid advancements in biotelemetry technology. Miniaturisation of transmitters and improved sensor capabilities has enabled a wide range of data to be obtained from smaller fish size classes and over extended periods without impact on the welfare and natural behaviours of fish (Cooke et al., 2013). Passive acoustic telemetry provides the possibility for increased numbers of individuals to be monitored remotely, with an array of receivers deployed over an extensive area (Heupel, 2004). This telemetry technology has been successfully used to determine individual home ranges, migration routes, site residency and patterns of activity and depth in both freshwater and marine ecosystems, and for numerous species and populations under a variety of conditions (Cooke et al., 2013). Worldwide, salmonids have been the focus of numerous telemetry studies (Young et al., 1997; Ovidio, 1999; Schmetterling, 2001; Gilroy et al., 2010, Yoon et al., 2015, Kaus et al., 2016), due to their high economic value as a commercial and recreational fishery resource, as well as their increasingly threatened global status. In Mongolia, these reasons have also been the motivation for conducting the current acoustic telemetry study that has focused on the *B. lenok* (*Brachymystax lenok*, Pallas 1773), as it is one of the main target species in the country's emerging recreational fishery and thus populations have already suffered from widespread declines in their abundance and distribution (Ocock et al., 2006).

The sharp-snouted lenok or *B. lenok* (from here on referred to as lenok) is a potadromous salmonid that can grow to a maximum size of 70 cm and 8 kg (Chyung, 1977; IGFA, 2001). This species inhabits the rivers and lakes of Eurasia including Siberian Russia, Kazakhstan, China and Mongolia (Dulmaa, 1999; Kottelat, 2006, Esteve &

McLennan, 2008). It is one of three in the *Brachymystax* genus that forms the most basal genetic clade of the subfamily Salmoninae (Shed'ko et al., 1996). The current understanding of lenok autecology is limited, as most publications concerning this species have focused on phylogenetic origins and relatedness of conspecifics (Froufe et al., 2003, 2008). Only a single ecological study has been conducted on a closely related lenok species (*B. tsinlingensis,* reported as a subspecies in the study) in the impacted Nakdong River in South Korea, which described individual movements and habitat use during specific seasonal periods (Yoon et al., 2015; Xing et al., 2015). The authors reported the maximum distance moved by a mature individual was 8.7 km in spring when fish were detected moving upstream and entering the surrounding tributaries that contained known spawning habitat. During during winter, less extensive movements were detected with individuals displaying limited mobility of less than 4.13 km (Yoon et al., 2015). Lenok movements were not monitored during summer or autumn and never before have they been investigated in an unimpacted, free-flowing river system. Thus fundamental ecological questions remain, regarding their complete range of seasonal movements, as well as their annual, unimpeded home ranges sizes. While the finer scale diel and seasonal behavioural patterns and depth use has only been previously understood from anecdotal evidence, it has been suggested that the species prefers to occupy surface waters down to 30 cm in summer before moving into deeper pools (1 - 2 m) to overwinter (Dulmaa, 1999; Yoon et al., 2015).

In recent decades, lenok has become a popular target species for recreational anglers throughout Mongolia where the fishing effort has grown rapidly with larger numbers of people catching and consuming fish on a regular basis (Chandra et al., 2005; Chapter 4). However, many local and foreign anglers are unaware or uncompliant towards the existing fishing regulations and so illegal activities are common and widespread (Bailey, 2012; Chapter 4). These regulation breaches threaten the long-term sustainability of lenok populations in Mongolia. While this threatened species is already included on Mongolia's Red List of Fishes (2006) as vulnerable, due to the increased fishing harvest, water pollution, habitat destruction and climate change impacts, the local populations are expected to decline by at least a further 30 % by 2021 (Ocock et al., 2006). Thus, further research, including an improved ecological understanding of this understudied species, is urgently required so authorities can improve, develop and implement practical management and conservation strategies. Therefore, the aim of this study was to identify and quantify the spatial and temporal shifts in individual movements and behaviours of mature lenok over a 15 month period using passive acoustic telemetry in an unimpacted, boreal river system in northern Mongolia. The research focused on identifying and describing the diel and seasonal longitudinal movements including linear home ranges and areas of increased occupancy, as well as diel and seasonal differences in behaviour (acceleration) and habitat use (depth). It is hypothesized that this species maintains a significantly larger home range than what has been previously reported in impacted river systems, while specific temporal movements are expected to closely match other boreal salmonids such as *Hucho taimen* (Pallas, 1773).

6.3 Materials and Methods

Study site

The Eroo River (also written as Yeruu / Ерөө in the literature) is located in northern Mongolia within the Selenge River basin (Figure 1). It flows over 250 km from its source in the Khan Khentii Mountain Ranges (< 2799 m a.s.l.) to its confluence with the Orkhon River. The core study reach was located in the upper Eroo River basin, where two major tributaries (Sharlan Gol and Khongiyn Gol) converge to form the main Eroo River channel at Khonin Nuga Ranger Station. From here, the Eroo River flows through steep sided valleys with a characteristic pool (0.5 – 1.5 km long; < 4 m deep) riffle sequence. The regional climatic conditions include extreme cold, dry winters with minimum air temperatures of - 40˚C, complete river ice coverage from November to April and short, hot summers with a maximum of 40˚C, when most of the 250 – 290 mm annual precipitation falls, initiating periodic flooding events (Schlütz et al., 2007).

Transmitter implantation, specifications and receiver deployment

Lenok were angled using single barbless hooks to minimize potential injury and tagged in the core study reach during two periods between the 4th and 20th of July 2011 (n = 20; 33 – 46 cm TL), and on the 23rd of May 2012 (n = 3; 43 – 49 cm TL) (**Table 2**). Although sex and maturity could not be determined externally, the age of tagged individuals was estimated to be between five and eight years old based on age-length data from the Eroo River populations (Kaus, *Unpublished Data*). Thus it was expected that the majority, if not all, of the tagged individuals were sexually mature (3 – 6 years, Froufe et al., 2003). Once captured fish were anaesthetised (AQUI-S, New Zealand), TL (cm) and weight (g) were recorded. A 10 – 15 mm incision was made on the ventral side of the individual, off centre between the pectoral and pelvic fins for the V9AP transmitter (9 x 45 mm; Vemco, Canada) to be inserted into the peritoneal cavity. The incision was closed with 3 - 4 interrupted, absorbable sutures and the individual was returned to a slow flowing section of the river and supported until full swimming ability had resumed approximately 15 min later. The transmitters had a unique alternating identification code for both acceleration (range: 0 - 3.43 m s^{-1}) and pressure (range: 0 – 50 m) and a battery life of 377 days.

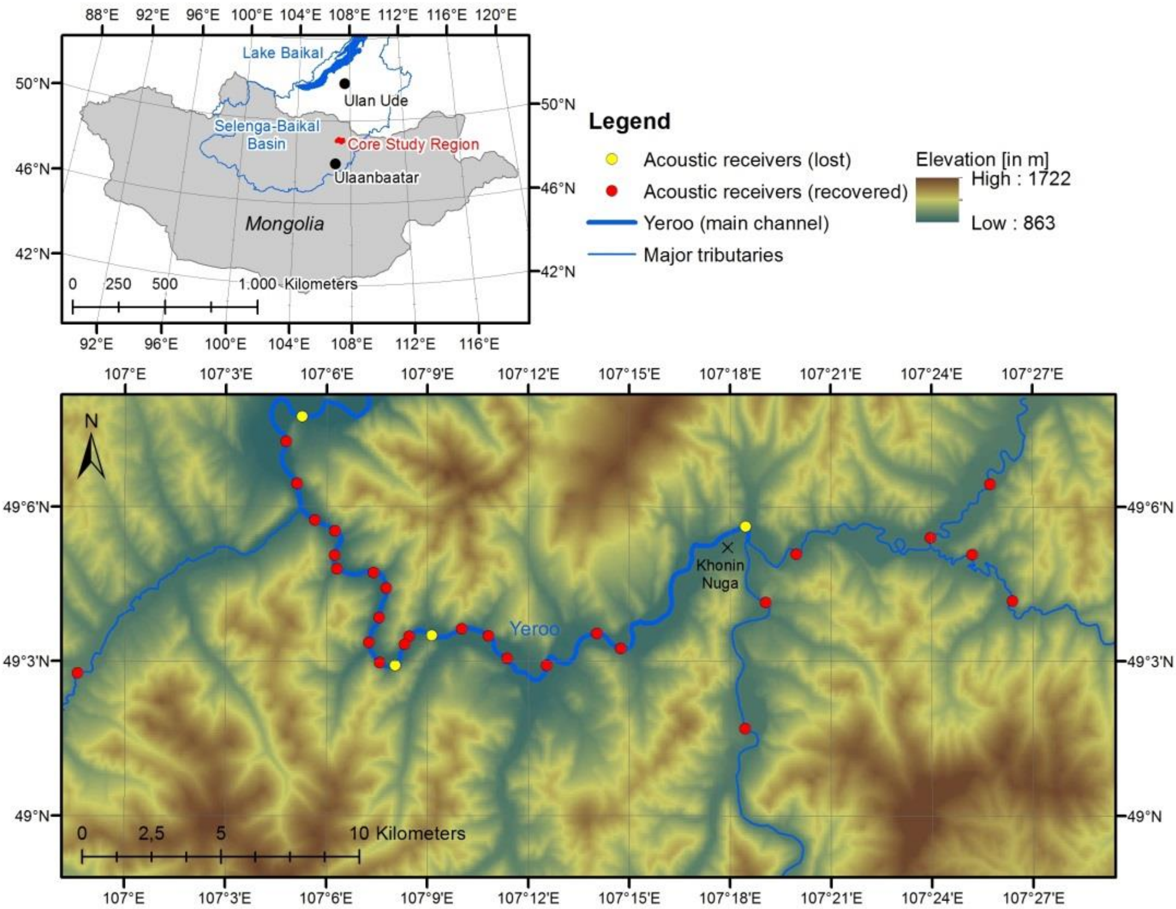

Figure 13. Map of Mongolia (top) with the location of the core study region (Upper Eroo River) indicated in red. Elevation map of the core study reach (bottom) showing the concentrated acoustic receiver array along the main river channel and the positions of the upstream receivers in the Sharlan, Ichlig, Khongiyn and Yalbac tributaries. Note: An additional two receivers were positioned further downstream, one in the middle basin and another close to the Eroo – Orkhon confluence – not shown.

Thirty-one acoustic receivers (VR2W; Vemco, Canada) were deployed in the upper Eroo River and its major tributaries (Sharlan, Khongiyn and Yalbac) in July 2011 (Figure 1). All receivers were separated by small riffles or bends in the river channel and thus did not have overlapping detection ranges (refer to range testing below). In addition, one receiver was placed in the main Eroo River channel downstream (~ 130 km) in the mid-basin, while a final receiver was deployed near the Eroo - Okhon river confluence (~ 245 km), in order to detect more extensive fish movements during the study. Receivers were deployed into deep, slow flowing pool sections to minimize loss and damage from flooding and floating debris and were positioned as far removed from areas of high turbulence as possible to restrict excess 'noise' created from entrained air bubbles associated with these locations (Cooke et al., 2013). In addition, the deployment of a concentrated receiver array within the core study reach, the focus region of fish capture and tagging, was aimed to improve detection of tagged fish as they move longitudinally along the river continuum. This was especially important due to the low sampling program of the transmitters that were used in order to have an extended battery life of 377 days to sample all seasonal extremes, while retaining the possibility of tagging smaller fish (> 340 g) and gathering data on acceleration and depth. Tidbit (Onset, USA) water temperature loggers were also placed in the river to record seasonal changes in water temperature. Motion sensor cameras (Waldkauz Digital Trail Camera, Germany) were also attached to riparian vegetation and used to define the adjusted seasonal periods. Eroo River discharge data was obtained from the Mongolian Academy of Sciences, and included daily measurements taken by a gauging station on the main Eroo River channel downstream of the core study reach.

Range Detection and Sensor Testing

In situ range detection tests were conducted on two random days within the core study reach, during river discharges of 139 $m^3 s^{-1}$ and 334 $m^3 s^{-1}$. A V9AP test transmitter with a 20 s random delay was placed in the river for 10 min each at a distance of 0, 50, 100, 150 and 200 m from the deployed receiver in both an up and downstream direction and on both sides of the river. Range detection tests could not be conducted in winter under the river ice due to accessibility of the study location. The acceleration sensor was tested for a stationary or deceased fish by placing the test transmitter in the river next to a receiver for a 20 min period. A pressure (depth) calibration test was also conducted by lowering the test tag into the water at 50 cm intervals for 10 min each until a depth of 2.5 m. Pressure values were detected with a manual tracking receiver (VR100, Vemco, Canada).

Data Analysis

All detections from the first 24 h post-surgery for each fish were excluded from the analysis to allow normal movements and behaviours to return. Two lenok were detected only once within the study area and so were removed from the analysis (Fish ID 73 / 74 and 31 / 32). Fish were assumed to have died or rejected the transmitter if the sensor values remained low (as per calibration test values) and constant without any longitudinal movements. As a result, Fish ID 45 / 46 was expected to have died or rejected its transmitter on the 1st of September 2011 (50 days post-surgery). The Residency Index (I_R) was calculated by dividing the number of days a fish was detected by the number of days between tagging and the last detection (O'Toole et al., 2010). A fish's linear home range was calculated as the distance from the most upstream to the most downstream detection point, including the distance travelled within a tributary, in order to estimate the total area of utilisation for each fish (Minns, 1995). Kernel densities (KD) were used to depict the probability of an animal occurring at a location within its home range as a function of the relocation points (receiver detection days) (White & Garrott, 1990; Pillans et al., 2014). A normal KD function with a bandwidth of 0.75 km was used to calculate the 50 % and 95 % KD for those fish that had been detected on > 15 days during the study period and on > 2 receivers (Worton, 1989; Vokoun, 2003; Duong, 2017). The seasonal periods used in the analysis were adapted to better match with local climatic conditions as well as fishery management regulations. Thus the adjusted period for autumn was from the first frost (16th of September 2011) until full river ice coverage on the 11th of November 2011; winter dates related to complete river ice coverage in the Eroo River (12th of November 2011 until the 1st of April 2012); spring was associated with the current closed fishing season dates in Mongolia (1st of April until the 15th of June 2012); and the adjusted summer period began on June 16th and lasted until the 15th of September 2012. The different periods of the day were divided into night (between one hour post sunset to one hour before sunrise), day (one hour after sunrise to one hour before sunset), dusk (one hour before sunset to one hour after sunset), and dawn (one hour before sunrise to one hour after sunrise).

Statistical differences were tested between season and period of the day for lenok total distance moved, acceleration and depth using the Kruskal Wallis test with a Tukey's HSD post-hoc test with a Bonferroni's adjustment. Correlations were performed to test the relationship between fish length and linear home range, and fish weight and linear home range. Linear mixed effect models were used to describe the relationship between lenok longitudinal movement, acceleration and depth, which were fixed factors, against water temperature, river discharge, photoperiod (period of the day) and fish TL included as co-variables. Fish ID was added as a random factor in all models and was used as the null model for comparisons. The Akaike information criterion (AIC) is $AIC = -2*logLM + 2*(nc + p + 1)$, where logLM is the maximized log likelihood (or maximized restricted log likelihood) of the model, and $nc + p + 1$ is the number of parameters estimated in the model. "p" is the number of fixed-effects coefficients, and "nc" is the total number of parameters in the random-effects covariance excluding the residual variance. The AIC was used to compare models with the null model and the most parsimonious were identified based on the lowest AIC value and its significance ($p < 0.005$) to the null model.

Data analyses and visualisation was performed in R (R Development Core Team 2010, version 1.0.44; package ggplot2) and MATLAB (The MathWorks, Inc., Natick, Massachusetts, United States, R2016a).

6.4 Results

River Conditions and Range Detection Tests

The mean (± SD) water temperature in the Eroo River for the study period was 2.3 ± 2.9 °C, with the lowest temperature of - 0.09 °C recorded in winter and spring, and the highest temperature of 11.6 °C recorded in summer (Table 3). River water temperature was significantly different ($p < 0.001$) between all seasons. The mean discharge in the Eroo River during the study period was 60.9 ± 76.6 $m^3 s^{-1}$, with the lowest discharge recorded in winter (0.17 $m^3 s^{-1}$; $p < 0.05$) and the highest discharge recorded in summer (413 $m^3 s^{-1}$; $p < 0.05$). River discharge was significantly different ($p < 0.001$) between all seasons. The first range detection test indicated the maximum distance a transmitter would be detected during a discharge of 139 $m^3 s^{-1}$ was 60 m, while during the second range detection test the maximum detection range was restricted to 5 m during a discharge of 334 $m^3 s^{-1}$. Below average discharge (< 60.9 $m^3 s^{-1}$) occurred on 334 days (72 % of the study period) where the detection range was estimated to be between 100 and 150 m. Flow conditions greater than 139 $m^3 s^{-1}$ occurred on 58 days (12.5 %) and flow conditions greater than 334 $m^3 s^{-1}$ occurred on only 7 days (1.5 %) out of the 467 day project duration. The accelerometer calibration trial identified that an immobile transmitter had a mean (± SD) value of 0.091 ± 0.03 m s^{-1} (0.041 – 0.163 m s^{-1}). While calibration trials of the pressure sensor indicated that transmitted values of 0, 1, 2 and 3 all corresponded to a depth of between 0 – 25 cm, a pressure sensor value of 4 indicated a depth between 26 – 50 cm, 5 = 51 - 75cm, 6 = 76 - 100 cm etc., until the maximum pressure value recorded in the study of 17 equated to a depth of 351 – 375 cm.

Fish Detections & Residency

Mean (± SD) lenok TL and weight was 41.4 ± 4.3 cm and 711.1 ± 355.0 gr respectively (Table 4). The mean (± SD) number of days an individual was detected in the study reach was 65.9 ± 67 days (4 - 209 days; Table 2). IR ranged between 0.06 and 1.00 (mean = 0.4 ± 0.3). Tagged fish were detected on every retrieved receiver (n = 26) in the array except at the most downstream location (~ 245 km) close to the Eroo - Okhon confluence. The median number of receivers visited was nine (mean ± SD, 10.3 ± 5.2). Tagged fish were detected in all seasons and discharge levels including under full ice coverage and during flood events (Figure 14).

Table 3. Summary table of the water temperature (˚C) including the mean (± SD), median and range, and river discharge ($m^3 s^{-1}$) including the mean (± SD), median and range for the Eroo River, Mongolia. Values are presented for the entire study period and per adjusted seasonal period between the 4th of July 2011 and the 9th of October 2012. Adjusted seasonal dates according to the observed climatic conditions and Mongolian fishing laws are presented. Significant differences were found for water temperature between all seasons, and for river discharge between all seasons (Kruskal Wallis, $p < 0.001$).

Eroo River Conditions	Study Period 4th Jul 2011- 9th Oct 2012	Summer 16th Jun- 15th Sep	Autumn 16th Sep- 11th Nov	Winter 12th Nov- 1st Apr	Spring 2nd Apr- 15th Jun
Water Temp. (°C)					
Mean (± SD)	2.3 ± 2.9	5.7 ± 1.7	2.6 ± 2.8	0.02 ± 0.1	2.1 ± 2.5
Median	0.3	5.5	1.9	0.0	1.0
Range	- 0.09 - 11.6	2.5-11.6	0.00-9.2	-0.09- 0.3	-0.09 - 10.1
River Discharge ($m^3 s^{-1}$)					
Mean (± SD)	60.9 ± 76.6	125.9 ± 90.0	39.9 ± 19.1	2.7 ± 3.7	47.5 ± 38.2
Median	39.1	94.2	33.4	0.91	40.4
Range	0.17 - 413.0	34.5 - 413.0	14.8 - 88.5	0.17-14.3	2.3 - 223.8
n (days)	467	168	82	141	76

Longitudinal Movements

Tagged lenok displayed a mean linear home range (LHR) of 19.1 ± 15.1 km (0.5 – 45.3 km; n = 21, Table 4). Thirteen lenok (62 %) had a LHR greater than 10 km, while six individuals (28%) had a home range greater than 30 km. No correlation was evident between total fish length (cm) and LHR size (km) ($r^2 = 0.336$, $p = 0.136$), nor between fish weight (g) and LHR (km, $r^2 = 0.387$, $p = 0.08$). The 50 % (core home range) and 95 % KD home range estimates extended from 0 – 10.7 km (mean ± SD, 5.8 ± 3.6) and 1.3 – 31.7 km (mean ± SD, 11.7 ± 8.0), respectively (Table 4). KD estimates, when considered at higher levels (*e.g.* 95 %), can be longer than the upstream to downstream distance because there is some level of probability that it moved beyond that point before or after the detection (Vokoun, 2003). While the largest LHR variance was detected in summer and spring compared to autumn and winter, there was no significant difference found for LHR between seasons (Kruskal-Wallis test, $p > 0.05$; Figure 15). There was also no significant difference found between the total distance lenok moved and season, and the total distance lenok moved and diel period ($p > 0.05$). The linear mixed effects modelling results indicated that the inclusion of temperature in the model produced a significant difference compared to the null model (Kruskal-Wallis test, $p < 0.01$); however the combination of temperature, discharge and photoperiod produced the best explanation of lenok total distance (Table 5).

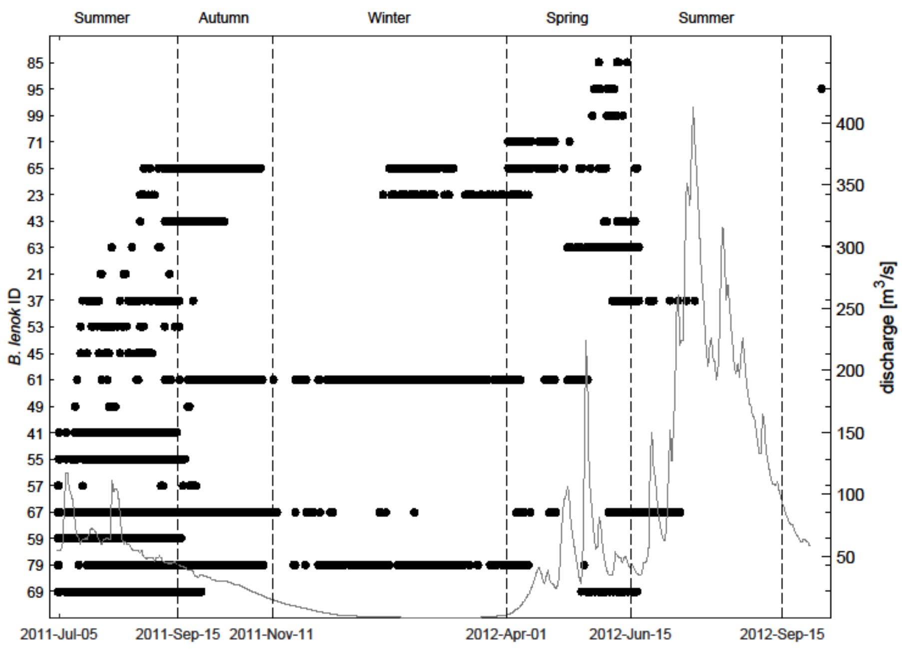

Figure 14. Detection plot of *B. lenok* (n = 21) in the Eroo River, Mongolia, between the 4th of July 2011 and the 9th of October 2012. Each solid black point indicates that an individual was detected on a specific day more than twice. The Eroo River hydrograph ($m^3\ s^{-1}$) is included for reference. The vertical dash lines indicate the change of adjusted seasons used for analysis.

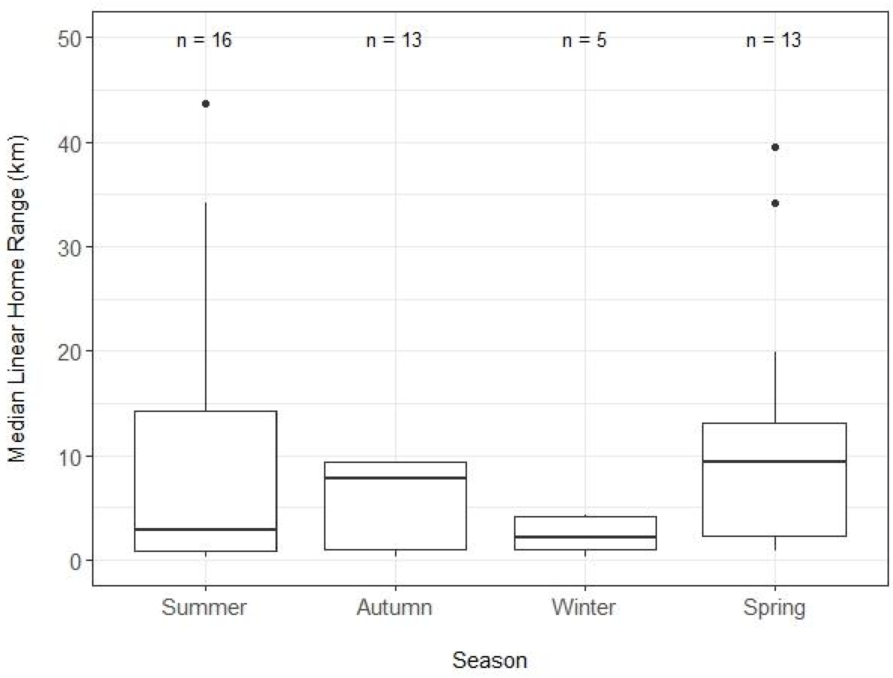

Figure 15. Median linear home range (km) detected for *B. lenok* per season in the Eroo River, Mongolia. The boxes represent the 10th and 90th percentile; the whiskers indicate 2 x percentile. The black dots are outliers. The total number of fish (n) detected per season and used in the analysis is shown at the top of the figure. No significant differences were detected between linear home ranges in each season (Kruskal-Wallis test, $p > 0.05$).

Table 4. Summary table of the tagged *Brachymystax lenok* including fish number (ID), total length (TL cm), total weight (Wt, g), fish tag and released date (TR), final detection date (FD), number of receivers visited (RV), total number of days detected (DD), residency index (I_R), linear home range (LHR) in km, 50 % and 95 % kernel densities (KD) in km (only for lenok detected on more than 15 days), mean acceleration (± SD) in m s^{-1}, and mean depth (± SD) in cm.

Fish ID	TL (cm)	Wt. (g)	TR	FD	DD	I_R	RV	LHR (km)	50% KD (km)	95% KD (km)	Mean Acc. (±SD)	Mean Dep. (±SD)
41/42	42	733	04.07.11	14.09.11	63	0.89	6	9.4	9.3	10.6	0.60±0.40	21.2±17.1
55/56	40.1	621	04.07.11	19.09.11	70	0.91	6	7.8	7.7	9	0.69±0.42	26.7±21.4
57/58	38.9	496	04.07.11	26.09.11	11	0.13	8	9.4	-	-	0.52±0.31	43.0±23.0
59/60	41.2	719	04.07.11	17.09.11	75	1.0	8	9.4	9.3	10.6	0.56±0.37	32.4±29.0
67/68	40.3	642	04.07.11	15.07.12	198	0.53	12	23.3	0.2	12.5	0.61±0.36	52.5±34.2
69/70	39.9	546	04.07.11	19.06.12	121	0.34	15	43.6	9.4	15.9	0.63±0.44	44.5±35.8
79/80	46.1	847	04.07.11	18.05.12	209	0.66	8	11.5	5.4	7.2	0.49±0.32	33.7±33.7
61/62	33.4	378	05.07.11	20.05.12	194	0.61	10	11.5	6.5	9	0.40±0.34	76.9±29.1
63/64	46.8	790	05.07.11	20.06.12	44	0.13	19	45.3	7.5	31.7	0.51±0.38	22.6±23.4
65/66	35.1	400§	06.07.11	19.06.12	133	0.38	13	27.3	2.9	6.7	0.47±0.35	34.1±22.7
49/50	38.4	442	11.07.11	22.09.11	7	0.1	9	10.4	-	-	0.58±0.21	24.7±14.3
73/74†	33.5	340§	11.07.11	31.07.11	1	-	1	-	-	-	-	-
53/54	44.8	720	12.07.11	16.09.11	23	0.35	5	5.8	5.6	7	0.69±0.42	20.7±20.2
43/44	47	670	16.07.11	18.06.12	43	0.13	18	33.2	10.7	20.2	0.57±0.34	42.6±30.0
45/46‡	45.3	750	16.07.11	30.08.11	19	0.42	2	0.5	0	1.3	-	30.3±16.5
71/72	40.3	630	16.07.11	09.05.12	24	0.08	3	2.1	0.5	2.3	0.61±0.28	32.7±20.7
37/38	39.5	550§	17.07.11	24.07.12	62	0.17	18	38.8	8.2	22.3	0.70±0.40	45.9±34.3
21/22	34	350§	20.07.11	10.09.11	5	0.1	3	4.4	-	-	0.27±0.23	24.8±12.6
23/24	39.2	550§	20.07.11	14.04.12	62	0.23	11	11.7	4.1	9.1	0.41±0.30	41.6±16.9
31/32†	34.9	340	20.07.11	29.07.11	1	-	1	-	-	-	-	-
85/86	43	900	23.05.12	13.06.12	4	0.19	12	15.3	-	-	1.13±0.24	114.6±114
95/96	49	1200	23.05.12	09.10.12	8	0.06	14	41.3	-	-	0.91±0.42	226.5±34.9
99/100	45	2000	23.05.12	10.06.12	7	0.39	16	39.5	-	-	0.83±0.59	54.4±35.1
Mean	41.4	711.1	-	-	65.9	0.4	10.3	19.1	5.8	11.7	0.62	45.13
±SD	4.3	355.0	-	-	67.0	0.3	5.2	15.1	3.6	8.0	0.35	35.13

† indicates fish was removed from analysis due to only being detected on one day and on one receiver.
‡ died during the study and only the values are shown when the fish was detected moving.
§ total body weights estimated from a length – weight relationship.

There were two periods of increased lenok movement detected in the Eroo River. The first occurred at the end of summer and beginning of autumn, with the second, more pronounced, period occurring between the middle of spring and start of summer (Figure 16 & Figure 17). During the summer / autumn 'cooling' period 10 (59 %) of 17 tagged lenok (4 missing individuals) moved in a downstream direction with falling water temperature (> 14 to 5 ˚C) and river discharge (100 to 45 m^3 s^{-1}). For the remaining lenok, three fish first moved downstream before immediately returning back upstream, three fish didn't move at all and one fish moved upstream > 10 km. All of those fish that moved downstream did so on or after the 10th of September 2011 and exited the core study area by mid October 2011. There was no mass coordinated movement, with no two lenok moving on the same day. Six individuals returned to the study area the following year. The lenok that remained in the study area (n = 5) did not record any substantial movements during this summer/autumn period, nor did they move more than 5 km while under the winter ice (n = 143 days).

Table 5. Summary table of the linear mixed effects modelling results used to describe the effects of season (represented by temperature and discharge), photoperiod and fish total length (TL) on mean total distance, acceleration and depth for *B. lenok*. Fish ID was included as a random effect in each model. AIC is the Akaike's Information Criterion; ΔAIC is the difference between the AIC model values; and the *P* values indicate the level of significance between each model and the null model based on the maximum likelihood method.

Model (response and fixed variables)	AIC	ΔAIC	*P* values
Distance			
Distance ~ Temperature + Discharge + Photoperiod	4161	0	<0.001
Distance ~ Temperature + Discharge + Photoperiod + TL	4163	2	<0.001
Distance ~ Temperature + Discharge	4163	2	<0.001
Distance ~ Temperature + Photoperiod	4164	3	<0.001
Distance ~ Temperature + Discharge + TL	4165	4	<0.001
Distance ~ Temperature + Photoperiod + TL	4166	5	<0.001
Distance ~ Temperature	4166	5	<0.001
Distance ~ Temperature + TL	4168	7	<0.001
Distance ~ Discharge + Photoperiod	4199	38	0,065
Distance ~ Discharge	4200	39	0,117
Distance ~ Photoperiod	4200	39	0,077
Distance ~ 1	4201	40	null model
Distance ~ Discharge + Photoperiod + TL	4201	40	0,139
Distance ~ Discharge + TL	4202	41	0,279
Distance ~ Photoperiod + TL	4202	41	0,207
Distance ~ TL	4203	42	0,781
Acceleration			
Mean Activity ~ Temperature + Discharge + Photoperiod	-138055	0	<0.001
Mean Activity ~ Temperature + Discharge + Photoperiod + TL	-138053	2	<0.001
Mean Activity ~ Temperature + Photoperiod	-136066	1989	<0.001
Mean Activity ~ Temperature + Photoperiod + TL	-136064	1991	<0.001
Mean Activity ~ Discharge + Photoperiod	-135534	2521	<0.001
Mean Activity ~ Discharge + Photoperiod + TL	-135532	2523	<0.001
Mean Activity ~ Temperature + Discharge	-134523	3532	<0.001
Mean Activity ~ Temperature + Discharge + TL	-134521	3534	<0.001
Mean Activity ~ Photoperiod	-132957	5098	<0.001
Mean Activity ~ Photoperiod + TL	-132956	5099	<0.001
Mean Activity ~ Temperature	-132687	5368	<0.001
Mean Activity ~ Temperature + TL	-132685	5370	<0.001
Mean Activity ~ Discharge	-130946	7109	<0.001
Mean Activity ~ 1	-128432	9623	null model
Mean Activity ~ TL	-128431	9624	0,511
Depth			
Mean Depth ~ Temperature + Discharge + Photoperiod + TL	45349	0	<0.001
Mean Depth ~ Temperature + Discharge + Photoperiod	45350	1	<0.001
Mean Depth ~ Temperature + Photoperiod + TL	45476	127	<0.001
Mean Depth ~ Temperature + Photoperiod	45477	128	<0.001
Mean Depth ~ Temperature + Discharge + TL	45897	548	<0.001
Mean Depth ~ Temperature + Discharge	45898	549	<0.001
Mean Depth ~ Temperature + TL	46043	694	<0.001
Mean Depth ~ Temperature	46044	695	<0.001
Mean Depth ~ Discharge + Photoperiod + TL	49620	4271	<0.001
Mean Depth ~ Discharge + Photoperiod	49620	4271	<0.001
Mean Depth ~ Photoperiod + TL	49622	4273	<0.001
Mean Depth ~ Photoperiod	49622	4273	<0.001
Mean Depth ~ Discharge + TL	49697	4348	0,009
Mean Depth ~ Discharge	49697	4348	0,007
Mean Depth ~ 1	49702	4353	null model
Mean Depth ~ TL	49702	4353	0,14

The second period of increased lenok movements occurred in the 'warming' mid-spring / early-summer timeframe when individuals moved rapidly upstream as the water temperature was between 5 and 8 ˚C, and there was lower discharge between flood pulse events (discharge < 50 $m^3 s^{-1}$; Figure 4 and Figure 5). Nine lenok (including fish that had returned from overwintering downstream out of the core study area and three newly tagged individuals) were detected entering the surrounding tributaries including the Sharlan (n = 5), Khongiyn (n = 3) and Yalbac (n = 1). These movements occurred between the 14th of April 2012 and the 26th of June 2012, with individuals remaining in the tributaries for between 5 and 37 days at a time.

Lenok Acceleration and Depth

Mean (± SD) acceleration for lenok (n = 20) was 0.62 ± 0.35 m s^{-1}, with values ranging from 0.04 - 3.47 m s^{-1} or the entire sensory capacity of the transmitters. Individual mean acceleration (mean ± SD) ranged between 0.27 ± 0.23 m s^{-1} and 1.12 ± 0.23 m s^{-1} (Table 4). Over half of all acceleration detections (55 %) were below 0.5 m s^{-1}, while over 90 % were under 1.0 m s^{-1}. The diel variation in acceleration for lenok was characterised by a significant decrease at night compared to day and dusk (Kruskal-Wallis test, $p < 0.05$; Figure 18a), with no other significant differences detected between diel periods (Kruskal-Wallis test, $p > 0.05$). Between seasons, lenok acceleration was significantly higher in summer compared to winter ($p < 0.05$), with no other differences found ($p > 0.05$). The highest mean acceleration for lenok was in summer at 15:00 (0.78 ± 0.5 m s^{-1}), while the lowest mean acceleration was detected at 05:00 in winter (0.13 ± 0.1 m s^{-1}). Linear mixed effects modelling results indicated there were interactions between all explanatory variables as temperature, discharge and photoperiod were each included in the first two models with considerably lower AIC values compared to the other models. All models, except the one with TL only, were significantly different from the null model (Kruskal-Wallis test, $p < 0.001$, Table 5).

Mean (± SD) depth of lenok in the Eroo River was 45.13 ± 35.13 cm including a range from 0 cm to 350 cm (Table 4, Figure 18b). However, lenok were most frequently detected between 0 and 25 cm, with 92.5 % of all depth detections fewer than one meter. Mean (± SD) depth per individual ranged from 20.7 ± 20.2 cm to 226.5 ± 34.9 cm (Table 4). Diel variation in depth differed significantly between dawn and dusk ($p < 0.05$) and between day and dusk ($p < 0.05$). Lenok summer depth was significantly shallower compared to all other seasons ($p < 0.05$). The lowest mean (± SD) lenok depth was detected at 12:00 in winter (97.41 ± 1.14 cm) and the shallowest mean depth detected at 22:00 in summer (36.5 ± 0.55 cm). The linear mixed effect models that included temperature as an explanatory variable returned the lowest AIC values, with each model significantly different to the null model (Kruskal-Wallis test, $p < 0.05$, Table 5).

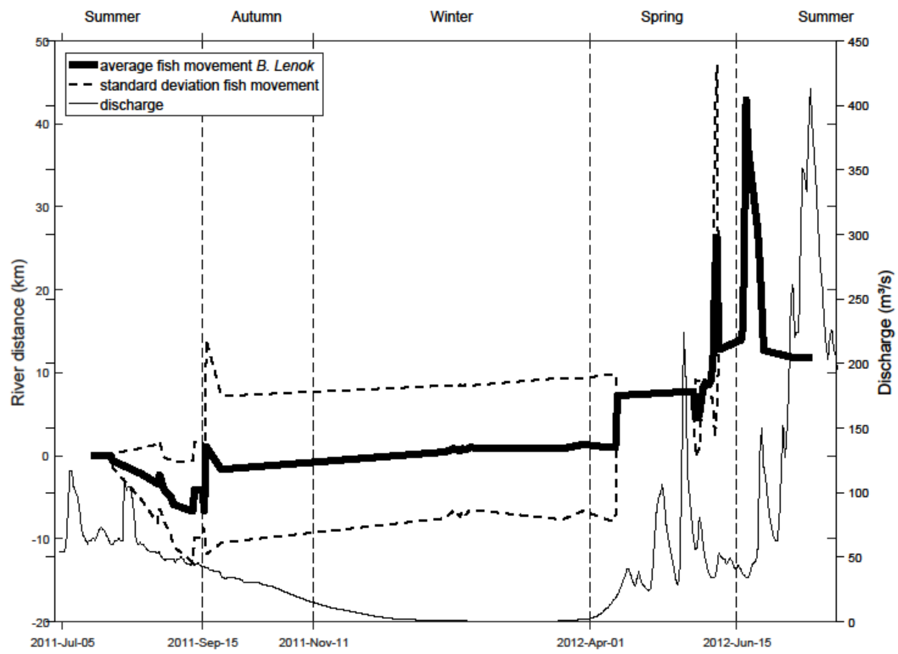

Figure 16. Average *B. lenok* (n = 21) movements (± SD) and daily river discharge (m^3 s^{-1}), in the Eroo River, Mongolia, between the 4th of July 2011 and 9th of October 2012. The vertical dash lines indicate the change of adjusted season.

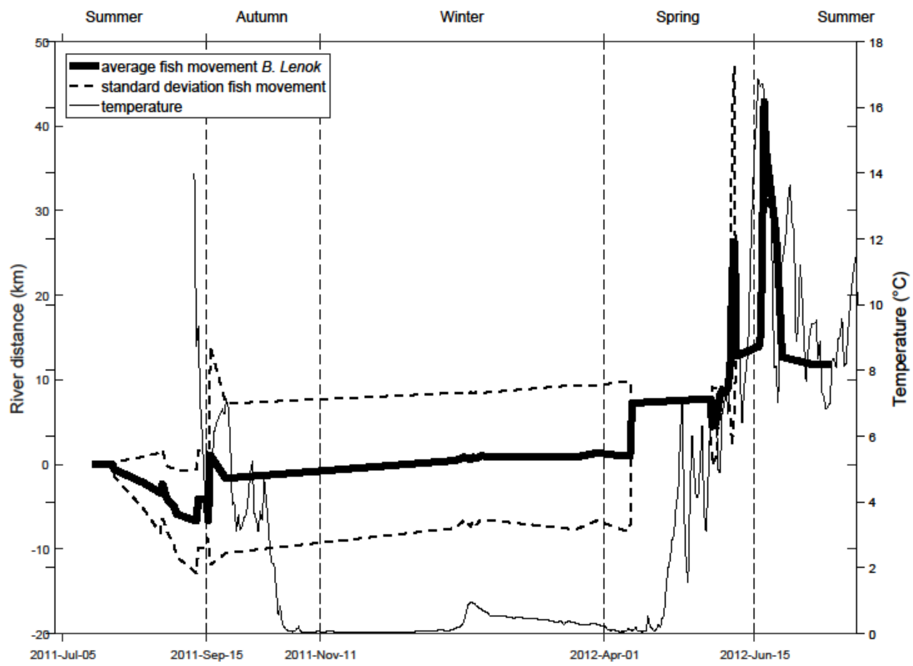

Figure 17. Average *B. lenok* (n = 21) movements (± SD) and daily water temperature (˚C) in the Eroo River, Mongolia, between the 4th of July 2011 and 9th of October 2012. The vertical dash lines indicate the change of adjusted seasons.

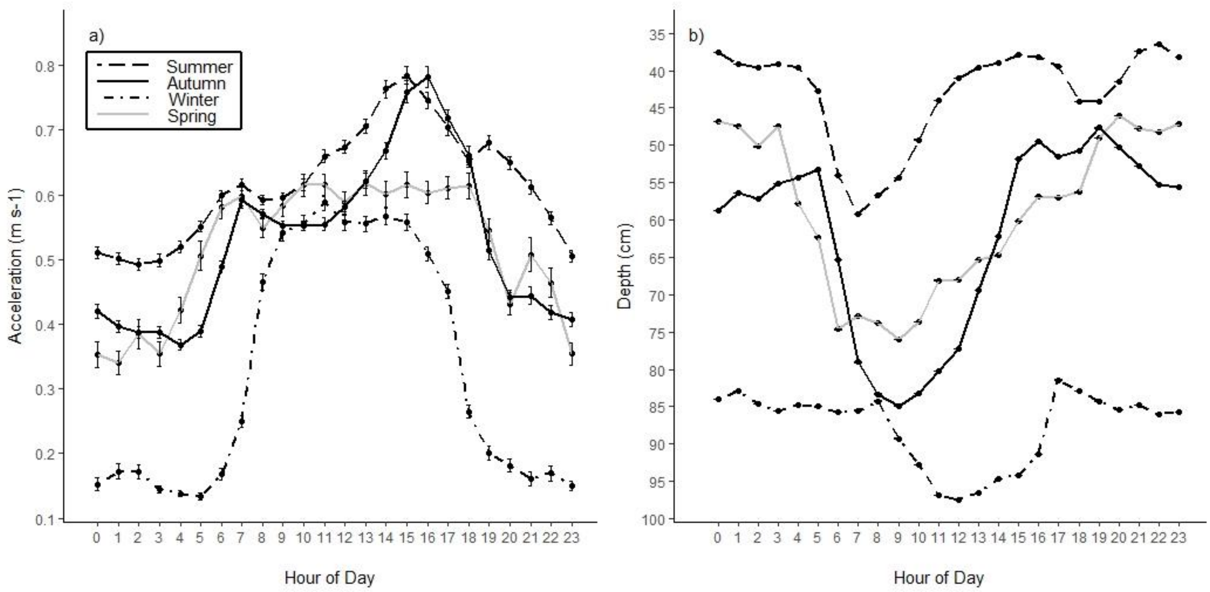

Figure 18. a) Mean hourly acceleration (m s^{-1}) and **b)** mean hourly depth (cm) for tagged *B. lenok* (n = 21) in the Eroo River, Mongolia, per season between the 4th of July 2011 and 9th of October 2012.

6.5 Discussion

This study was the first to describe and quantify the diel and seasonal longitudinal movements (home range), acceleration and depth of *Brachymystax lenok* in an unfragmented river system, while being one of the first projects to implant acoustic telemetry transmitters with acceleration and pressure sensors into riverine fish. Passive acoustic telemetry was chosen for the study as it had been previously used successfully to collect *in situ* fish movement data remotely and under extreme environmental conditions (Honda et al., 2014; Mathes et al., 2010; Gilroy et al., 2010; Bass et al., 2014). We found that this threatened species maintained a considerably larger mean LHR in this unimpacted, free-flowing and highly connected river system than what has been previously reported for this genus in more fragmented habitats. Extensive individual movements were detected during the spawning period of upwards of 45 km. Clear diel and seasonal acceleration patterns and depth usage were also identified under natural river conditions.

B. lenok Longitudinal Movements

The mean home range (19.1 ± 15.1 km) for lenok in the Eroo River was close to ten times larger than what was previously described for *B. tsinlingensis* in a Korean River, where radio tagged individuals were found to have a mean home range of 2.14 ± 1.92 km, with maximum tracked movements of only 8.17 km (Yoon et al., 2015).

Although being considerably smaller than lenok home ranges in the Eroo River, the close proximity of the release locations to suitable spawning habitat, infrequent tracking intervals and upstream dam construction in the Korean study all likely impacted on the detected movements of the tagged fish (Yoon et al., 2015). Therefore, our study has shown that lenok movements in a natural system can be extensive, which is an important consideration for the design and implementation of potential spatial protected areas (*i.e.* Freshwater Protected Areas; Abell et al., 2007). It appears lenok is one of the more mobile, potadromous salmonid species as they have similar mean home ranges as reported for cutthroat trout (*Oncorhynchus clarki lewisi*) with 31 km (3 – 72 km) (Schmetterling, 2001) and taimen (*Hucho taimen*) with 23 – 27.7 km (0.5 – 126.1 km; Gilroy et al., 2010; Kaus et al., 2016). In addition, lenok home ranges are larger than other stream-dwelling trouts such as brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*), which have reported mean home ranges of 2.1 and 11.9 km respectively (Ovidio, 1999; Clapp et al., 1990; Young et al., 1997). Although the longitudinal movements of tagged lenok in the upper Eroo River did not display a positive allometric relationship between home range size and body length, as has been described for many freshwater fish species (Minns, 1995), the restricted body length range of lenok included in the study was a likely explanation. No lenok larger than 50 cm TL was caught in the Eroo River during the study, which is likely an effect of the increased fishing pressure in the region that has reduced the abundance of larger size classes within the lenok population.

Three different home range movement patterns were detected for tagged lenok with each reflecting patterns previously described for taimen by Gilroy et al., (2010). While most tagged lenok displayed a restricted core home range with separate seasonal departures, there were some individuals that exhibited a restricted core home range with no seasonal departures and a restricted home range with a separate seasonal range. The identification of a mean core home range of 5.8 ± 3.6 km (50 % KD) suggests that there is no strict, one pool only, site fidelity displayed by lenok, as such a range encompasses multiple pools and riffles within the study reach. This extended size of a core home range, with respect to body length, likely reflects the larger river distance that is required to search for sufficient resources. Although the limited time and detection area in the study minimized the possibility of identifying a home range shift behaviour, as has been reported in taimen (Gilroy et al., 2010), it was suspected that several individuals did display this behaviour as they left the array in autumn (2011) without returning to the detection area for the remaining 12 months of the study. However only a longer, inter annual approach would be able to confirm such behaviour in this species. In any case it was confirmed that no tagged lenok had exited the basin during the study, as there were no fish detections on the most downstream receiver deployed at the Eroo - Orkhon confluence. It is recommended, however, that additional research such as a large scale genetics study be conducted in order to ascertain the level of inter basin connectivity that exists on both a spatial and temporal scale for Mongolian lenok populations.

During the ‘cooling’ period (summer – autumn) over two thirds of tagged lenok undertook extended longitudinal movements in the Eroo River with most fish moving in a downstream direction. While taimen are also known to move extensively during this period (Matveyev et al., 1998; Gilroy et al., 2010), this is the first time concentrated lenok movements have been confirmed and described for this species at this time. As with other species in boreal rivers, these movements would be associated with fish transitioning from shallower summer feeding habitats to more suitable deeper overwintering pools where there is a lower water velocity (Fausch & Young, 1995). Although no single *en masse* migration was detected in the Eroo, the majority of individuals that moved did so in a short window of time, starting on the 10th of September. Although there was no obvious, single event that appeared to trigger these increased movements, the linear mixed effect modelling suggested that there was a combination of the steady decline in water temperature, river discharge and photoperiod that had reached some critical threshold for lenok that induces movements. It was not until days later, on the 15th of September 2011, that air temperatures first dropped below zero and frost blanketed the river valley, which saw a noticeable increase in aggression by resident taimen, but not by lenok (*pers. obs.* A. Kaus). It is expected that those fish that did not move (n = 5) at this time were already in habitats that provided adequate resources to survive the extreme winter conditions (Heggenes & Dokk, 2001).

During the harsh Palearctic winter, riverine fishes not only need to endure prolonged low temperatures and reduced light intensities, but they also face extensive river ice coverage that can fundamentally alter river discharge, hydraulics, habitat availability and gaseous exchange throughout the water column (Prowse, 2001; Nykänen et al., 2004). As a result, fish have reduced swimming abilities, depleted energy reserves, as well as an overall lower metabolism and physical condition (Brown et al., 2011; Cunjak, 1996; Huusko et al., 2007). Thus unsurprisingly, all tagged lenok in the Eroo River displayed limited movement under the ice as they typically remained in one or two pools for the entire period in an effort to conserve energy (Cunjak and Power, 1987). The radio tagged *B. tsinlingensis* in Korea were also reported moving short distances in winter of < 4.13 km (Yoon et al., 2014), with comparable reduced movements in other stream dwelling salmonids such as cutthroat trout (*Oncorhynchus clarki lewisi*) and bull trout (*Salvelinus confluentus*) (Schmetterling, 2001, 2003; Jakober et al., 1998). Any movements that did occur in winter under the ice were attributed to the need to move due to the formation of subsurface frazil and anchor ice in refuge pools, or the requirement to forage further afield for increased food resources and predator avoidance.

Spawning migrations in the Eroo River began in late spring and early summer when lenok left the main channel overwintering pools and moved upstream in to smaller tributaries in search of shallow, upwelling sites with coarse gravel, high dissolved oxygen and low water temperatures (Esteve & McLennan, 2008). Again, lenok were not detected moving in any single coordinated event, but instead entered and remained in the tributaries from the 27th of April until the 3rd of July 2012. This period falls within the recognised spawning time for lenok, which has been reported to be in May in the Eg - Uur River, Mongolia (Gilroy et al., 2010; Esteve & McLennan, 2008), and between April and May in the Nakdong River, South Korea (Kim & Park, 2002). While more than half of the tagged lenok did not move into a tributary during the study period, over a quarter still made a substantial movement upstream at this time, suggesting that the main channel is also an important spawning location for this species (Esteve & McLennan, 2008). The length of time each lenok remained in a tributary was highly variable, with the shorter, faster trips of four and five days likely undertaken exclusively for spawning, while the longer visits of 37 and 78 days were related to additional summer feeding opportunities or thermal / hydrological refuge. Six lenok were not detected re-entering the Eroo River at all before early July when flood waters began to rise rapidly and ultimately limited the detection probability of the transmitters. In addition, in the following weeks most lenok transmitters expired, thus it is unknown exactly how long some of these individuals remained in the tributaries over the summer period. In Korean rivers, *B. tsinlingensis* stayed at the spawning grounds for 14 to 21 days before returning downstream (Yoon et al., 2015). While not all lenok were detected moving extended distances, the sedentary individuals may have been in a resting reproductive state or an alternate year spawners such as been observed in both taimen and bull trout previously (Gilroy et al., 2010; Paragamian & Walters, 2011).

B. lenok Behaviour and Habitat Use

The extensive data set gathered on the behaviour of lenok revealed clear circadian patterns of activity and rest combined with rhythmical changes in depth occupancy. The mean hourly activity was observed increasing in the hours before dawn and remaining elevated during the day, before decreasing again at dusk, while the mean hourly depth occupancy decreased rapidly at sunrise and gradually got shallower in the afternoon and evening.

These elevated daily acceleration levels are typical of diurnal species that rely on sight to capture prey such as lenok, and thus is contrasted with lower activity or resting periods during the night. The daily variation in photoperiod and its influence on fish depth has been widely documented for fish inhabiting deeper environments such as marine and lake ecosystems (Mehner, 2012), but has not been extensively quantified in lotic species. These diel vertical migrations exhibited by lenok is more likely to be diel bank migrations, a benthic form of diel vertical migration, where depth is transitioned in close association with the river substrate, rather than through the water column (Cott et al., 2015). This movement has been observed previously in lake resident salmonids (Gorman et al., 2012) and burbot (Cott et al., 2015). Although in the Eroo River, the mean hourly depth change between night and day was determined to be in the range of only 10 to 50 cm depending on the season, even these small vertical movements are likely to provide certain benefits including minimising energy expenditure by resting at night in shallower, more sheltered river margins away from the main river currents. These areas may also be more optimal with regards to warmer water temperatures at low river discharge levels, which can aid metabolism and digestion (Mehner, 2012). Although the exact spatial location of fish at night could not be explicitly determined from acoustic telemetry data, previous fisheries research in the river indicated that there is increased lenok capture when electrofishing on the Eroo River margins at night compared to electrofishing the same areas during the day (*pers. comm*. M. Schäffer). The observed systematic pre - dawn movements back into deeper habitat in the main river channel is likely driven by improved feeding opportunities as well as enhanced predator avoidance from both above and below the river surface. Although lenok are morphologically adapted to feeding on the substrate *e.g.* stomach content analysis has identified benthic macroinvertebrates as a major food source (Chanda et al., 2005; Olson et al., 2016), during the late afternoon in summer, lenok appeared to take advantage of the hatching aquatic invertebrates drifting on the water surface as is indicated by their shallowest mean depth at this time.

Seasonal differences in the mean acceleration and depth of lenok at night, is also attributed to fluctuating river discharge and water temperature. Higher flow in summer and spring demand increased locomotory movements in order to maintain the same position in the water column, including on the margins. As a result summer mean hourly acceleration was generally elevated above all other seasonal means. An unexpected observation regarding lenok in winter was the highly elevated mean hourly diurnal acceleration compared to night. This heightened activity may indicate the increased effort required to forage adequate food on the substrate during the full river ice coverage, a change in diet from macroinvertebrates to fish (*e.g. Phoxinus phoxinus*) and / or the need to avoid increased predation in the somewhat segregated overwintering pools. In addition, the short sampling period of the V9AP transmitters meant that the full range of behaviours, particularly rapid ambush movements has likely not been detected at the frequency that would have been determined if longer sampling times were possible (O'Toole et al., 2010). Thus the current data likely underestimates the occurrences of these short-term bursting movements that have only been captured at a low frequency. The rapid movements that were detected also attained the maximum acceleration capacity of the transmitter's sensor *i.e.* 3.43 m s^{-1}, thus demonstrating that lenok is capable of accelerations greater than the sensor limits. This issue has also been identified with tagged barracuda acceleration in the Bahamas (O'Toole et al., 2010).

In regards to the use of passive acoustic telemetry to monitor fish movements in a dynamic lotic system in the Palearctic, this method allowed a high number of fish to be monitored in a remote location and across most seasonal conditions including when the river reach was not readily accessible such as during the prolonged winter period. As long as adequate precautionary measures are taken, such as deploying receivers in deep, upright positions on heavy cement blocks and in consecutive pools, then loss of equipment and detections can be minimised. While we gained a high number of detections for several tagged fish under a lower river discharge, higher discharges remain a challenge. Thus future research will need to carefully consider the trade-offs between transmitter sampling period, transmitter power, battery life and size depending on the species studied and the objectives of the research. In any case, it is recommended that more comprehensive range detection tests be undertaken in such a dynamic riverine environment, along with the deployment of multiply sentinel tags within the study reach to more accurately quantify the changing detection range of receivers throughout the entire study period particularly during flood events and under winter ice (Payne et al., 2010).

Conclusions

This new information detailing the movements and behaviour of *Brachymystax lenok* can help guide the design and development of improved conservation and management regulations for this threatened species throughout its distribution. Spatial protection measures, such as the implementation of FPAs, must consider the extensive mean home range sizes including upstream movements of > 45 km that have been undertaken by mature lenok during the spawning season. Like taimen, these distances are large enough to encompass more than one local administrative zone in Mongolia and thus specific coordination and cooperation between authorities will be necessary in order to implement adequate protection for river basin populations across several regions. In contrast, the mean core home range of less than six km is small enough for lenok populations to benefit from a series of smaller FPAs, which could focus separately on protecting downstream overwintering pool habitats and upstream critical spawning tributaries, with carefully enforced fishing zone inbetween. In addition, current temporal management measures including national fishing closures from the 1st of April until the 15th of June likely needs to be revised and extended as the current results indicate the peak spawning period for the Eroo River lenok population occurs after the fish spawning closed season. This means that the influx of local anglers that flock to the Eroo and other Mongolian rivers for the opening of the fishing season on the 16th of June represent a significant threat to the long-term sustainability of this threatened species, as a high number of pre-spawned, ripe individuals are likely caught and removed from the system before they can reproduce each year. Although, these results so far only relate to one population and in one season, further reproductive ecological research is recommended on lenok populations in other river basins so authorities can be appropriately advised, and if need be, can extend the opening date of the close fishing season or consider a 'floating' date that would depend on the annual seasonal conditions including water temperature and river discharge of specific regions across Mongolia. This data can also provide a baseline for future work regarding river restoration design, which is urgently needed in certain areas due to the damage from past large scale, alluvial gold mining operations, as well as the development of environmental flow regimes, which will be needed if the proposed hydroelectric dam projects on several of Mongolia's largest rivers are approved in the near future.

7 Seasonal home range shifts of the Siberian taimen (*Hucho taimen*; Pallas, 1773): Evidence from passive acoustic telemetry in the Onon River and Balj tributary (Amur River basin, Mongolia)

Kaus, A., Büttner, O., Schäffer, M., Balbar, G., Surenkhorloo, P., Borchardt, D. (2016). International Review of Hydrobiology, 101, 1-13. doi: 10.1002/iroh.201601852

7.1 Abstract

Hucho taimen, the world's largest salmonid, is a potadromous species that is listed as endangered in Mongolia. While mature individuals are known to have extended longitudinal movements of over 90 km along main river channels, details of the seasonal movements and residency of individuals within and between tributary habitats have been largely undocumented. The current research aimed to detect and quantify the seasonal distances moved by adult taimen (65 – 96 cm; n = 10) within and between the Onon River (Amur River basin) and a major tributary (Balj) over 12 months using passive acoustic telemetry. The median distance moved by taimen in spring was 17.4 km (n = 6), in summer 9.1 km (n = 4), autumn 4.7 km (n = 9) and winter 0.4 km (n = 8). However, there were no statically significant differences amongst these median seasonal home range sizes. Two taimen traversed between the Onon River and the Balj tributary during the study period, recording overall home ranges of 44.5 km and 126.1 km. One of these individuals moved twice, exiting the tributary in autumn and returning again in spring where it remained for 36 days, while the second taimen moved only once into the tributary in spring and re-entered the main channel in late summer after 85 days. Another two taimen entered surrounding smaller tributaries and recorded home ranges of 26.1 km and 29.2 km, while all remaining individuals were detected moving only within the waterway where they were originally captured and released (0.8 – 20.1 km). Taimen movements within tributaries such as the Balj can be extensive (< 60 km), as they provide access to important spawning, feeding and overwintering habitats as well as refuge from adverse thermal and hydrological conditions. Thus to enhance population recovery, it is essential that current and future management and conservation efforts include preserving or restoring the ecological integrity and hydrological connectivity of these critical tributaries and the main river channel throughout the Onon and Amur River basins and across the remaining distribution of this endangered species.

7.2 Introduction

The unique aquatic fauna of Mongolia's vast lake and river networks has faced increasing pressure recently from multiple anthropogenic threats. Along with habitat loss (Hartwig & Borchardt, 2014; Hartwig et al., 2016), water pollution (Stubblefield et al., 2005; Hofmann et al., 2010, 2011; Thorslund et al., 2012; Pfeiffer et al., 2014; Nadmitov et al., 2015; Kaus et al., 2016), water abstraction (Karthe et al., 2015a) and climate change (Menzel et al., 2011; Karthe et al., 2013; Malsy et al., 2016), the primary threat facing many resident fish populations is their intentional mortality resulting from rapidly growing recreational fishing activities by both local and foreign fishers (Chandra et al., 2005; Ocock et al., 2006; Vander Zanden et al., 2007). While these anglers target several native species, none are pursued more intensely than the Siberian taimen (*Hucho taimen*; Pallas, 1773), an aggressive fighting salmonid, which in Mongolia has experienced a substantial population decrease of 50 % and a range reduction of 60 % since 1985 (Ocock et al., 2006). Due to these declines, taimen have been listed as endangered on the Mongolian Red List of Fishes (2006) and as there is an estimated 37 % species wide reduction over the past three generations, taimen are now also included as vulnerable on the IUCN Red List of Threatened Species (Hogan & Jensen, 2013). Although since 2012 legislation in Mongolia has prohibited the killing of this species, widespread illegal poaching continues due to the lack of compliance of these laws (Ocock et al., 2006; Bailey, 2012; Free et al., 2016), including an uncertain amount of illicit trade to China (Hogan & Jensen, 2013). Any potential poaching is significant as even with a low level catch and kill harvest, computer modelling has indicated that there is an elevated probability that a resident taimen population could go locally extinct (Jensen et al., 2009). Therefore, the need to continue to improve our autecological understanding of this species is essential in order to develop and adapt new and existing conservation and management policies to provide better protection and enhance the recovery of this threatened freshwater fish throughout its declining geographic range.

The Siberian taimen is one of four *Hucho* species and the largest salmonid in the world capable of reaching a length of 2 m and weight of 105 kg (Holćík et al., 1988). Taimen are long lived (up to 60 years old), potamodromous fish that historically inhabit rivers and streams at low population densities across Russia and several northern river basins of Kazakhstan, China and Mongolia (Dulmaa, 1999; Vander Zanden et al., 2007; Hogan & Jensen, 2013). Taimen are iteroparous salmonids and so mature individuals can spawn repeatedly over the course of their lives, with fish in spawning condition migrating each spring following the winter ice break up as water temperatures rise (6 – 10 °C) and river discharge increases (Holćík et al., 1988; Matveyev et al., 1998; Dulmaa, 1999; Vander Zanden et al., 2007; Gilroy et al., 2010). To spawn, individuals move into shallow tributaries with clean gravel substrate, fast current or areas with ground water upwellings, where females prepare elliptical redds and deposit eggs for a previously paired up male to fertilize (Esteve et al., 2009). Then in late spring and summer, depending on water temperatures and river discharge, taimen are either forced back downstream due to declining water levels or move further upstream to avoid warming waters (> 14 – 15 °C) (Matveyev et al., 1998). A second period of increased taimen movement has been described in autumn when individuals in Lake Baikal again ascend rivers to feed on spawning omul (*Coregonus autumnalis migratorius*) (Matveyev et al., 1998), or, in Mongolian rivers, taimen retreat downstream into deeper pools to overwinter and escape the freezing upper tributaries (Dulmaa, 1999; Gilroy et al., 2010).

The extent taimen move each season is expected to vary amongst rivers (Matveyev et al., 1998); however, to date only one study conducted by Gilroy et al. (2010) has quantitatively measured these movements by tracking individuals using modern biotelemetry methods. In that project, the authors successfully documented the broad–scale distances travelled and behavioural patterns of adult taimen over an extended period in the Eg - Uur River, Selenge basin, Mongolia. Their results indicated that individual taimen can move as much as 93.2 km, although a much smaller median home range size of 13.8 km (mean of 23 km) was reported (Gilroy et al., 2010). While an expansive study, taimen movements within and between critical tributary habitats and the main river channel were not documented. This information gap is significant as tributaries are known to provide important spawning, feeding and refuge locations (hydrological and thermal) for resident taimen populations (Holćík et al., 1988; Matveyev et al., 1998; Dulmaa, 1999) and thus should be considered in such research. Moreover, a detailed knowledge of the distances taimen move each season and the inter population and catchment variability with regards to these seasonal movements and behaviours is absent from the literature.

This is the first biotelemetry study of an Amur River basin taimen population, a genetically discrete phylogroup compared to the Yenisei (Selenge), Volga and Ob river basin taimen (Froufe et al., 2005; Maric et al., 2014). This project was conducted within the region of the Onon-Balj National Park in north - eastern Mongolia where taimen have been explicitly identified as the focus aquatic species for conservation. The aim of this research was to gather information regarding taimen seasonal home range sizes, movements and residency within and between the Onon River and a major tributary, the Balj, over a 12 - month period. Knowledge of the distances taimen move each season can provide authorities with the capacity to assess the current fishing management approaches in the Onon River region and adapt or customise them with regards to the size and location of protected areas and timing of current closed fishing seasons.

7.3 Materials and Methods

Study Site

The Onon River flows from the Khan Khentii Mountain ranges in north central Mongolia eastwards over 800 km before converging with the Ingoda River to form the Shilka River, which enters the Amur-Heilong River on the Russian – Chinese border. The Amur-Heilong River basin drains into the Pacific Ocean and is the largest river system in northeast Asia and the ninth longest river in the world (Bogutskaya et al., 2008). Along the 298 km the Onon River is in Mongolian territory, several major tributaries enter from the north including the Balj. In the region where the Balj meets the Onon, a 3973 km^2 National Park was established in the year 2000, consisting of two separate protected zones (A and B) that cover large stretches of both waterways (**Figure 19**). The climate of this region is harsh, with air temperatures ranging from – 40 °C to + 40 °C and low annual precipitation of 350 – 450 mm (Dorjgotov & Tseveenmyadag, 2006). Complete river ice coverage lasts from November to April each year, which is followed by increased river discharge and periodic flooding events in the spring and summer months and declining water temperatures and levels in autumn. As well as taimen, the Onon River is home to approximately 47 fish species including the Amur grayling (*Thymallus grubii*), both the sharp and blunt-snout lenok (*Brachymystax lenok*, *Brachymystax* sp.) and the Amur pike (*Esox reichertii*) (Shed'ko et al., 1996; Kottelat, 2006; Balakirev et al., 2014).

Transmitter Implantation and Receiver Deployment

A total of 10 taimen ranging in length from 65 to 96 cm (median = 69 cm) were tagged, released and monitored between the 10th of September 2013 and the 18th of September 2014, with five individuals tagged in the Onon River and five individuals tagged in the Balj tributary. The project's original intentions were to implant and monitor the movements of 15 taimen but due to programming errors, five transmitters could not be utilised. Upon capture, individuals were anaesthetise (AQUI-S, New Zealand), measured and weighed before a V13-1L acoustic transmitter (Vemco, Canada) was surgically implanted into the fish's peritoneal cavity. The transmitters had a random delay of 30 – 60 s and a battery life of 486 days. Clean river water was continually poured over the gills of the fish for the duration of the surgery (3 – 5 min) to maintain health and aid in recovery. The incision was closed with three to five interrupted, absorbable sutures before the individual was returned immediately to a slow flowing section of the river and supported until full orientation and swimming ability returned. During the same period 25 acoustic receivers (VR2W) were deployed into the Onon (16) and Balj (9) (**Figure 19**) in deep (1.5 – 2.5 m), slow flowing pool reaches to minimise interfering noise associated with turbulent river sections and reduce the possibility of damage from river ice formation and break up. Unfortunately, one receiver in the Onon River was still lost during the study. The mean distance between acoustic receivers in the Onon River was 4.8 ± 2.7 km (± SD; 2.2 ≤ x ≤ 12.4 km) and in the Balj tributary it was 5.4 ± 5.1 km (± SD; 0.8 ≤ x ± 15.6 km). A total of more than 130 river kilometres made up the complete study range across both rivers. In situ range testing of a V13-1L transmitter indicated a detection distance of ≤ 100m during regular flows or more than adequate to cover the width of both the Onon and Balj channels (15 – 80 m). In addition, a TidbiT data logger (Onset, USA) was also installed in each river to record water temperature at regular intervals throughout the study.

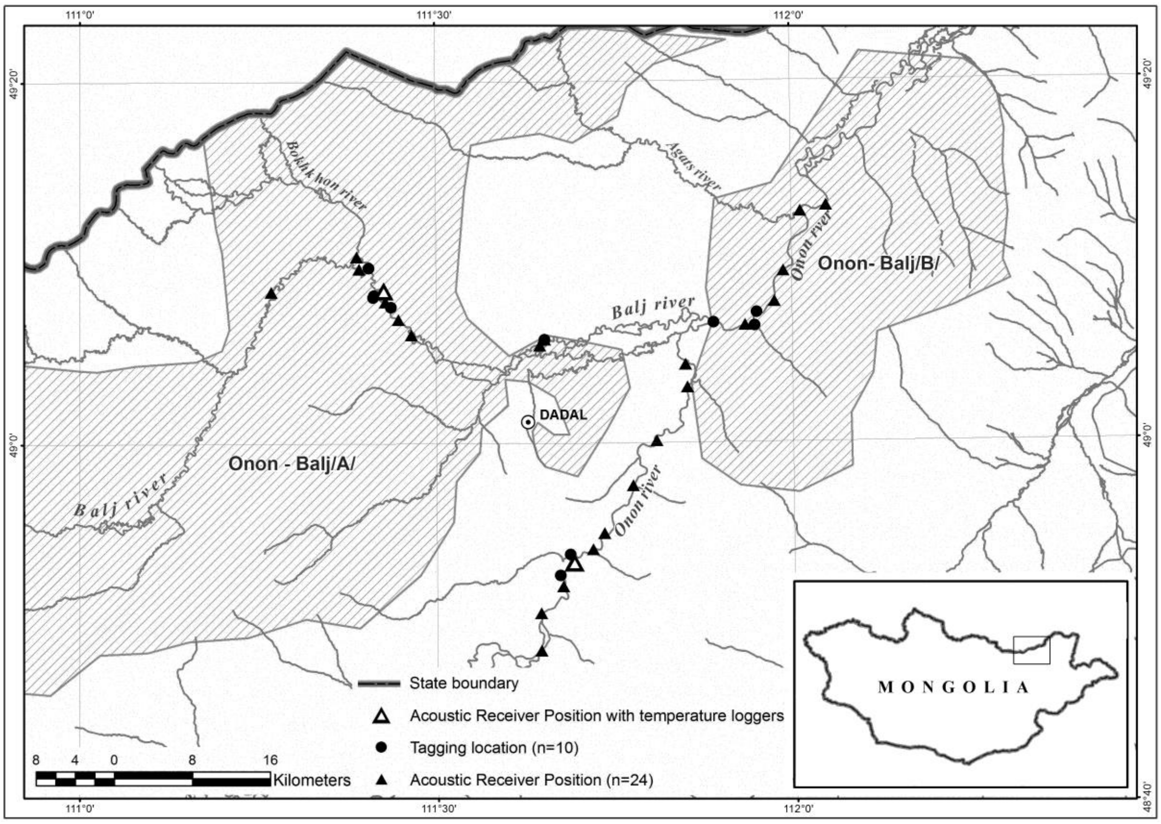

Figure 19. Map of the study region where the Onon River and Balj tributary converge in north-eastern Mongolia. The position of the deployed acoustic receivers (two with temperature loggers) and taimen tagging locations are shown, as is the Onon- Balj National Park Zones A and B boundaries.

Data Analysis

Seasonal dates used for analysis were adjusted periods that related to specific climatic changes observed in the river basin and the Mongolian fishery management regulations. The adjusted seasonal period for autumn was from the first frost on the 10th of September 2013 until complete river ice coverage on the 20th of November 2013; winter dates related to the complete river ice coverage period from the 21st of November 2013 until the 31st of March 2014; adjusted spring dates were matched to the closed fishing season in Mongolia and were from the 1st of April 2014 until the 15th of June 2014; while the adjusted summer dates in the study lasted from the 16th of June 2014 until the 9th of September 2014. Water temperature data were converted into mean (± SD) seasonal values and reported in Table 6, but displayed as mean daily values in the individual fish timeline plots (Figure 22). However, due to the Onon River temperature logger freezing for an 88 day period in winter, false water temperatures were recorded and so these values were not included in the analysis. The Mann-Whitney U Test was used to determine differences between the daily water temperatures per season in the Onon River and Balj tributary.

As most receivers were deployed several days following taimen capture and transmitter implantation, no detections were removed from the data set as complete recovery and normal behaviour of tagged taimen was expected to have returned by this time. The distance from the most upstream to the most downstream detection point over the complete study period as well as for each season, including the distance moved in the Balj tributary, was used as an estimation of an individual's annual and seasonal home range size (Minns, 1995). The I_R was calculated as per O'Toole et al. (2011), where the total number of days detected for a fish was divided by the total number of days in the array (*i.e.* number of days between the date of release and the last date of detection). Due to data non-normality, the Mann-Whitney U Test was also used to assess the differences in home range size between the Eg - Urr taimen population as reported in Gilroy et al. (2010) and Onon-Balj taimen from the current study. A repeated measures one-way analysis of variance (rm ANOVA) was used to test the statistical differences between seasonal home range sizes (km) of Onon-Balj taimen detected in the study reach during all seasonal periods. The seasonal home ranges were log2 (x + 1) transformed to adhere to the normality assumption for the rm ANOVA. A Spearman's Rank correlation was used to identify the relationship between fish length (cm) and home range size (km), fish length (cm) and the number of days in the array and fish length (cm) and the number of days detected. Data analysis and figures were completed in MATLAB (Statistics Toolbox Release 2012b, The Math Works Inc., US), R (R Development Core Team, 2010, Version 3.1.3) and SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.).

7.4 Results

River Conditions

The daily water temperatures in the Onon River and the Balj tributary were significantly different ($p < 0.05$) between all seasons according to the Mann-Whitney U Test results. Maximum water temperatures in the Onon River were detected in summer (21.29 °C), while in the Balj tributary they were detected in spring (17.32 °C). Both rivers recorded minimum water temperatures in winter of 0.08 and 0.01 °C, respectively (Table 5).

Taimen Detections and Site Residency

The median number of days between the tagging date and the date of last detection for taimen was 295 (22 – 367 days) with the median number of days an individual was detected being 18 (5–98 days; Table 6). The median I_R for taimen was 0.10 ($0.02 \leq x \leq 0.73$). Tagged taimen visited between one and 18 receivers in the two rivers over the study period (median = 4 receivers). In autumn, nine taimen were detected on 12 different receivers over 100 separate days, although 79 days were recorded on only three receivers (two in the Balj and one in the Onon; Figure 20). Out of the 74 days taimen were detected in winter, six of the seven individuals were recorded on Onon receivers (two receivers detecting taimen on 44 days) and only one taimen was detected for 13 days in the Balj tributary. In spring, taimen were recorded on 20 receivers, with seven days being the maximum a receiver recorded tagged fish. Spring was also the only season when the most upstream Balj tributary receiver detected taimen. Eleven receivers recorded four fish on 53 separate days in summer. Only one receiver in the Onon and one receiver in the Balj detected taimen on more than 10 days during this period. More Balj receivers ($n = 7$) detected taimen than Onon receivers ($n = 4$) in summer. Four individuals went missing from the middle of the detectable area by the 1st of January 2014 and were not recorded again in the study.

Taimen Home Ranges and Seasonal Movements

The median overall home range of tagged Onon-Balj taimen was 18.2 km (0 – 126.1 km, $n = 10$) although for those individuals detected for more than two-thirds of the study (> 8 months, $n = 6$) the median home range was 27.7 km (0.8 – 126.1 km). Spearman's rank correlation indicated there was no significant relationship between fish length and home range size ($r_S = 0.58$, $n = 6$, $p > 0.05$), fish length and the number of days in the array ($r_S = 0.29$, $n = 6$, $p > 0.05$) and fish length and the number of days detected ($r_S = 0.58$, $n = 6$, $p > 0.05$). For taimen detected in the study reach during each season, the median home range size was 17.4 km ($0.8 \leq x \leq 98.8$ km; $n = 6$) in spring; 9.1 km ($0 \leq x \leq 45.3$ km; $n = 4$) in summer; 4.7 km ($0 \leq x \leq 43.6$ km; $n = 8$)

in autumn and 0.4 km ($0 \leq x \leq 19$ km; $n = 7$) in winter (Figure 21). The greatest variance in home range size was detected in spring, followed by summer and autumn with the smallest variance detected during winter.

According to the rm ANOVA, there was an overall significant effect of season on taimen home range size ($F_{(1, 2)} = 136.28$, $p = 0.007$), but no significant difference ($p > 0.05$; $n = 3$) identified by the pairwise comparisons for home range size among seasons. Two taimen were detected moving between the Onon River and Balj tributary during the study period (Figure 22, a and b). One individual moved from the Balj to the Onon in autumn and returned again from the Onon to the Balj and back in spring staying 36 days (Figure 22a), while the second individual entered the Balj in spring and remained there for 85 days until returning back to the Onon River in summer (Figure 22b). The remaining taimen that were detected for eight months or longer moved only within the rivers in which they were originally captured, tagged and released (Figure 22, c – f), although on their last detection, one individual moved into the Bokhkhon tributary in the upper Balj (Figure 22e), and another individual entered the Agats tributary in the lower Onon (Figure 22c).

Taimen Behavioural Patterns

For those individuals with sufficient detections ($n = 5$), one taimen was observed having a restricted home range with no seasonal movements (Figure 22f), one taimen had a home range with a separate seasonal range (Figure 22e), and two taimen displayed a home range with seasonal departures (Figure 22b and 22d) and one taimen showed a possible shift in its home range. While this individual overwintered downstream in the Onon, it did not display any fidelity to this location, as after embarking on likely spring spawning movements into the Balj and re-entering the Onon, this fish instead moved upstream and left the study region without returning to its previous overwintering location downstream in the final four months of the project (Figure 22a).

Table 6. Mean (± SD), median, range (minimum - maximum) and number of days of recorded water temperatures (°C) in the Onon River and Balj tributary (Mongolia) per seasonal period during the study from September 2013 until September 2014.

River Water Temp. (°C)	Onon River				Balj River			
	Autumn 10th Sep-20th Nov	Winter 21st Nov-31st Mar	Spring 1st Apr-15th Jun	Summer 16th Jun-09th Sep	Autumn 10th Sep-20th Nov	Winter 21st Nov-31st Mar	Spring 1st Apr-15th Jun	Summer 16th Jun-09th Sep
Mean (±SD)	1.0±1.3	0.1±0.0	10.4±5.5	17.6±1.8	1.5±1.4	0.2±0.1	8.3±5.3	13.8±1.3
Median	0.4	0.1	10.0	17.7	1.1	0.14	8.3	13.7
Range	0.1-5.4	0.1-0.2	0.1-20.5	13.0-21.3	0.1-5.2	0.1-0.4	0.1-17.3	11.5-16.8
n (days)	41	43	75	87	41	43	75	87

Table 7. Summary table of the tagged taimen in the Onon River and Balj tributary (Mongolia) including Fish ID and the river captured, total fish length, date of capture and last detection, number of detections and receivers visited, number of days between capture and last detection, number of days detected in the array, residency index (I_R), overall home range (km) and seasonal home range (km) during the study from September 2013 until September 2014.

Fish ID	River Captured	Total Lt.(cm)	Capture Date	Last Detection Date	No. of Detections	No. of Receivers Visited	No. of Days in Array	No. of Days Detected	I_R	Home Range (km)	Seasonal Home Range (km)			
											Autumn	Winter	Spring	Summer
152	Balj	85	10.09.2013	15.05.2014	666	18	248	20	0.08	126.1	43.6	16.1	98.8	-
153	Balj	67	28.09.2013	17.11.2013	11,420	4	51	11	0.22	5.1	5.1	-	-	-
154	Balj	65	29.09.2013	15.09.2014	32,596	8	352	33	0.09	26.1	23.1	0.8	18.4	6.4
157	Balj	66	04.10.2013	25.10.2013	22,651	4	22	16	0.73	5.1	4.2	0	-	-
171	Balj	68	11.10.2013	17.09.2014	2,955	2	342	27	0.08	0.8	0	-	0.8	0
158	Onon	67	30.09.2013	13.09.2014	2,698	6	349	34	0.10	16.3	0	2.4	16.4	11.8
159	Onon	96	02.10.2013	06.12.2013	1,917	1	66	5	0.08	4	4	0	-	-
160	Onon	85	03.10.2013	04.10.2014	1,773	4	367	7	0.02	29.2	-	19.1	10.1	-
162	Onon	71	05.10.2013	01.01.2014	4,611	4	89	13	0.15	20.1	20.2	0	-	-
166	Onon	70	07.10.2013	18.09.2014	27,498	7	347	98	0.28	44.5	0	0	24.6	45.3

'-' Indicates a taimen was not detected during that season, '0' represents the individual was detected but no movement was recorded

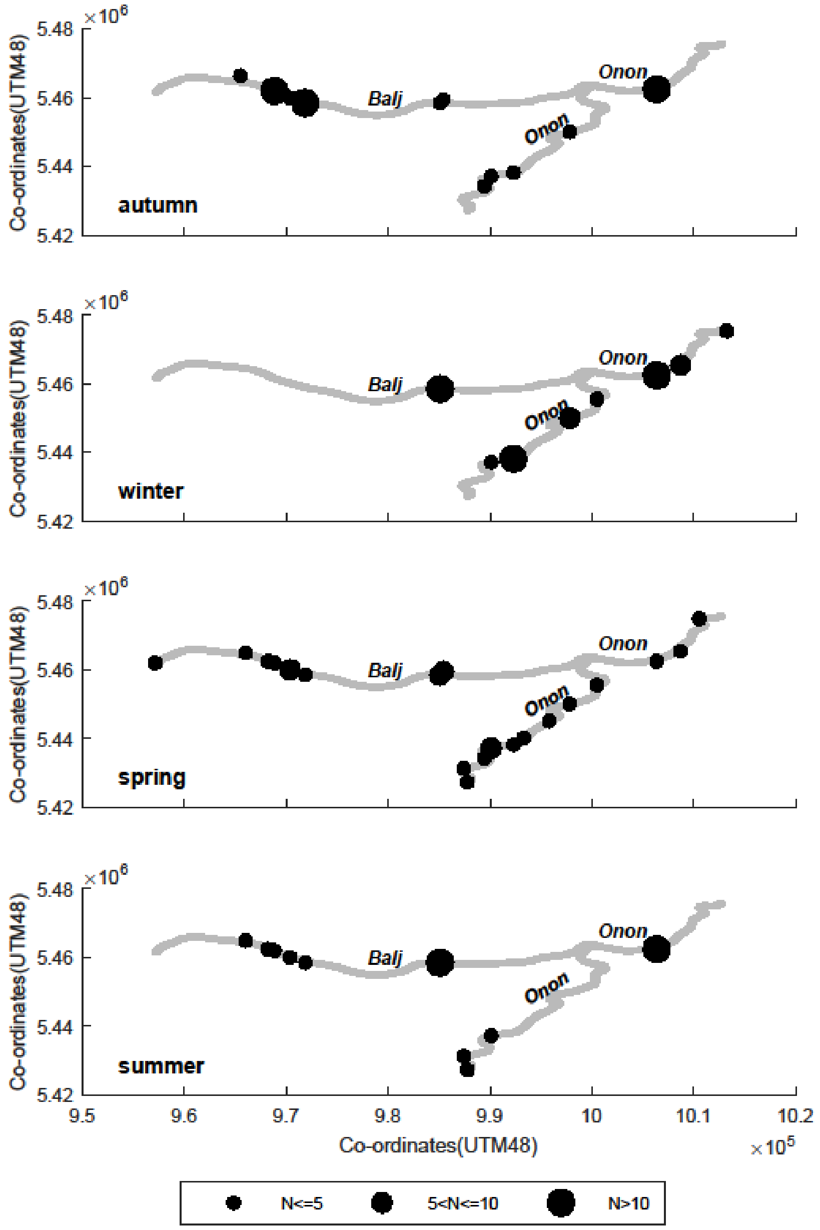

Figure 20. Taimen detection frequencies within the acoustic receiver array deployed in the Onon River and Balj tributary in autumn (n=9), winter (n=7), spring (n=6) and summer (n=4) between September 2013 and September 2014. The black circles represent the location of a receiver, while the size indicates the total number of days that tagged taimen were detected there in each season (small circles: ≤ 5 detected days; medium circle: >5 to ≤10 detected days; and large circle: >10 detected days).

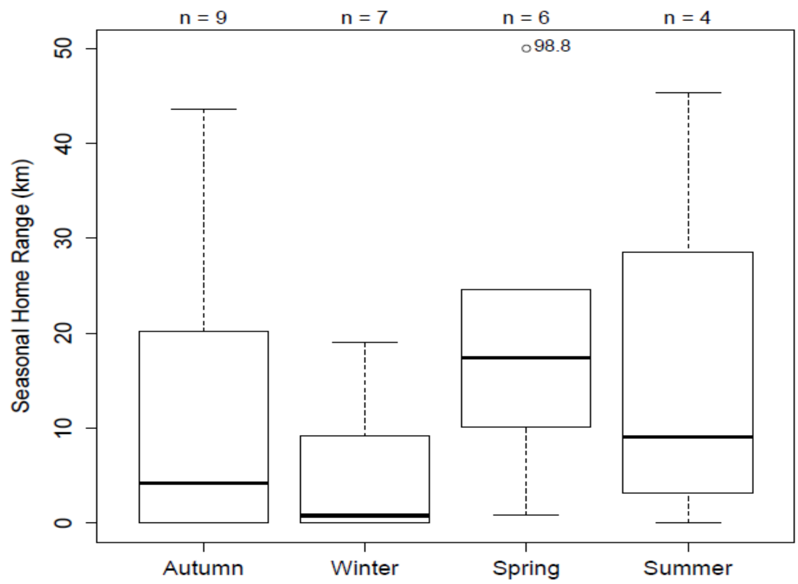

Figure 21 Boxplot of the median home range size (km) detected for taimen present in the study reach (n) during each seasonal period, in the Onon River and Balj tributary between September 2013 and September 2014. Boxes indicate the median and 25th / 75th percentile, whiskers display the minimum and maximum values and an outlier is shown as a circle.

7.5 Discussion

Documenting the distance, timing and conditions when taimen utilise different main channel and tributary reaches within their home range is valuable for authorities to help evaluate both spatial and temporal management strategies. This is particularly so as river networks in north and central Asia are becoming progressively polluted and fragmented, and the impacts of climate change on continental river systems (*e.g.* elevated temperatures and flooding events) are expected to increase further in the future (Cai et al., 2013; Hofmann et al., 2015; Hülsmann et al., 2015; Karthe et al., 2015a; Malsy et al., 2015). In this taimen biotelemetry study, the first to be conducted on an Amur River basin population, a substantial data set was obtained. Seasonal home range sizes and individual behaviour patterns within and between the Onon River and a major tributary were identified. This helped to fill an important knowledge gap for regional conservation of this endangered species and river basin management in data-scarce Mongolia (Karthe et al., 2015b). The median home range estimate across all seasons for Onon-Balj taimen was 18.2 km (n = 10), while for those individuals that were detected for eight months or more, the median home range was 27.7 km (n = 6). This larger home range distance is a more realistic estimate as it includes all of the detected spring spawning movements. Even though the median home range size for Onon-Balj

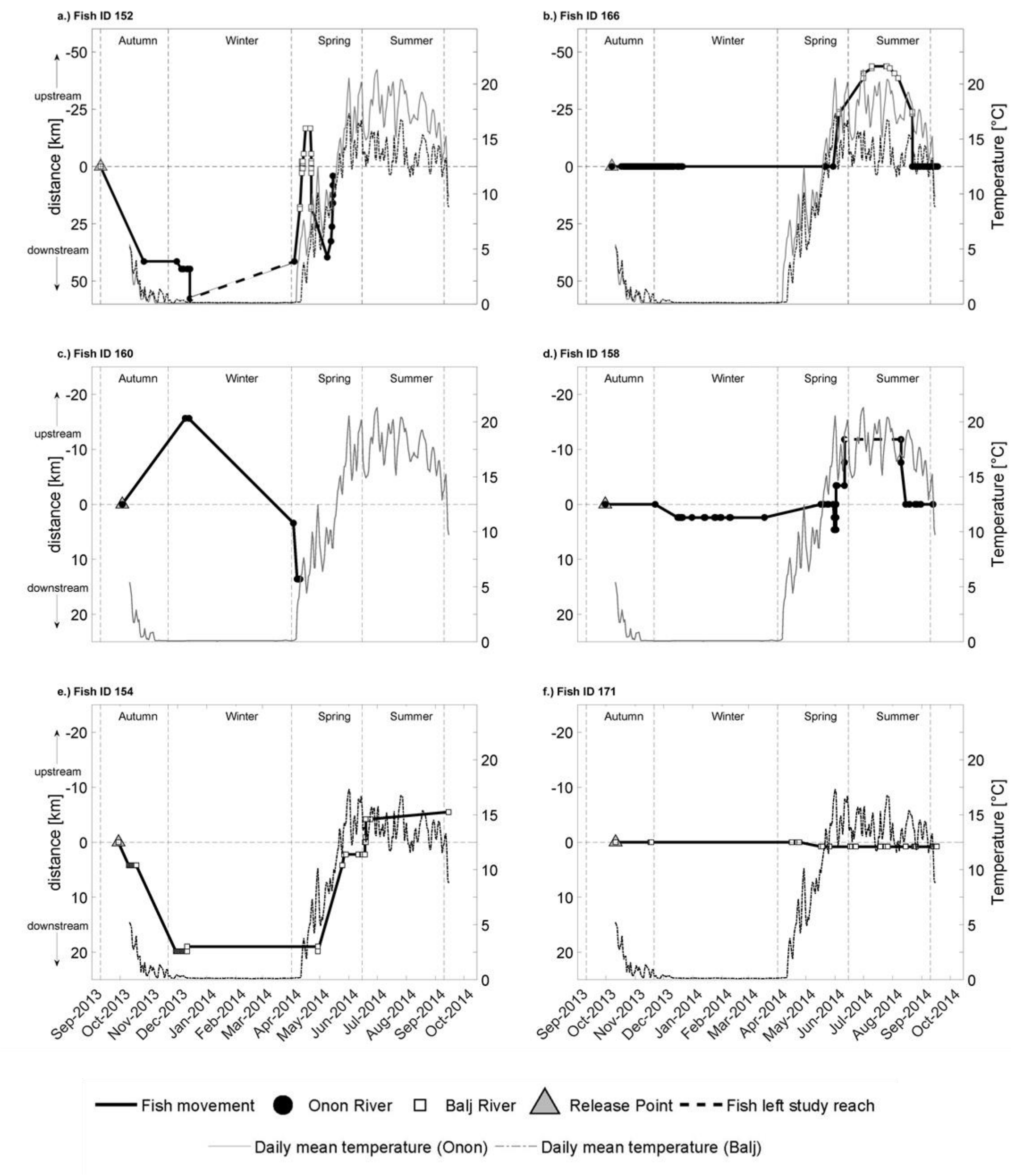

Figure 22. Timeline plots displaying the distance and location of taimen movements detected in the study for individuals present for eight months or more. Fish ID 152 (a) and 166 (b) moved between both the Onon River and Balj tributary; Fish ID 160 (c) and 158 (d) moved within the Onon River only; and Fish ID 154 (e) and 171 (f) moved within the Balj tributary only. A grey triangle specifies when the fish was tagged and released. The black circles (Onon River receivers) and white squares (Balj tributary receivers) indicate that the individual was detected on a given acoustic receiver on a specific day. A dotted line represents a known period when an individual left the detectable study area. Water temperature data from the Onon (grey line) and Balj (dashed line) during the study period are also displayed.

River taimen was more than double that of the median home range size reported for the Eg-Urr River taimen population (13.8 km) by Gilroy et al. (2010), there was no statistical difference identified between these river basin populations (Wilcox sign rank test $p > 0.05$). This result suggests that there is potentially home range size homogeneity for mature taimen across geographically separate river catchments over short-term (1 – 4 year) time frames. Although it is difficult to directly compare projects with largely different tracking methods in separate river basins and dissimilar numbers of taimen, one similarity that was identified, was the detection of highly transient taimen that moved substantial distances compared to the median home ranges in both studies. In the Onon-Balj River, an 85 cm taimen recorded a home range of 126.1 km, while in the Eg - Uur River a 92 cm taimen recorded a home range of 93.2 km (Gilroy et al., 2010). This distance of 126.1 km is the largest quantified home range recorded for an individual of this species to date and further confirms the ability of individual taimen to traverse extensive geographic scales, crossing both local (*i.e.* National Park) and international borders. Although these large scale movements were the exception in both studies, they likely provide an important link between separated populations by maintaining gene flow, and helping to increase the resistance to local population declines via immigration. A basin wide investigation to identify the existence of genetically discrete clusters or stocks of taimen across the upper Amur basin, would be a suitable next step to determine the scale of this potential widespread connectivity between geographically separate populations. In any case, there must be an emphasis on the need to apply management and conservation efforts on the same extensive scale, which is especially difficult for such transboundary rivers as the Onon and Amur. It is essential to increase coordination and cooperation between Mongolian, Russian and Chinese authorities, to adequately protect the threatened Amur-Heilong River basin taimen, especially as downstream populations are facing even greater declines (Zolotukhin, 2013).

Autumn movements are typically associated with individuals repositioning themselves into deeper, low velocity overwintering pools, which are more optimal habitats to conserve energy and better survive the pending winter conditions (Fausch & Young, 1995). Taimen have been reported to generally move downstream from upper tributaries to lowland river courses or return to the littoral zones of lakes at this time (Matveyev et al., 1998; Dulmaa, 1999; Gilroy et al., 2010). However, in the Onon-Balj River, most tagged taimen (66 %) did not move large distances, with four individuals remaining in the upper tributary being detected on only five receivers during this cooling period. This is the first record of taimen remaining in upper tributaries in the autumn period and thus demonstrating that mature individuals do not always move downstream into larger river channels before winter. However, two individuals from the Balj River still undertook an extended downstream movement of 23.1 km and 43.6 km, with one of these individuals entering the Onon River before the complete ice coverage. Taimen movement was also limited in the Onon at this time, with only five receivers out of 15 recording fish, when river discharge was declining and thus the detection range of the receivers was optimal. Autumn is a period of intense taimen feeding and aggression (*pers. obs*.), a trait that considerably increases the possibility of being captured and thus exploited by poachers. Therefore, from mid-September to mid-November, increased patrolling of both main channel and tributary reaches by National Park Rangers is needed in order to detect illegal fishing parties that pose an even greater risk due to the increased susceptibility of taimen at this time.

During the long, harsh winter months, resident salmonids in boreal rivers typically display restricted movements under the river ice where the near freezing water temperatures, the minimal river discharge and the potential formation of ice barriers in the water column all impact on an individual's movements, activity, aggression and feeding (Linnansaari et al., 2005; Huusko et al., 2007). Although the median home range in winter for Onon - Balj taimen was only 0.4 km, three individuals recorded substantial movements under the ice of up to 19 km, having been detected on nine receivers. Movements at this time have been reported to be in response to the accumulation of frazil and anchor ice in preferred refuge habitats, which has induced under ice movements in other salmonids (Lindström & Hubert, 2004). Gilroy et al. (2010) also reported taimen movement of up to 8 km under the ice coverage in the Eg - Urr River. As four out of the five tagged taimen in the Balj River appeared to have remained in this tributary for the entire winter, there is evidently suitable habitat and adequate resources to survive the extreme Mongolian conditions at this time. These observations, whilst preliminary, suggest that major tributaries such as the Balj, are important for taimen throughout the year.

Tagged taimen moved a median distance of 17.4 km following the river ice break up in spring. Individuals were detected entering the Balj, another small tributary (Agats), or displayed direct movements both upstream and downstream in the river where they had spent the winter. Twenty receivers detected five fish moving past them at this time, with one individual not recording any longitudinal movement. The largest detected spring movement was 58.6 km by one of the taimen that moved into the Balj tributary, although actual spawning was not confirmed. This is the longest quantified spring movement reported for a taimen to date, as previous movements described have been 12 and 25 km in tributaries of Lake Baikal (Matveyev et al., 1998) and over 40 km up the Tompuda and Bolshaya rivers in Russia (Ustinov, 1979 reported in Matveyev et al., 1998). While it is suspected that the first taimen to enter the Balj in April embarked on a typical spawning movement (direct trip upstream following the ice break up), the extended stay (85 days) of the second fish potentially indicates it has entered the Balj to take advantage of additional feeding opportunities and / or seek thermal refuge in the cooler tributary waters. The Onon River was significantly warmer than the Balj tributary in summer, with the Onon obtaining a mean temperature of 17.63 °C and thus remaining above 14 – 15°C, the optimal temperature for taimen (Matveyev et al., 1998), for a prolonged period of time. In summer the median home range for taimen in the Onon-Balj was 9.1 km, which was in contrast to the study by Gilroy et al. (2010) who reported minimal summer movements including zero fish passes in the month of July in the Eg - Uur River. However, any taimen movements in the surrounding Eg - Uur River tributaries would have been missed as monitoring did not cover the tributaries in the region. Given the expectation that climate change will continue to increase temperatures and reduce precipitation in Mongolia (Saladyga et al., 2013; Malsy et al., 2015), maintaining the hydrogeological connectivity of these tributaries to ensure access to thermal refuge areas during the warming summer months is critical for minimising potential future mortalities of many sensitive fish species including taimen.

Onon-Balj River taimen showed no generalised coordinated movements but instead displayed a variety of behavioural patterns that could be categorised into four distinct home range types, as previously described for taimen by Gilroy et al. (2010). One taimen displayed highly sedentary behaviour, only being detected on two receiver stations that were 800 m apart during the entire study. Although it has been reported that mature taimen do not produce gametes and thus participate in spring spawning movements every year (Matveyev et al., 1998), why this individual did not move any substantial distance during other seasons, *e.g.* autumn or summer, is uncertain. It can only be assumed that this taimen had spawned the year before and thus was in a reproductive resting phase, in addition to the river reach providing adequate resources for all seasonal conditions, so there was no need for this individual to move any significant distances during the study period (Heggenes & Dokk, 2001). Other tagged taimen displayed behavioural patterns consisting of an identifiable home range with either a separate seasonal range or a specific seasonal departure. Two individuals appeared to have maintained a restricted home range during autumn and winter before embarking on spawning movements or seeking out thermal refuge in tributaries during spring and summer, with both taimen returning to the same river reach by autumn. A fifth taimen was detected for several weeks post-surgery in one river location before moving downstream to overwinter and returning back upstream to the same river location in spring where it remained for several more weeks on its way further upstream. In addition, the movement patterns illustrated by another individual that travelled excessively throughout the study region over an eight-month period indicated a potential home range shift behaviour pattern. It is possible that this taimen had left the area and shifted its home range upstream, as this fish was not detected again in the region in the following four months after it had exited the detectable range. A longer monitoring period would have been preferable in order to confirm such behaviour.

Passive acoustic telemetry was successfully used to capture the extent of a broad range of taimen movements and behaviours in the remote Onon River and Balj tributary over an extended period of time, although as with most telemetry studies conducted in open lotic systems there were several issues of concern. Firstly, it must be considered that all detected distances are underestimates as no individual was recorded continuously during the entire study period (Heupel et al., 2004; O'Toole et al., 2010) as taimen regularly moved into and out of the study's detectable range. Secondly, passive acoustic telemetry is reliant on fish moving within the detection range of a stationary receiver and so if individual taimen displayed more sedentary behaviour, outside the detection range of the acoustic receivers, then the individual would not be recorded. Thirdly, it is known that during certain environmental conditions such as elevated river discharge or excessive ice formation that the detection range of these acoustic receivers is reduced (Cooke et al., 2013), thus lowering the probability of detecting a fish moving past during these times. These issues, along with the possibility of illegal fishers catching and removing tagged taimen from the river must all be considered as potential explanations as to why tagged fish disappeared or were not detected for various lengths of time during the study. In any case, the inevitability of missing individuals in such biotelemetry research conducted in a free-flowing river system reduced further the already limited number of tagged taimen in the study and ultimately the potential interpretation of the results. Thus recommendations for future telemetry research on taimen or other fish species living in boreal rivers includes tagging increased numbers of individuals to compensate for missing fish and deploying multiple sentinel transmitters to quantify the changes in the detection probability under changing environmental conditions (Payne et al., 2010). Future research efforts should focus on smaller taimen size classes to determine the autecological requirements and tributary usage of immature individuals, in addition too, diel depth and activity investigations of taimen and how these behaviours change under extreme conditions.

Tributaries such as the Balj are important for local taimen populations as they not only provide access to optimal upstream spawning habitat, additional feeding locations and critical overwintering pools but also likely offer refuge from thermal and hydrological extreme events. In the near future, the significance of such tributaries will increase even further in the region with rising mean air temperatures and greater fluctuations in the annual precipitation occurring due to climate change (Jiang et al., 2016). It is therefore, crucial to maintain the ecological integrity and hydrological connectivity of multiple spatially separated tributaries throughout the Onon River basin to help conserve and recover local taimen populations. In addition, across the Amur River basin and throughout most of the remaining distribution of the taimen, the increasing number of dams that have been constructed or are planned in major tributaries presents further threats to critical taimen habitat and essential movements. Freshwater protected areas have been successfully implemented in many regions around the world as a fisheries management tool to protect threatened fish stocks (Demartini, 1993; Abell et al., 2007; Suski & Cooke 2007). The Onon - Balj National Park and the newly established Onon River fishing zones (Fishing Game Management Plan of Fishing Zones in the Onon and Balj River Basin, 2015; Report for Game Management of Fishing Zone of Onon River, 2015), these FPAs can help to safeguard taimen population recovery in the region and be a model for taimen conservation throughout north and central Asia and Siberia.

8 Fish conservation in the land of steppe and sky: evolutionary significant units of threatened salmonid species in Mongolia mirror major river basins

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8.1 Abstract

Mongolia's salmonids are in decline; therefore genetically valuable populations must be identified so management resources can be prioritized. The unfragmented river basins provide unobstructed connectivity for resident fish species, so genetic structure is expected to be primarily segregated between river basins. We tested this hypothesis by investigating the geographic population structure of three salmonid genera (*Hucho, Brachymystax* and *Thymallus*), and identified ESUs and priority populations. Genetic markers were used to analyse populations from two major basins in Mongolia. *H. taimen* exhibited a dichotomous population structure forming two ESUs, with priority populations identified in five rivers. The *Brachymystax* genus had three *B. lenok* ESUs and one *B.* sp. ESU, with priority populations identified in six rivers. While *B.* sp. was confirmed to display divergent mtDNA haplotypes, we report haplotype sharing between *B. lenok* and *B.* sp. For *T. baicalensis,* only a single ESU was assigned, with priority populations located in five rivers and Lake Hovsgol. Additionally, we showed that *T. nigrescens* from Lake Hovsgol is a synonym of *T. baicalensis*. ESUs for both *H. taimen* and *B. lenok* included their major phylogeographic linages in different river basins. Across all species, the most prominent pattern was strong differentiation among major basins with low differentiation and weak patterns of isolation by distance within basins corroborating the hypothesis of high within-basin connectivity. Conservation priority should focus on priority populations within each ESU, where an ecosystem based management approach via the establishment of freshwater protected areas should be implemented.

8.2 Introduction

Until recently Mongolia's fish populations inhabited some of the least impacted river basins in the world as they were unfragmented by major dams, unaltered for navigational purposes, suffered negligible pollution, had low numbers of introduced fish species and experienced minimal fishing intensities (Kottelat, 2006; Ocock et al., 2006; Chandra et al., 2005; Hofmann et al., 2015). Thus river connectivity and fish population structure has persisted in a near natural state, which is a unique feature for such extensive river systems characterized by extreme continental climates in the 21st century (Karthe et al., 2015). However, as Mongolia's economy continues to develop at a fast rate there are a growing number of threats which would have significant impacts on the aquatic environment and its fish fauna, including several planned hydroelectric dam projects, increased waste water discharge, industrial pollution, mining contamination, nutrient runoff, riverbank erosion and widespread illegal fishing (Ocock et al., 2006; Hofmann et al., 2010; Hartwig et al., 2016; Kaus et al., 2016a). In order to mitigate these effects on the threatened fish populations, current fisheries management strategies in Mongolia need to consider meaningful biological units and identify genetically diverse and differentiated populations within the distribution of each species so that the limited resources can be more efficiently implemented to better focus protection and conservation efforts.

The identification of biological or conservation units is an essential first step in exploited species management, so authorities and policy makers can be informed about the functional scale of the population/s they are trying to manage (Funk et al., 2012). ESUs are a common management tool in conservation biology, which involves the identification of an intraspecific group which represents a measurable genetic and / or ecological divergence within the species due to sufficiently low or no contemporary gene flow (Avise, 2000; Fraser & Bernatchez, 2001; Bernard et al., 2009). ESUs can consist of multiple allopatric populations and can cover extensive geographic regions depending on the species and its ecology (Moritz, 1994; Palsbøll et al., 2006). Units are usually defined based on neutral and sometimes adaptive genetic variation, which represent the effects of both historical spatial processes and environmental selection (Moritz, 1994; Crandall et al., 2000; Funk et al., 2012; Casacci et al., 2013). For the initial demarcation of an ESU, researchers have focused on genetic markers including maternally transmitted, slowly evolving mtDNA and bi-parentally transmitted, quickly evolving microsatellites, as both yield relevant information on complementary spatio-temporal scales (Vogler & DeSalle, 1994; O'Connell & Wright, 1997). The identification of ESUs and genetically distinct populations of threatened and exploited fish stocks is increasingly used in modern fishery management to ensure that conservation actions and resources can be better matched with biological relevance (Xia et al., 2006. Geist et al., 2009; Zhivotovsky et al., 2015).

Freshwater salmonids from the genera *Hucho, Brachymystax* and *Thymallus* (Family *Salmonidae*) live in sympatry throughout the major river basins of northern Eurasia, occurring in the upper Yenisei and Selenge river basins (Arctic Ocean drainages) and the upper Amur River basin (Pacific Ocean drainage) in northern Mongolia. While some stable viable populations of these species still exist in the more remote river reaches, they have experienced substantial declines and local extinctions over recent decades (Ocock et al., 2006). Three of these more widely distributed and recreationally targeted species include the Siberian taimen (*Hucho taimen*, Pallas 1773, Classification: *Endangered* in Mongolia and *Vulnerable* internationally, IUCN), the largest salmonid in the world and the top predatory species in these Palearctic systems (Holčík et al., 1988. Ocock et al., 2006; Hogan & Jensen, 2012); the sharp-snouted lenok (*Brachymystax lenok*, Pallas 1773, *Vulnerable*), a medium size species (Shed'ko et al., 1996; Ocock et al., 2006); and the Baikal grayling (*Thymallus baicalensis*, Dybowski 1874, *Near Threatened* – nominative species *T. arcticus*, Pallas 1776) (Ocock et al., 2006), which is part of a genus that comprises several species across the region (Knizhin et al., 2006; Weiss et al., 2007). In addition the blunt-snouted lenok (*B*. sp., not classified), which is only found in certain tributaries of the Amur basin in Mongolia, and the Hovsgol grayling (*T. nigrescens*, Dorogostaisky 1923, *Endangered*), which is limited to Lake Hovsgol in northern Mongolia, were also considered as both of these species also currently face existential risks in the country.

Phylogeographic research on these threatened salmonid species has revealed population structure across various geographic scales, however with little or no data existing for the Mongolian populations. Broad-scale phylogroups have been identified between major river basins across Siberia for both *H. taimen* and *B. lenok* (Froufe et al., 2003, 2005, 2008; Maric et al., 2014), with intra-basin structure also identified for both species in Chinese rivers (Xia et al., 2006; Kuang et al., 2009, 2010; Liu et al., 2011). Within the *Brachymystax* genus, a clear genetic divergence was evident between the closely related sharp-snouted (*B. lenok*) and blunt-snouted lenok (*B.* sp.), with no evidence of shared haplotypes despite natural hybrids occurring between the species in regions of sympatry (Ma & Jiang, 2007; Froufe et al., 2008). In the *Thymallus* genus, Eurasian river basins have been described as having a fixed divergence that has resulted in multiple species with restricted distributions (Froufe et al., 2003; Weiss et al., 2007; Knizhin & Weiss, 2009; Slynko et al., 2010). In Mongolia, there are five *Thymallus* species currently recognised, although further clarification is required to identify whether *T. nigrescens* from Lake Hovsgol represents a unique species or not, as it has been treated as a separate species by some authors (Berg, 1962, Pivnička & Hensel, 1978; Bogutskaya & Naseka, 2004) but not by others (Koskinen et al., 2002; Froufe et al., 2005; Knizhin et al., 2006).

The overall objectives of this research was to identify the previously unknown genetic structure of threatened salmonid populations within Mongolia's extensive river basins by determining and delineating ESUs within species as well as assessing the genetic diversity within and differentiation among populations. We used a combination of mtDNA sequencing and microsatellite marker analyses to identify ESUs for each species sampled from across their Mongolian ranges, *i.e.* the upper Yenisei, the Selenge and upper Amur River basins. We hypothesise that the hitherto unfragmented river basins in Mongolia allowed for unobstructed connectivity between salmonid populations within basins and thus their genetic structure should be primarily segregated between basins with minimal differentiation within basins. We also wanted to shed light on the phylogenetic relationships of the blunt-snouted lenok (*B.* sp.) and Hovsgol grayling (*T. nigrescens*). This research can offer a detailed genetic understanding for these threatened freshwater fish in Mongolia, by providing local and national authorities a more effective way to disseminate resources and protect rivers that contain the most genetically important populations of these species to further safeguard their evolutionary potential for the future.

8.3 Materials and Methods

Study area

Mongolia contains the most upstream regions of several major continental Asian drainages (Figure 23). The Selenge River basin drains most of north-central Mongolia before flowing into Siberia and forming the main inflow of Lake Baikal, from where water exits via the Angara River to converge with the Yenisei River. The Shishged River is a smaller tributary of the upper Yenisei with approximately 100 km in Mongolian territory. The Onon and Kherlen rivers are located in eastern Mongolia and are the most upper tributaries of the Amur River basin. Although currently disjunct, there is evidence of large scale paleo-hydrological exchange of the Yenisei / Selenge, Amur and Lena river basins in the late to post Pleistocene period, having a predominant effect on the ichthyofaunal diversity and distribution (Grosswald, 1998, 1999; Koskinen et al., 2002; Froufe et al., 2003).

Field sampling

Our sampling design was intended to capture the complete genetic diversity of *H. taimen, B. lenok* and *T. baicalensis* from across their Mongolian distributions. We sampled fish at 19 sites from the Shishged, Selenge, Onon and Kherlen river basins in Mongolia in 2011 and 2012 (Table 7, Figure 23). Sample locations were selected due to the species present, the isolation by river distances and river accessibility. Sample sites were typically in the upper reaches of each river, but due to the low abundances of some species in certain regions it was necessary to cover tens of kilometres along the river in order to collect sufficient numbers of samples. In total we collected fin clips from 127 *H. taimen* from eight populations, 371 *B. lenok* from 18 populations, and 274 *T. baicalensis* from 11 populations. We also collected samples of blunt-snouted lenok (*B. sp.*) from the Amur basin (12 individuals, 3 populations) and *T. nigrescens* from Lake Hovsgol (15 individuals). Fish were caught using backpack electrofishing units (Hans Grassel GmbH, Germany; Type ELT 60) and angling by researchers and international fishing guides, with all individuals being released alive. Several samples were also collected from fish caught by Mongolian recreational fishers that were encountered on the river. Fin clips were stored in 96 % ethanol prior to analysis.

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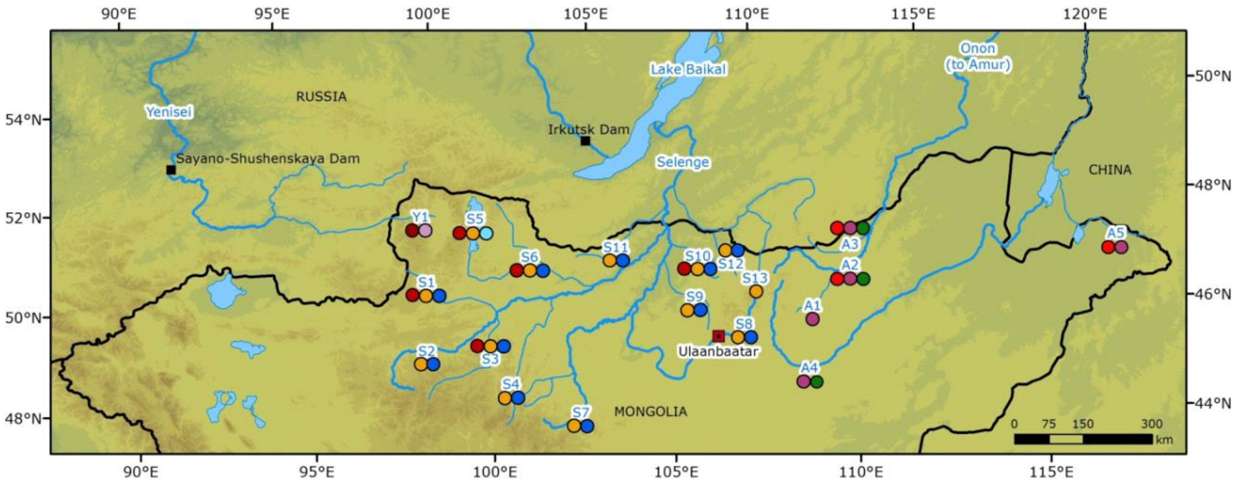

Figure 23. Map of northern Mongolia displaying the rivers and lake where fish were sampled in 2011 and 2012. The major river basins in Mongolia include the Selenge River basin (Arctic drainage) and the Amur River basin (Pacific drainage), while the upper Yenisei River basin also reaches into Mongolian territory (Y1). Coloured dots under each sample location ID indicates which species were caught in that river (*Hucho taimen* – red dots with different shades for each river basin; *Brachymystax lenok* –orange dots for Selenge basin, dark pink dots for Amur basin and a light pink dot for the Shishged River; blunt-snout lenok (*B. sp.*) dark green dots; *Thymallus baicalensis* - dark blue dots and *T. nigrescens* – a light blue dot).

Genotyping

Fish DNA was extracted using the DNeasy Blood and Tissue kits (QIAGEN, Hilden, Germany) following the manufacturer's instructions. We sequenced the control region ("D-loop") of mitochondrial DNA of 31 individuals from seven populations of *H. taimen*, 35 samples from 12 populations of *B. lenok*, 11 samples from two populations of the blunt-snout lenok (*B. sp.*), as well as 20 samples from six populations of *T. baicalensis* and three samples of *T. nigrescens* from Lake Hovsgol using primers LRBT-25 and LRBT-1195 (Uiblein et al., 2001). Further details of the sequencing reactions and protocols are given in Appendix 4. All *H. taimen*, *Brachymystax* and *Thymallus* samples were genotyped at eleven, eight and eight microsatellite loci, respectively (Table A4- 1). A small number of loci produced multiple bands which could be consistently scored as independent loci, one in *Brachymystax* (BleTri4) and two in *H. taimen* (BleTri4 and BleTet6). We used a PCR protocol with CAG/M13R-tagged forward primers and GTTT-"pigtailed" reverse primers following Schuelke (2000). Primer sequences and details of the PCR protocol are given in Table A4- 1 in Appendix 4.

Data analysis

All analyses were carried out separately for populations from the three different genera. Mitochondrial DNA data and additional sequences acquired from GenBank (for *Brachymystax* spp. and *Hucho taimen*) were aligned using Geneious® Pro 5.6.7 (Kearse et al., 2012) and the built-in multiple alignment option. Haplotype networks were obtained by using a median-joining algorithm (Bandelt et al., 1999) implemented in PopART v1.7.2 (http://popart.otago.ac.nz). For *H. taimen* and *Brachymystax spp.*, haplotypes were labelled following Froufe et al. (2005; Figure 2c) and Froufe et al. (2008; Figure 5), respectively, using new names as necessary. In the analysis of *Brachymystax* we also included sequences of *B. tsinglingensis* from China (Liu et al., 2012; Xing et al., 2015).

From the microsatellite datasets we calculated descriptors of population genetic variation, *i.e.* the number of alleles (A), allelic richness (A_R), expected heterozygosity (H_e) and inbreeding coefficient (F_{IS}) and its significance (*p*-value) using FSTAT v2.9.3.2 (Goudet, 2001). The presence of distinct genetic clusters was assessed with STRUCTURE 2.3.4 (Pritchard et al., 2000), where a burn-in period of 100,000 was used and 1,000,000 Markov-Chain Monte-Carlo repetitions were performed with 10 replicates. This model based Bayesian approach excludes prior information on the origins of individuals. The number of clusters run was between K = 1 and K = number of populations + 1. The most likely number of clusters was determined by evaluating both, the likelihood of models and the ΔK method (Evanno et al., 2005). Independent runs were merged with CLUMPP 1.1.2 applying the Greedy algorithm and plotted with Pophelper (Francis, 2016). When multiple clusters were found, we reanalyzed these clusters separately as the STRUCTURE software is sensitive to hierarchical population structure. Population differentiation was quantified with hierarchical analyses of molecular variance (AMOVA) conducted in GeneAlEx 6.5 (Peakall & Smouse, 2006, 2012). We tested for isolation by distance within basins, *i.e.* a correlation between genetic differentiation and distance along the river with Mantel tests in R (R Development Core Team, 2016). River distance was estimated between hydrologically connected sites by tracing the main river channel and using the measuring ruler "path" in Google Earth 7.1.7.2600 (Google Inc., 2016). River distances ranged from 465 km to 4994 km (mean 1637 km) in the Yenisei basin (incl. Shishged) and 256 km to 3245 km (mean 1977 km) in the Amur basin.

Populations were assigned to separate ESU's when the combined evidence of mitochondrial and nuclear genetic data indicated genetic isolation. To further identify priority populations, which are the most genetically diverse and/or distinct populations within each ESU, we used the microsatellite data with the Contrib Software v1.02 (Petit et al., 1998). Calculations were based on allelic richness thus correcting for unequal sample sizes. The contribution of each population to total diversity is partitioned into two components, the diversity within each population and the differentiation from other populations.

8.4 Results

mtDNA analysis

Four haplotypes were identified for Mongolian *H. taimen* (Figure 24, Table 7). These could be grouped into two main clusters, separated by four mutations. The first cluster included Selenge and Shishged populations (identified by two different shades of darker red), while the second cluster was made up of Amur *H. taimen* (bright red). All Selenge populations grouped into a single haplotype (H1), while only some Shishged *H. taimen* contained H1. The remaining Shishged individuals displayed two additional and exclusive haplotypes (H6* and H7*). *H. taimen* sampled from the three Amur populations all contained in haplotype H3/4/5.

Eight haplotypes were found in the *Brachymystax* populations that were sampled in Mongolia (Figure 25, Table 7). Sharp-snouted lenok showed a separation of the Selenge populations, which have three haplotypes (H16, H20*, H21*), from the Amur and Shishged populations, which also displayed three haplotypes (H11/12, H15, H22*). Three of the sharp-snouted lenok haplotypes had been found previously, while the other three haplotypes (denoted with an asterisk) were closely related but new for the species. Haplotypes identified in blunt-snouted lenok belonged to two highly divergent clusters. Some individuals contained two haplotypes from a blunt-snout specific cluster (H3/5/8 and H23*), one of which was new. However, most of the blunt-snouted lenok samples displayed the common sharp-snout haplotype H15.

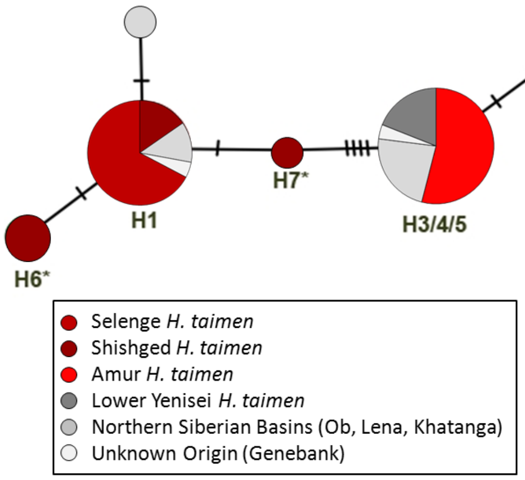

Figure 24. Mitochondrial DNA haplotype network for *Hucho taimen* sampled from Mongolia and from Froufe et al. (2005), with haplotypes detected in this study labelled using existing haplotype names (Froufe et al. 2005, Fig. 2c). New haplotypes found in this study are denoted with an asterisk (*). Note that some of the previously identified haplotypes (Froufe et al. 2003, 2005) collapsed into a single haplotype because the total alignment was shorter.

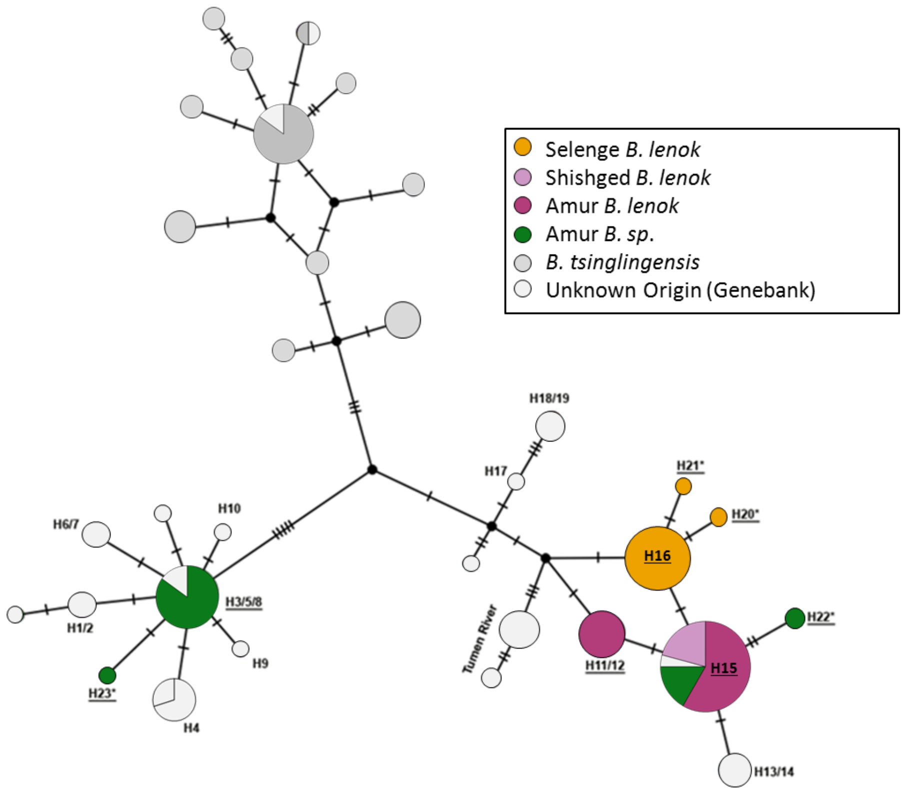

Figure 25. Mitochondrial DNA haplotype network of *Brachymystax* species, *i.e.* sharp-snouted lenok (*B. lenok*), blunt-snout lenok (*B. sp.*) and *B. tsinlingensis* sampled from Mongolia and Genbank. Haplotypes found in this study are underlined, haplotype names used in Froufe et al. (2003, 2008) were maintained and new haplotypes are denoted with an asterisk (*). Note that some of the previously identified haplotypes (Froufe et al. 2003, 2008) collapsed into a single haplotype because the total alignment was shorter.

Table 8. Genetic diversity of three salmonid genera sampled from the Yenisei, Selenge and Amur rivers basins in Mongolia in 2011 and 2012. The table lists the basin and river, the population identification code, sample size (n), the average number of alleles (A), the allelic richness (A_R) (with a rarefaction sample size of 4 for *Hucho*, 6 for *Brachymystax* and 9 for *Thymallus*), the expected heterozygosity (H_e), and inbreeding coefficient (F_{IS}) where bold F_{IS} values indicate significance. For mtDNA data, sample size (n) is shown along with the haplotypes identified, where those haplotypes with an asterisk (*) are new. The Evolutionary Significant Units (ESUs) as identified for each genus according to the microsatellites and mtDNA results is shown along with the pirority populations that displayed above average genetic diversity, differentiation as well as those populations that exhibited new haplotypes for the species or exclusive haplotypes for Mongolian populations.

Sample site information			Microsatellites					mtDNA		Evolutionary Significant Units		*Priority Populations*
Basin	**River**	**Pop. ID**	**n**	**A**	**A_R**	**H_e**	**F_{IS}**	***n***	***Haplotype No.***	***Micro-satellite clusters***	***mtDNA groups***	***Contribute * / exclusive haplotypes****
					Hucho taimen							
Yenisei	Shishged	Y1	6	2.6	2.03	0.333	0.000	6	H1, H6*, H7*	1	1	**
Selenge	Delgermoron	S1	12	4.0	2.16	0.337	-0.019	3	H1	1	1	*
	Chuuluut	S3	4	2.1	1.93	0.269	0.072	2	H1	1	1	
	Eg-Urr	S6	8	3.1	2.12	0.343	-0.016	2	H1	1	1	*
	Eroo	S10	45	5.3	2.01	0.322	**0.053**	8	H1	1	1	
Amur	Onon	A2	44	6.3	2.49	0.424	**0.077**	7	H3/4/5	2	2	*
	Balj	A3	4	2.3	2.36	0.361	**0.215**	-	-	2	-	
	Khalkhin	A5	4	2.7	2.71	0.492	0.153	3	H3/4/5	2	2	*
					Brachymystax species including sharp-snouted lenok (*B. lenok*) and blunt-snouted lenok (*B. sp.*)							
Yenisei	Shishged	Y1	9	2.1	2.13	0.338	**0.342**	5	H15	2b	2	*
Selenge	Delgermoron	S1	16	5.9	4.65	0.634	-0.008	3	H16, H20*	1	1	*
	Ider	S2	17	5.4	4.38	0.598	-0.049	-	-	1	-	
	Chuuluut	S3	20	5.6	4.43	0.603	**0.073**	2	H16, H21*	1	1	**
	Humen	S4	6	4.1	4.89	0.674	0.038	-	-	1	-	*
	Hovsgol	S5	11	5.0	4.65	0.606	0.066	-	-	1	-	
	Eg-Urr	S6	24	6.3	4.66	0.614	0.000	3	H16	1	1	
	Orkhon	S7	45	6.3	4.37	0.622	**0.050**	1	H16	1	1	*
	Tuul	S8	13	4.4	4.31	0.576	-0.007	-	-	1	-	*
	Kharaa	S9	61	6.4	4.28	0.593	0.024	3	H16	1	1	
	Eroo	S10	38	6.0	4.14	0.538	-0.002	3	H16	1	1	
	Zelter	S11	13	5.3	4.50	0.566	-0.132	-	-	1	-	
	Huder	S12	31	6.8	4.40	0.576	-0.007	-	-	1	-	
	Minj	S13	11	3.9	3.78	0.557	**0.195**	1	H16	1	1	
Amur	Barch	A1	13	6.0	4.73	0.646	**0.145**	-	-	2c	-	
	Onon	A2	11	6.0	4.76	0.672	**0.102**	2	H15	2c	2	*
	Onon	A2-B.sp	10	4.5	4.01	0.540	**0.173**	10	H15, H22*, H3/5/8, H23*	2a	2, 3	**
	Balj	A3	13	5.5	4.45	0.622	-0.031	1	H15	2c	2	
	Balj	A3-B.sp	1	1.5	-	-	-	1	H15	2a	2	*
	Kherlen	A4	7	4.0	4.07	0.564	0.042	5	H15	2c	2	*
	Kherlen	A4-B.sp	1	1.1	-	-	-	-	-	2a	-	*
	Khalkhin	A5	12	5.3	3.98	0.597	**0.101**	6	H11/12, H15	2c	2	*
					Thymallus species including *T. baicalensis* and *T. nigrescens* (Lake Hovsgol)							
Selenge	Delgermoron	S1	24	10.1	6.75	0.674	-0.093	3	H4	1	1	*
	Ider	S2	14	7.6	6.18	0.640	-0.631	-	-	1	-	
	Chuuluut	S3	16	9.6	7.05	0.624	0.010	1	H4	1	1	
	Humen	S4	15	8.6	6.92	0.662	**0.089**	-	-	1	-	
	Hovsgol	S5-Tn	15	7.13	5.79	0.633	-0.092	3	H4	1	1	*
	Eg-Urr	S6	55	13.9	6.92	0.653	**0.043**	3	H4	1	1	
	Orkhon	S7	27	10.4	6.83	0.684	**0.081**	7	H4, H5, H6	1	1	*
	Tuul	S8	10	6.8	6.52	0.682	-0.055	-	-	1	-	*
	Kharaa	S9	24	9.4	6.05	0.607	-0.020	4	H4, H6	1	1	
	Eroo	S10	54	14.0	6.84	0.641	**0.015**	2	H4	1	1	
	Zelter	S11	21	10.3	7.05	0.707	-0.010	-	-	1	-	*
	Huder	S12	14	8.1	6.69	0.699	0.009	-	-	1	-	*

Nine haplotypes were found among five *Thymallus* species. The haplotype network showed four distinct clusters (Figure 26, Table 7). Three of these clusters were comprised of haplotypes from a single species with the *T. brevirostris* cluster having one haplotype (T3), *T. svetovidovi* having two haplotypes (T1 – T2) and *T. grubii* having three haplotypes (T7 – T9). The fourth cluster comprised of a haplotypes that included *T. baicalensis* and *T. nigrescens* with both species sharing the most common haplotype (T4), with two additional rarer haplotypes (T5, T6) found in *T. baicalensis.*

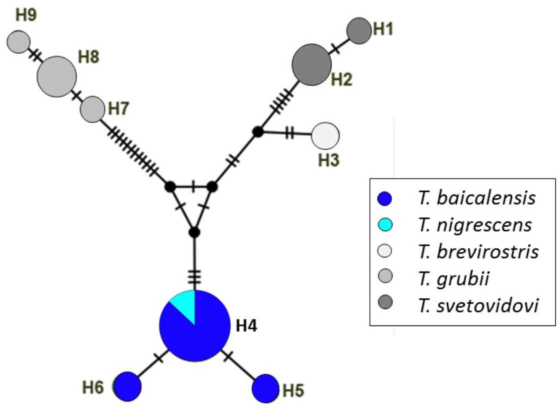

Figure 26. Mitochondrial DNA haplotype network for *Thymallus* species (*T. baicalensis, T. grubii, T. nigrescens, T. svetovidovi,* and *T. brevirostris*) sampled from the Shishged (Yenisei), Selenge, Amur and Central Asia river basins in Mongolia.

Microsatellite analyses

For the sampled *H. taimen* populations, mean allelic richness (A_R) was 2.23 (SD 0.27) with a range from 1.93 in the Chuuluut to 2.71 in the Khalkhin (Table 8). The populations in the Amur displayed a higher mean allelic richness (mean = 2.52, SD ± 0.18) than the Selenge (2.06, SD 0.10), while the Shishged population had an A_R of 2.03. Three out of eight *H. taimen* populations from both the Selenge and Amur showed significant inbreeding coefficients (S6, A2 and A3). STRUCTURE analyses revealed *H. taimen* displayed two genetic clusters consisting of the Shishged and Selenge rivers, and the Onon and Kherlen rivers, respectively (Figure 27a, Appendix 4: Figure A4. 1). No further genetic structure was evident when each basin cluster was analysed separately. The AMOVA for *H. taimen* indicated that 29 % of the genetic variance was partitioned among basins, 1 % among populations within basins, and the rest residing within populations (Table A4- 5a). Separate analyses for the Selenge (incl. Shishged River, Yenisei) and Amur basins revealed F_{ST} = 0.027 (p = 0.001) and F_{ST} = 0.052 (p = 0.008), respectively (Table A4- 5b/Table A4- 5c). The overall F_{ST} value for *H. taimen* was 0.302.

In *B. lenok*, the Shishged population (Y1) recorded an allelic richness (A_R) of 2.13 whereas much higher values were evident in the Selenge (mean 4.42, SD 0.28) and Amur populations (4.40, SD 0.36). In each river basin, there was at least one population that had significant F_{IS} values indicating deviation from Hardy-Weinberg Equilibrium (HWE). The blunt-snouted lenok in the Onon had similar values of genetic variation as the sharp-snouted lenok with significant F_{IS} values. STRUCTURE analyses of all *Brachymystax* samples (including both *B. lenok* and *B. sp.*) revealed a total of four genetic clusters. The first analysis displayed two clusters representing the separation of populations in the Selenge from the Amur and Shishged (Figure 27b, Figure A4. 2). Notably, the sympatric sharp-snouted and blunt-snouted lenok from the Amur clustered together rather than forming separate "species" clusters. The Selenge cluster (orange) displayed no further structure in additional analyses. In contrast, the 'green cluster' comprises the Shishged and Amur populations including blunt-snouted lenok, displayed additional substructure (Figure A4. 2 c, Figure A4. 2 d). First, the blunt-snouted lenok was separated as a distinct gene pool represented in three rivers (Figure 27b, Figure A4. 2 c). Second, the Shishged population was clearly separated from both blunt-snouted lenok (Figure A4. 2 d) and from sharp-snouted lenok in the Amur basin (Figure A4. 2e). The latter representing a single cluster (Figure A4. 2 f). Thus, the *Brachymystax* genus comprised four genetic clusters across Mongolia, representing sharp-snouted lenok from the Selenge, Shishged and Amur, respectively, as well as the blunt-snouted lenok from the Amur. This structure was also corroborated by the pairwise F_{ST} values (Table A4- 3). The AMOVA results for the *Brachymystax* genus (sharp-snouted *B. lenok* only) indicated that 16 % of the genetic variance was among basins, 2 % among populations within basins and the rest residing within populations (Table A4- 5) with the overall F_{ST} value being 0.181. Population differentiation among sharp-snouted lenok was similar in the Amur (F_{ST} = 0.056) and the Selenge basin (F_{ST} = 0.049). Mantel tests indicated a pattern of isolation by distance for sharp-snouted lenok populations in both the Selenge (r = 0.41, p = 0.004; Figure A4.5a) and the Amur basin (r = 0.76, p = 0.045; Figure A4.5b).

For *T. baicalensis*, mean allelic richness was 6.72 (± SD 0.31) across the Selenge populations, with *T. nigrescens* in Lake Hovsgol displaying an A_R of 5.79. Four *T. baicalensis* populations had significant F_{IS} values indicating deviation from HWE. The STRUCTURE analysis revealed only one genetic cluster for *T. baicalensis* and *T. nigrescens* (Figure 27c, Figure A4. 3 & Figure A4. 4). This is corroborated by very weak genetic structure amounting to only 1% of molecular variance among populations (Table A4- 5b). The overall F_{ST} for *T. baicalensis* and *T. nigrescens* according to the AMOVA results was 0.014. However, *T. nigrescens* was more strongly differentiated from all *T. baicalensis* populations as the mean pairwise differentiation among

T. baicalensis populations was $F_{ST} = 0.014$ but $F_{ST} = 0.033$ between the two taxa (Table A4- 4). The *Thymallus* populations showed no significant pattern of isolation by distance (r = 0.22, p = 0.12, Figure A4. 6).

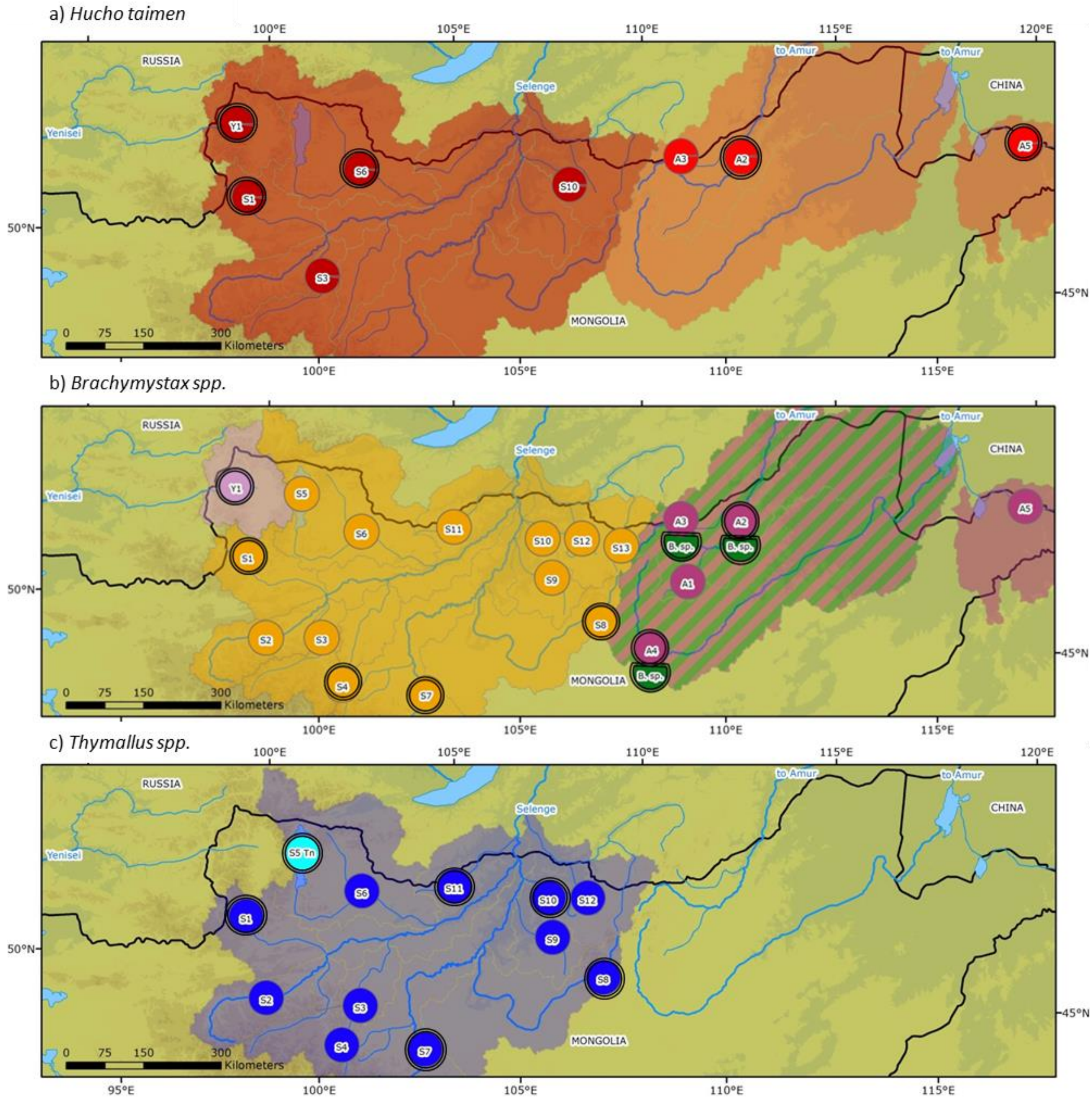

Figure 27. Results of model based clustering of microsatellite data of salmonid populations within Mongolia. Pie charts show proportional memberships of identified genetic clusters from STRUCTURE (a) *Hucho taimen,* (b) *Brachymystax* spp. (sharp-snouted, *B. lenok*, and blunt-snouted lenok, *B. sp.* (dark green)) and (c) *Thymallus* spp. (*T. baicalensis* and *T. nigrescens*). Refer to Table 8 for sample sites and supplementary Figures A4.1 - A4.4 for details of the STURCTURE analyses. The coloured shading represents the different ESUs determined for each species using mtDNA and microsatellites data. Populations highlighted with a black double line are priority populations for conservation due to above average genetic diversity, differentiation or presence of new or exclusive haplotypes.

Identification of priority populations

Priority populations within river basins were identified as those that contained high genetic diversity or differentiation components in the contribution analysis (Figure 28, Table 8). For *H. taimen,* two populations in the Selenge and two in the Amur were identified as priority populations (Figure 28a & Figure 28b). For sharp-snouted lenok (*B. lenok*) four populations were identified in the Selenge (Figure 28c), with two identified in the Amur (Figure 28d); and for *T. baicalensis* (including *T. nigrescens*), six populations were considered to be priority populations (Figure 28c). In most cases total diversity was determined by high diversity contributions rather than differentiation contributions, in line with low within basin divergence.

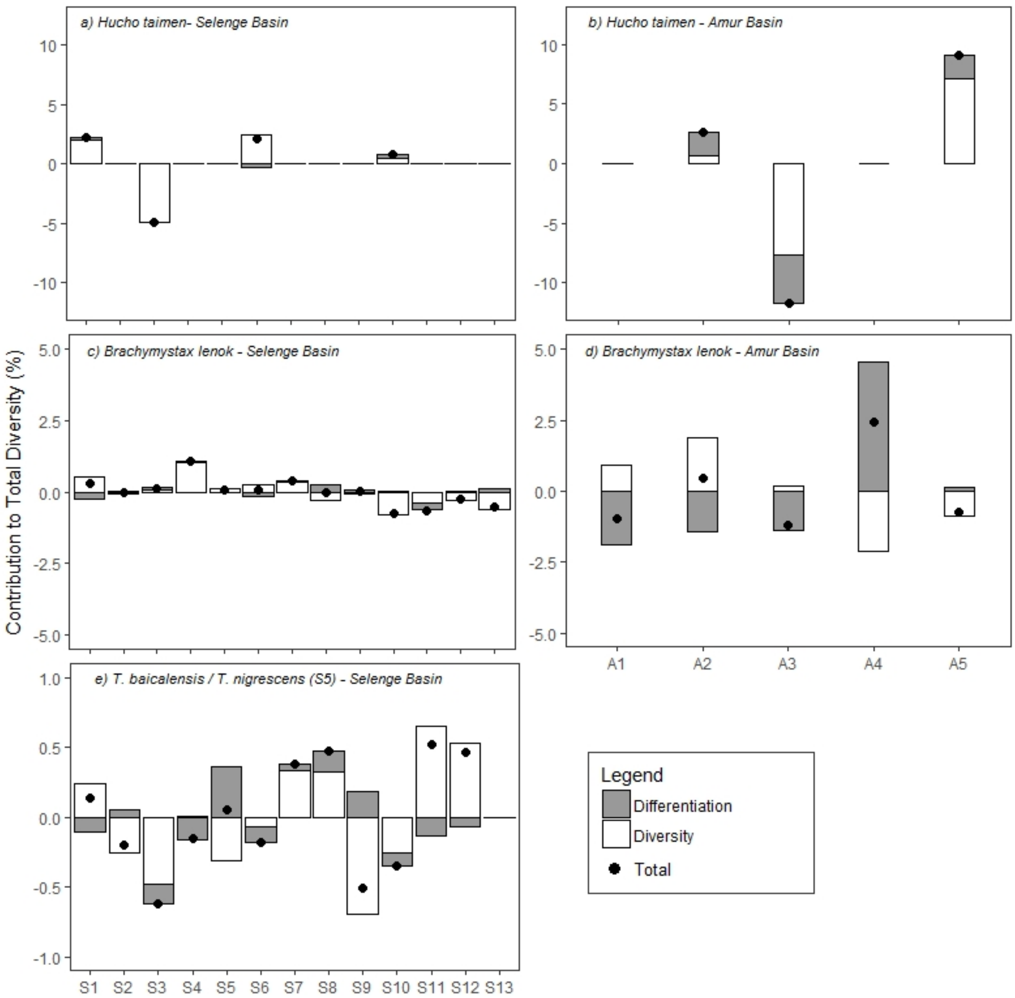

Figure 28. Displays the contribution of each population to total diversity based on allelic richness, thus correcting for unequal sample sizes. This figure contains the sampled populations of *H. taimen* (top), *B. lenok* (excluding the blunt-snouted lenok, *B. sp.*) (Centre) and *T. baicalensis* (bottom, including *T. nigrescens* in S5) from the Selenge (left) and Amur (right) river basins, Mongolia. The black dots indicates total genetic diversity partitioned into the contribution of genetic diversity within the population (white bar) and contribution of genetic differentiation of the population (grey bar). Note that Shishged River (Yenisei basin) populations were not included in the analysis due to their large genetic differentiation from the other Selenge River basin populations.

8.5 Discussion

For three taxa of freshwater salmonids with high conservation concern in Mongolia we found that population structure was primarily segregated between Mongolia's major river basins, although exact patterns were not completely concordant among species. The genetic differentiation was strong among basins but rather weak within basins, with sharp-snouted lenok, the only species to show a clear pattern of within-basin isolation by distance. Furthermore, patterns of diversity and differentiation allowed for the identification of priority populations across rivers, with some rivers important for multiple species. These results can be used to guide conservation and management strategies of threatened salmonid populations across Mongolia.

Genetic population structure and priorities for conservation of H. taimen

The historical distribution of *H. taimen* is vast, extending from the Urals Mountains to the Pacific Ocean; however despite this extensive range only two major phylogeographic groups have previously been identified (Froufe et al., 2005; Maric et al., 2014). Here we showed that the Mongolian populations represent the most upstream extents of these two phylogroups, and should be treated as independent ESUs. The Selenge and Shishged ESU form part of the western phylogroup that consists of the greater Yenisei, Khatanga, Volga and Ob river basin populations, while the Onon and Kherlen ESU is part of the eastern Amur phylogroup together with the Lena basin populations (Froufe et al., 2005; Maric et al., 2014). The broad geographic distribution of these phylogroups, along with the low allelic richness, exhibited by *H. taimen* has been attributed to an historical population bottleneck that has occurred within the species prior to the relatively recent range expansion throughout the region, including into Mongolia during a period of hydrological exchange between river basins (Grosswald, 1998; Froufe et al., 2003). It has been hypothesised that if the population bottleneck occurred after the species range expansion, then multiple genetic lineages would have likely been the result, which is not the case (Froufe et al., 2003). In addition, slow growth, low natural mortality, late maturation and low fecundity, along with the ability of mature *H. taimen* to move and disperse extensive distances particularly during the spawning season (Holčík et al., 1988; Matveyev et al., 1998; Jensen et al., 2007; Kaus et al., 2016b) are also traits that have likely contributed to the minimal genetic diversity found within this species. While, similar patterns of negligible genetic structure across large geographic scales has been observed for other larger bodied, mobile freshwater fish (So et al., 2006; Stepien et al., 2009; Ferreira et al., 2017), for one closely related anadromous species, the Sakhalin taimen (*Parahucho perryi*, Brevoot, 1856), substantial population declines have reduced immigration rates and created pronounced genetic differentiation between hydrologically connected populations (Zhivotovsky et al., 2015). Thus in order to ensure all possible genetic diversity is conserved for this already endangered species across Mongolia, it is imperative that the most genetically diverse populations are urgently protected and that large scale river connectivity is preserved between them so the future evolutionary potential of *H. taimen* is maintained.

While ESUs define management regions of genetically distinct and reproductively independent groups within a species distribution, the identification of priority populations based on elevated genetic diversity and differentiation provides a targeted approach for implementing management strategies within an ESU. Such a directed approach for *H. taimen* conservation and management in Mongolia must therefore start with the Shishged River population and include the four additional priority populations that were identified across the two basins, which include the Delgermoron, Eg-Uur, Khalkhin and Onon rivers. With anecdotal evidence suggesting that these rivers also hold some of the last remaining robust *H. taimen* populations left the country, their complete protection from illegal fishing activities and unsustainable catch and release practices is paramount going forward as these populations likely act as a source of immigrant individuals to the neighbouring sink populations.

Genetic population structure and priorities for conservation for Brachymystax species

The *Brachymystax* genus is distributed from Central Asia to North - East Asia and Siberia, with the literature suggesting there are three putative species including *B. lenok* (sharp-snouted lenok), *B. sp*. (blunt-snouted lenok) and *B. tsinlingensis* (Ma et al., 2007; Froufe et al., 2008; Xing et al., 2015). For the two species found in Mongolia, *B. lenok* and *B. sp*., our genetic analysis revealed a total of four distinct ESUs. We identified three allopatric ESUs belonging to sharp-snouted lenok from the Selenge, the Shishged, and Amur basins, and confirmed blunt-snouted lenok from the Amur as a separate, sympatric ESU. The Selenge ESU formed an exclusive genetic cluster based on mtDNA and nuclear markers which are expected to extend downstream as far as Lake Baikal according to the findings of Froufe et al. (2008). Such genetic divergence can be attributed to the prior isolation of the Selenge basin and Lake Baikal from the Yenisei and Amur basins approximately half a million years ago (Mats et al., 2001). This genetically unique *B. lenok* phylogroup has recently become the focus of increased research on the species including studies on feeding ecology (Olson et al., 2016), thermal tolerances (Hartman & Jensen, 2016), growth in both lotic and lentic systems (Tsogtsaikhan et al., 2017) as well as diel and seasonal movements, depth usage and activity patterns (Chapter 6).

The other two sharp-snouted lenok ESUs in the Shishged and Amur basin displayed no distinction at the mtDNA level but were genetically separated from each other according to nuclear microsatellite markers. Thus together with their geographic isolation, their status as separate ESUs were justified. The shared mtDNA haplotype that was found between these ESUs highlighted the relatively recent divergence of these populations, while supporting the hypothesis of the late Pleistocene hydrological connectivity between the Amur and Yenisei basins (Grosswald, 1998; Froufe et al., 2003, 2008). However, despite this shared haplotype, most of the genetic differentiation for sharp-snouted lenok was distributed among basins (Xia et al., 2006; Froufe et al., 2008; Liu et al., 2011), which indicated large scale, intra-basin gene flow within Mongolia's vast, unfragmented river networks. However, *B. lenok* was the only species to demonstrate isolation by distance within both river basins, which is in line with the expectation of a reduced dispersal ability compared to the larger bodied *H. taimen* (Gilroy et al., 2010; Yoon et al., 2015; Kaus et al., 2016; Chapter 6).

Blunt-snouted lenok has been shown to represent a genuine biological species that has undergone a long, independent evolutionary history (Shed'ko et al., 1996; Froufe et al., 2003; 2008). This is principally confirmed by the current results that demonstrate that the sympatric populations of blunt-snouted and sharp-snouted lenok from the Amur basin are genetically highly divergent. Thus blunt-snouted lenok represents the fourth ESU for the *Brachymystax* genus in Mongolia. However, and in contrast to previous studies, strong evidence was found for nuclear introgression from *B. lenok* into *B. sp.* Although this indicates incomplete reproductive isolation, there was only one first generation hybrid identified in the low number of samples collected, thus suggesting there is a low level of mitochondrial introgression also occurring between these populations in this region. This rarity of mixed ancestry in general indicates that hybridisation is infrequent or was largely an ancient event. Haplotype sharing could principally be also due to shared ancestral polymorphism, but hybridisation appears more likely to be the case, as this is the first such observation reported in these species. Hybridisation between congeneric fish is common and molecular markers are highly suited to test specific hypotheses (Hänfling et al., 2005), however the present data set is too limited to allow for more detailed conclusions. In any case, the blunt-snouted lenok should be formally recognized on an updated official species list of Mongolian fishes and be further afforded comprehensive protection to prevent this already rare and fragmented species from declining further or becoming regionally extinct. Our results also rekindles the discussion regarding the species status and correct taxonomic classification for the blunt-snouted lenok as the previously used scientific names including *B. tumensis* and *B. savinovi* have since been revealed to be misidentifications of sharp-snouted lenok in the

Tumen River (China / North Korea) and Lake Markakol (Kazakhstan) respectively (Alekseev & Osinov, 2006; Ma et al., 2007). Consequently these names are regarded as invalid and thus a new scientific name for the blunt-snouted lenok in the Amur basin should be assigned (Ma et al., 2007; Froufe et al., 2008).

The priority populations for conservation within the *Brachymystax* genus not only includes the sharp-snouted lenok ESU from the Shishged and the blunt-snouted lenok ESU from the Amur, but also an additional six sharp-snouted lenok populations identified within the Selenge and Amur basins. With both of these basins being extensively sampled, including all major rivers, it was obvious that the overall genetic differentiation of this species in Mongolia was low. It was only the Kherlen population that displayed substantial genetic differentiation compared to the other basin populations and thus should be earmarked for additional protection measures, particularly as the Kherlen River upper reaches are a popular fishing destination for a growing number of Ulaanbaatar residents due to its close proximity and easy access from the capital.

Genetic population structure and priorities for conservation of Thymallus species

Although the genus *Thymallus* is widely distributed across Eurasia, this taxon often shows divergence on an intra basin scale such as *T. svetovidovi* in the upper Yenisei River basin (Knizhin & Weiss, 2009) and *T. burejenis* from the Bureya River, lower Amur River basin (Anton, 2004). This genetic divergence has been attributed to strong natal homing tendencies and poor dispersal abilities that are characteristic of the genus (Koskinen et al., 2002; Weiss et al., 2002; Froufe et al. 2005). In contrast, *Thymallus* populations from the Selenge showed no clear evidence of genetic structure among populations as far apart as almost 2000 km and should therefore be considered a single *T. baicalensis* ESU within Mongolia. This finding then has implications for the species status of the sampled *T. nigrescens* from Lake Hovsgol. While some authors still recognise it as an independent species based on both morphological and biological indices including the number of gill rakers and pyloric caeca (Berg, 1962; Pivnička & Hensel, 1978; Bogutskaya & Naseka, 2004), other authorities have expressed the need for additional analyses or have already outright disregarded *T. nigrescens* as its own species (Koskinen et al., 2002; Knizhin et al., 2006; Weiss et al., 2007). The result from the current research supports the opinion that *T. nigrescens* is not genetically distinct from the other grayling populations across the Selenge basin, and is therefore a synonym of *T. baicalensis*. Our nuclear marker analysis revealed the lack of genetic distinction between *T. nigrescens* and *T. baicalensis,* which suggests there is a significant amount of gene flow between these groups, or else it has ceased only recently. As both forms are present in Lake Hovsgol (Tsogtsaikhan et al., 2017), it is likely that these represent two different ecotypes of the same species as is found in many lake dwelling salmonids including lake trout (*Salvelinus namaycush*), Arctic charr (*Salvelinus alpinus*) and coregonids (*Coregonus clupeaformis*) (Moore et al., 2014; Laporte et al., 2016; Perreault-Payette et al., 2017). The morphological differences displayed by individuals that inhabit Lake Hovsgol, including significant differences in the length-weight and age-length relationships compared to *T. baicalensis* populations (Tsogtsaikhan et al., 2017), are likely due to the high ecological flexibility and phenotypic plasticity of this genus, which has also caused confusion previously between intraspecific forms in Lake Baikal (*i.e.* black and white Baikal graylings, Knizhin et al., 2006). Thus Lake Hovsgol individuals should still be recognised as a unique population that is under significant threat and be afforded adequate conservation and protection efforts to mitigate the growing impacts of overfishing, pollution and climate change that are currently impacting this ancient lake system (Ahrenstorff et al., 2012; Free et al., 2016).

For *T. baicalensis,* only minimal differences in the genetic diversity and differentiation contributions were detected within the Selenge ESU. However, six populations contributed an above average genetic diversity, with the Zelter and Huder, and Orkhon and Tuul appearing to share the same genetic contribution of the total diversity percentage for each population. This is likely due to the close geographic location of the river confluences that allows for regular movement and genetic exchange between these river populations. The contrib analysis and the pairwise Fst values also identified the grayling from Lake Hovsgol as being the most genetically differentiated from the other grayling populations, thus confirming the genetic importance of the Lake Hovsgol population and justifying its status as a priority population within the *T. baicalensis* ESU.

Patterns across species and implications for broader conservation strategies

Based on genetic markers we identified ESUs and priority populations for three salmonid taxa across Mongolia. While the ESUs for both *H. taimen* and *B. lenok* included their major phylogeographic linages, the ESU for *T. baicalensis* incorporated a considerable region of the species total distribution. The most prominent genetic structure identified in this study existed between river basins, although there was not complete concordance among species, likely due to both biological and ecological differences with regards to natal homing tendencies, home range sizes and individual mobility. The paleogeography of these extensive river systems appears to have been the dominant influence on the genetic structure of these species, with the isolation of the Selenge / Baikal basin creating a separate phylogroup of sharp-snouted lenok, as well as the genetically distinct *T. baicalensis* species. The ancient hydrological connectivity between the Yenisei and Amur basins has also resulted in shared genetic material between sharp-snouted lenok populations in these currently disjunct basins.

The identification of genetically important priority populations within each ESU can now provide a focused approach for fisheries management and conservation efforts in Mongolia. Protection of the most genetically diverse and differentiated populations is critical, especially as all species investigated already displayed a remarkable lack of genetic structure across their Mongolian range. Thus as these priority populations retain the highest potential for evolutionary adaptations within each ESU, ensuring they are sufficiently protected will better facilitate their survival amid future environmental perturbations, which is expected with the imminent onset of climate change. A preliminary conservation strategy for Mongolian salmonids may be to link priority population protection across species in order to maximise the resources available for management. Therefore, the Shishged, Delgermoron, Orkhon, Tuul and Onon rivers were each deemed important for two or even three of the species investigated and thus these regions should be made the focus of initial conservation efforts along with Lake Hovsgol and the Kherlen River. If fully protected, the local fish population densities are likely to also increase with a higher number of individuals then being able to emigrate to nearby sink populations over time. This is particularly critical as both the Selenge and Amur rivers are transboundary drainages and downstream populations of each of these species are reportedly facing even greater existential threats than they are in Mongolia (Kuang et al., 2010; Zolotukhin, 2013).

In order to achieve adequate species conservation in Mongolia, it is recommended to establish a network of spatial protected areas throughout the country that focus on specific rivers where priority populations have been identified. Such FPAs have been successfully implemented in many regions around the world to conserve genetic diversity and aid in the preservation and recovery of threatened and exploited fish populations (Abell et al., 2007; Suski & Cooke, 2007). These FPAs must encompass a range of important fish habitats (*e.g.* spawning tributaries and overwintering pools) in each river system and should consist of both total protected zones in the most ecologically important regions where all fishing activities are prohibited and strict catch and release only zones where each species can only be caught using single barbless hooks during the normal fishing period, with all individuals being released unharmed. The purpose behind having specific catch and release only zones is to provide a financial incentive for local communities to accept the conservation and protection plan as they would benefit from the increased business from anglers coming to their region to shop for food or stay before or after their fishing trips. In addition, any implemented FPA should also contain a buffer zone along the river's edge where logging, mining and grazing are forbidden so habitat quality and river connectivity can be maintained.

Conclusions

Attaining a detailed knowledge of the genetic structure and diversity of the main target species in Mongolia's emerging recreational fishery will help guide necessary improvements and develop a more comprehensive national fisheries conservation and management strategy. This information is particularly important at this time with widespread anthropogenic pressures increasingly threatening the resident fish communities and impacting the rivers and lakes they inhabit, both throughout Mongolia and further downstream in the Russian and Chinese reaches. By acting promptly and incorporating this new genetic information into existing action plans, authorities can prevent further losses of genetic diversity by better protecting the most genetically valuable salmonid populations that have now been identified. In addition, translocations or introductions of genetically dissimilar individuals can be avoided and inbreeding minimized within fragmented populations (Hänfling et al., 2004; Hänfling & Weetman, 2006; Balakirev et al., 2014; Slynko et al., 2015; McDougall et al., 2017).

DISCUSSION

9 Solutions for Sustainable Fisheries in Mongolia

9.1 Overview and Linkages of Key Research Findings

In order to gain a more complete and detailed understanding of Mongolia's emerging recreational fishery, roving creel surveys were conducted in three river basins known to be popular fishing locations with anglers. The main findings highlighted two angler types in the fishery, a rural angler predominant in the Kharaa and Onon river basins and an urban angler predominant in the Eroo River basin. These two angler types displayed significant differences in several important details including fishing group sizes, number of annual fishing trips and economic expenditure, while they were not significantly different in other aspects such as targeted and captured species, size of *B. lenok* caught (main species caught across all basins) and CPUE. The survey results also suggested fishing pressure (median number of annual fishing days) was not significantly different between the river basins, even though the Kharaa is in close proximity to Darkhan and Ulaanbaatar, while the Eroo and Onon river basins are more remote and less accessable to many anglers (**Hypothesis I = False**). Furthermore, while a substantial number of anglers said they did know the fishing regulations, a considerable number still didn't or were unsure of them, especially in the KRB (**Hypothesis II = True).** Thus there remains a large proportion of active anglers, across all three basins, who are fishing frequently but are still unaware of the current fishing regulations. This lack of knowledge and education is likely a major contributor to the occurence of illegal fishing activities which has been witnessed by more than half (56 %) of all fishing groups surveyed.

While the creel surveys indicated that fish consumption across the three basins was generally low, almost half of respondents in the KRB were still frequent consumers of locally caught species, including one retired couple who ate fish almost daily during the ice free period. Thus the potential human health risks associated with the regular consumption of contaminated fish due to the heavy metal contamination at numerous 'hotspot' locations in the basin raised serious concerns. The ensuing sampling program of five consumed fish species revealed elevated muscle contents of Cr, As, Hg and Pb in individuals caught from the middle and lower river reaches, while there was elevated Zn in *B. lenok* collected from the upper tributaries. Maximum median muscle contents of Cr, Cu, Pb and Hg increased in the higher trophic level species (**Hypothesis III = True).** Hg posed the most serious risk, with 10.7 % of all fish sampled exceeding the internationally recommended threshold for this toxic heavy metal in fish tissue for human consumption, however direct intervention such as restrictions of fish consumption was not immediately warranted (**Hypothesis IV = False**).

Creel surveys also confirmed *H. taimen*, *B. lenok* and *T. baicalensis* as the three most targeted and captured species in the emerging recreational fishery, with each having already suffered from widespread population declines across Mongolia (Ocock et al., 2006). Thus filling critical knowledge gaps regarding their spatial ecology and genetic population structure was essential to help not only improve the ecological understanding of these threatened species, but also enhance and guide management strategies and decisions in the future. The autecology of *H. taimen* and *B. lenok* was investigated using passive acoustic telemetry in order to identify periods of heightened movements, shifts in habitat usage, seasonal behaviours and home range sizes in a highly-connected river system. The most extensive distances moved by a tagged individual was 126.1 km for *H. taimen* and 45.3 km for *B. lenok*, with the home range for *B. lenok* being significantly larger than had been previously reported for a species in this genus (**Hypothesis V = True**). *B. lenok* also displayed increased activity at a greater depth during the day and were less active in shallower habitats during the night across all seasons (**Hypothesis VI = True for activity / False for depth**). Both *H. taimen* and *B. lenok* displayed peak movements in late spring and early summer during the reproductive period, while a second less pronounced concentration of movements were detected in late summer and early autumn (**Hypothesis VII = True**). However, not all tagged *H. taimen* descended the Balj tributary during the cooling period to overwinter in the Onon River, but instead remained during the entire ice coverage in the smaller Balj tributary (**Hypothesis VIII = False**). In addition, and quite concerningly, the majority of *B. lenok* in the Eroo River basin undertook spawning movements in late June, after the opening fishing season start date, which would expose a significant proportion of the spawning population to increased fishing pressure during their critical reproductive period.

In addition, the interconnectedness of conspecific populations, together with the genetic diversity of *H. taimen*, *B. lenok* and *T. baicalensis* in Mongolia were investigated. Both nuclear and mitochondrial genetic markers were used to demarcate species specific ESUs which formed separate haplotype clusters that mirrored the major river basins (Selenge and Amur). These results demonstrated an overall low genetic diversity between populations of the same species and thus indicated large scale, intra-basin gene flow and connectivity (**Hypothesis IX = True**). All species displayed large spatial scale genetic homogeneity irrespective of their body size, with only *B. lenok* displaying increased isolation by distance (**Hypothesis X = False**). Priority populations were also identified within each ESU, which were found to contribute an above average genetic diversity and differentiation across their Mongolian distributions and thus are deserving of more management resources and enhanced protection.

Table 9. Overview of the major recommendations discussed in the following pages for improving the management and conservation strategies for *H. taimen*, *B. lenok* and *T. baicalensis* populations across Mongolia, while further enhancing the sustainability of the emerging recreational fishery.

Recommendations	Potential Benefits / Outcomes	Sub-Section
1. Establishing additional FPAs (Freshwater Protected Areas)	Mitigating the impacts from both current and future threats including illegal fishing, overexploitation, water pollution, overgrazing, mining, dam construction and climate change. **Based on acoustic and genetic data.**	9.2
2. Shifting Open Fishing Season Start Dates	Better protection for resident *B. lenok* populations from fishing activities being conducted during their critical spawning period. **Based on acoustic telemetry tracking of *B. lenok* in the Eroo River.**	9.3
3. New Prohibited Species – blunt-snouted lenok (*B.* sp)	Molecular research has illustrated that the blunt-snouted lenok is a genetically distinct species in Mongolia. The species' restricted distribution and fragmented populations demands increased protection. **Based on genetic data.**	9.3
4. Species Specific Minimum (& Maximum) Size Limits	Protecting immature individuals will increase the resilience of fish stocks to current and future fishing pressure by ensuring all fish spawn at least once before they can be legally removed. **Based on biomentric data collected for biocontamination work.**	9.3
5. Biomonitoring Program	Biomonitoring heavy metal contents using bioindicator species can help to mitigate human health risks associated with fish consumption, while lessening the number of threatened species that need to be sacrificed. **Based on biocontamination work**.	9.4
6. Widespread and Comprehensive Angler Education Programs	Improving angler knowledge of fisheries regulations can increase compliance; help drive shifts in long held bad habits, and can create a sense of community responsibility for a specific river and fish population. **Based on creel survey results.**	9.5
7. Including Fish Passages / Environmental Flows	Reduce impacts of proposed dams on threatened fish populations by allowing movements to spawn and find thermal refuge, maintain gene flow and retain some ecological processes. **Based on acoustic and genetic data.**	9.6
8. Fisheries Dependent & Independent Assessments	Guide management decisions based on changes in fishing pressure, evaluating the effectiveness of newly implemented management tools, track regional fish population abundances / recruitment, and identify overfishing. **Improving management.**	9.9
9. Merging Fish Ecology & Water Resource Management Plans	Improved ecosystem functioning, increased fisheries production and health, preserving water security for human requirements. **Improving management.**	9.9
10. Improving Transboundary Coodination of Fisheries	ESUs could be managed as a single entity over international boundaries, incongruent domestic policies streamlined, better fight illegal fishing and cross border trading, maintaining river connectivity on a meaningful scale. **Improving management.**	9.9

9.2 Freshwater Fish Conservation in a Transitional Society

The continued growth of human populations, urbanisation and per capita consumption has ultimately resulted in the unsustainable exploitation of the Earth's biodiversity (Adams et al., 2004; Rands et al., 2010). These losses have been accelerated in many developing and transitional countries due to the unwavering desire of governments to reach national growth targets and endemic corruption, which has often inhibited conservation efforts (Peh & Drori, 2010). However, the creation of a global network of protected areas has proven to be one of the more effective solutions for reversing these trends (Bruner et al., 2001; Saunders et al., 2002). With terrestrial and marine environments commonly designated protected areas, freshwater habitats have usually only been incidentally protected as part of their inclusion within terrestrial reserves (Skelton et al., 1995; Abell et al., 2007). Thus a greater number of protected areas, which specifically target critical freshwater habitats, are urgently needed in order to stem the loss of aquatic biodiversity (Saunders et al., 2002). Establishing a series of FPAs in a transitional society such as Mongolia may provide the greatest benefits for the threatened fish populations.

Establishing Freshwater Protected Areas across Mongolia

Although 17.4 % of Mongolia's total territory already falls under protective legislation (Appendix 5), it has been described as ecologically inadequate both in terms of size and inclusion of suitable ecosystems as both riparian and riverine habitats currently have a very low representation (UNDP, 2017a). Thus with an ultimate target set by the government of achieving 30 % protective area coverage by 2020 (UNDP, 2017b), there is potential for increasing the protection of Mongolia's unique river ecosystems in the near future. Implementing a series of FPAs across the Selenge, Amur and Central Asian river basins is highly recommended and urgently needed for protecting targeted fish species and critical habitats, and ultimately improving the sustainability of the emerging recreational fishery (Abell et al., 2007). Currently the low number of Strictly Protected Areas are the only places in the country that prohibit all fishing activities, as fishing still occurs in Mongolia's National Parks (Appendix 5). Thus major rivers such as the Kherlen, Orkhon, Kharaa, Chuuluut, Ider and Eg-Urr have zero spatial protection, while many others have only minimal areas that are currently protected *e.g.* Eroo, DelgerMoron and Khalkhin.

The effective design and placement of an FPA is central to its long-term success, but in any case, it should ensure the longitudinal continuity of the river, maintain the hydrological connectivity of its tributaries, preserve a considerable strip of the riparian vegetation and completely prohibit development, mining, logging and fishing mortality (Saunders et al., 2002). However, strict catch and release fishing can still be allowed in certain areas to maintain economic incentives. While larger FPAs encompassing entire river basins or extensive river reaches would generally be more conducive to conservation objectives, they are typically seen as less feasible by authorities. Thus smaller-scale intra-basin FPAs are proposed for Mongolia, which could protect specific river reaches or tributaries. Although the general location of any new FPA should reflect the priority populations for each of these species that has been identified in Chapter 8 (Figure 27), the exact sites would need to be selected following a detailed habitat assessment to identify suitable intact habitats. The specific size of such an FPA would likely vary with the local topography and surrounding human footprint, however, a meaningful minimum size should encompass the median longitudinal movements detected in the acoustic telemetry research for both *H. taimen* (27.7 km) and *B. lenok* (19.1 km; Chapters 6 & 7). While two *H. taimen* sanctuaries have already been established in Mongolia in collaboration between international fly fishing outfitters, NGO's and local fishing clubs, several more are still urgently needed throughout the country, specifically in the Eg-Urr and Kherlen rivers which currently have no protection and are facing a substantial threat.

9.3 Addressing Management Shortfalls to Curb Intensifying Fishing Activities

Shifting the Open Fishing Season Start Dates

Closed fishing seasons are a key management tool to protect exploited populations from fishing pressure during their critical spawning periods. However, in Mongolia, the dates of the closed season have been based on only one species, *H. taimen*, as the Ministry of Nature and Environment have set the opening date as the latest reported spawning of *H. taimen* in Mongolia *i.e*. the 15th of June in the Darkhad Depression (Vander Zanden et al., 2007). Although a focus on *H. taimen* is justifiable and highly beneficial to the protection of this endangered species, giving little or no consideration for the specific spawning periods of other heavily targeted and threatened species, such as *B. lenok*, may be inadvertently exposing these vulnerable populations to an increased risk of overexploitation. Such a potential situation has become evident during the acoustic telemetry research that was conducted on *B. lenok* in the Eroo River (Chapter 6), as two specific dates of increased upstream movements were found to occur following the river ice break up. While some movements were detected shortly before the 15th of June (the opening date of the fishing season), the second and more predominant period of concentrated movements occurred several days after the 15th of June. Although data is only available for a single population in a single year, if the spawning period for *B. lenok* regularly occurs after the start of the opening fishing season each year, then a high proportion of the spawning stock are being exposed to the large influx of anglers that arrive at their favourite fishing location on the 16th of June. Therefore if *B. lenok* spawning dates can be confirmed as occurring after the 15th of June in other regions and years, then authorities need to extend the opening date by 7 to 10 days in order to better protect *B. lenok* populations from further declines.

In addition, there have been calls to implement a staggered opening fishing season across Mongolia, where fishing could begin before the 15th of June in certain regions. The proposal is based on computer modelling of climate data that predicted *H. taimen* commence spawning in river reaches that have a lower elevation and thus surface water temperatures that increase to 6 – 8 ˚C (the temperature range that triggers *H. taimen* spawning; Holćík et al., 1988) a few weeks earlier (20th of May) than in rivers that are at higher elevations and consequently *H. taimen* spawning later (15th of June; Vander Zanden et al., 2007). By rolling back the 'over-protective' start date in those lower elevation rivers, the authors argue that international fishing companies can conduct more catch and release expeditions each year and in turn provide increased conservation benefits for *H. taimen* (Vander Zanden et al., 2007). Although such a proposal may be justifiable in terms of conservation, this plan, once again, is only focused on a single species and seems to not have considered the impacts that would be associated with recreational fishing being conducted during the critical spawning periods of other threatened species, which would be incidentally caught while targeting *H. taimen*. Furthermore, the proposal is based on modelled results with no validation of *H. taimen* spawning behaviour in the rivers where a roll back start date is recommended. However with the current research results of *H. taimen* movements in the Onon / Balj (Chapter 7), a region where Vander Zanden et al., (2007) recommended a rollback start date of the 20th of May, upstream movements that are likely associated with spawning behaviour were still detected in individual fish after this date and well into June. While there were only a few individuals that demonstrated these movements during the study, it generates some doubts over such a proposed rollback plan across Mongolia, especially as the anticipated Eroo River start date was also suggested to be the 20th of May, which falls well before *B. lenok* spawning activities that were detected in the basin (Chapter 6). Thus, it is recommended that no such open fishing season start date rollback be implemented anywhere in Mongolia, especially not before specific spawning dates, for both *H. taimen* and *B. lenok*, are confirmed in the proposed rollback rivers.

New Prohibited Species – blunt-snouted lenok (B. sp.)

The 2012 federal legislative amendment to prohibit the intentional killing of *H. taimen* in Mongolia was a landmark decision by authorities to help promote population recovery of this endangered species across the country. However, recent research and observations suggest that an additional targeted and commonly misidentified salmonid should also be afforded total protection status in order to prevent population declines and potential expiration in the future. Blunt-snouted lenok (*B*. sp.) populations in Mongolia have a geographically restricted distribution that is limited to the Onon and Kherlen river basins where they reside in small, fragmented populations but are still captured and retained by local anglers (Froufe et al., 2008; *pers. observs*). As the blunt-snout lenok has been considered an interspecific form of *B. lenok* in the past, it has not been included on the Mongolian Red List of Fishes (2006). However, the recent molecular research focused on the Mongolian populations (Chapter 8), has demonstrated that the blunt-snouted lenok is not just a morphologically different form but a genetically distinct and independent species as well, which lives in sympatry with *B. lenok*. Thus the blunt-snout lenok should be formally recognised as a separate species in Mongolian waters and correctly re-described and added to the official list of Mongolian fishes. This species should then be afforded a formal population assessment within the country, which would likely see it included onto an updated Mongolian Red List of Fishes with an assigned category relating to its suspected threatened status *i.e. endangered*.

Introduction of Species Specific Minimum (& Maximum) Size Limits

A further proposal to enhance the sustainability of Mongolia's recreational fishery is the introduction of species-specific size limits. This management tool is commonly used in many countries around the world in an attempt to control the size and thus the age of individual fish that are captured and killed legally within a fishery. The strategy is based on the theory that if the limit is set above the size (TL) at first maturity, then an accepted proportion of the population should have had a chance to spawn at least once and contribute to the next generation before they can be removed. As *B. lenok* and *T. baicalensis* make up a considerable proportion of the total surveyed catch within Mongolia's emerging recreational fishery (Chapter 4), these two species are considered to be at most risk of being captured before they have reached maturity. Both *B. lenok* and *T. baicalensis* have been reported to reach maturation between 3 and 6 years of age or approximately 18 and 48 cm TL for *B. lenok,* and 22 and 33 cm TL for *T. baicalensis* (Froufe et al,. 2003; Tsogtsaikhan et al., 2017). Therefore, based on the limited published data and the preliminary age-length and maturity investigations of both species in the Kharaa and Eroo river basins (Appendix 6b and 6c), potential minimum size limits were calculated. If complete protection (100 %) of all immature individuals was deemed to be warranted by authorities then a minimum size limit of 48 cm TL for *B. lenok* and 33 cm TL for *T. baicalensis* could be set. However, if this was the case, then according to the catch data from the creel surveys (Chapter 4) very few individuals could have been legally retained. However, managers are generally required to make concessions and agree to accept a lower percentage of protection for the spawning population. Therefore, in order to maintain the fishery, while protecting a significant proportion of the spawning stock, potential minimum size limits of 34 cm TL for *B. lenok* and 25 cm TL for *T. baicalensis* could be implemented (Appendix 6b and 6c). These limits would mean that two-thirds (66 %) of all captured and killed individuals reported from the creel surveys (Chapter 4) would have had the chance of reaching sexual maturity and have potentially spawned at least once before being retained legally. The implementation of these minimum size limits would mean approximately half of all current *B. lenok* catches across the country would need to be returned as the mean length of caught individuals was 34.18 cm TL. However, the mean length of caught *T. baicalensis* individuals was only 21.79 cm TL, which is substantially lower than the proposed limit of 25 cm TL. The introduction of minimum size limits for the two most commonly caught species in Mongolia would go a long way to increasing the resilience of these populations to both current and future fishing pressure by maintaining a higher spawning stock biomass as long as all undersize fish are returned to the river and survive.

The implementation of a maximum size limit for both *B. lenok* and *T. baicalensis* would also be hugely beneficial to protect the older larger individuals within the population, as larger fish are generally known to produce an exponentially higher number of eggs and increased larval quality than younger, smaller but still mature individuals (Wootton, 1998; Berkeley et al., 2004; Arlinghaus et al., 2010). Thus protecting highly fecund larger fish could represent a powerful strategy for managing fisheries sustainability (Gwinn et al., 2015). Although detailed data is currently not available, a maximum size limit for *B. lenok* would likely be around the mid to high 40's cm TL, while for *T. baicalensis* a maximum size limit would likely be around the mid to high 30's cm TL.

9.4 Biomonitoring to Mitigate Human Health Risks

Bioindicator Species

In addition to the proposed fishery dependent and independent monitoring in Mongolia, there is also an urgent need to establish a meaningful biomonitoring program that is focused on quantifying the heavy metal contents in consumed fish species from contaminated river basins (Chapter 5). As was identified in the KRB, heavy metal biocontamination, specifically Hg, was detected in several fish species and could potentially pose a human health risk as fish catch and consumption rates increase across the country (Chapter 4). While the total heavy metal concentrations in environmental media (*e.g.* water and sediment) can indicate the relative degree and extent of the contamination, they do not reflect the level of exposure faced by the resident aquatic fauna (Cain et al., 2000) or species further up the food chain, including humans. Therefore, studies involving aquatic organisms identify the bioavailability of contaminate in the ecosystem and can subsequently help determine the true level and impact of the contamination (Costa & Hartz, 2009). Resident aquatic species that accumulate heavy metals from the surrounding environment, in a representative way, make ideal bioindicators and thus can be used to monitor the contamination trends over an extended period of time without the need to sacrifice high numbers of targeted or threatened species. The proven suitability of selected bioindicator species is essential to the success of such important programs. The stone loach, *Barbatula* spp. (Balitoridae), is a potential suitable candidate as a bioindicator species in the Selenge River basin. It is common and widely distributed, small in size, inhabits even the smallest tributaries, is benthic and thus closely associated with the substrate (Boscher et al., 2010) and is expected to have a restricted home range so would represent the local conditions. While the suitability of *Barbatula* spp. as a heavy metal bioindicator requires confirmation under local conditions, implementing such a biomonitoring program in specific hotspot areas is crucial for avoiding more potentially serious human health issues in the future.

9.5 Improving Angler Compliance with Increased Education

Illegal fishing is a major problem for many recreational fisheries around the globe, with the impacts of these activities potentially accumulating to a point where they can render desired management and conservation outcomes ineffective (Pinder et al., 2014; Chen et al., 2017). Thus high levels of angler compliance and enforcement of regulations are critical for safeguarding the sustainability of exploited fish stocks. However, in countries and regions where personnel and resources for implementing adequate enforcement measures are limited, increasing angler awareness through community education programs may be one of the best ways to mitigate the number of potential offenders (Granek et al., 2008). This description reflects the current situation in Mongolia as the emerging recreational fishery is under managed, under resourced and thus illegal fishing activities have been allowed to largely continue in impunity. Therefore a comprehensive angler awareness and education program could provide, at least, part of the solution.

Creel surveys not only revealed the widespread occurrence of illegal fishing activities within the three river basins but also the lack of knowledge among anglers regarding the Mongolian fishing laws (Chapter 4). Thus as a first step to try and improve compliance within the fishery, it was clear that increased numbers of anglers needed to be made aware or reminded of these regulations and the science behind them, and the associated fines for breaching them. This task was initiated during the current body of research and in collaboration with the World Wildlife Fund (WWF) Mongolia, where informative pamphlets were distributed to anglers and posters were provided to rangers and gatehouse officers close to popular fishing locations (Appendix 7). These materials highlighted the existing fishing laws and fines, as well as additional recommendations such as proposed minimum size limits, best practice methods for handling and releasing *H. taimen* and various other conservation concerns that had been observed during the extensive time spent in the region. This advice related to the use of soaps and detergents in the river, discarding rubbish during camping trips and throwing away cigarette filters. While only a preliminary project, it was planned that this material will continue to be distributed by WWF employees within their existing community outreach work in an attempt to make a more lasting impact.

In order to make further inroads towards creating a lasting legacy of compliant behaviour and more sustainable fishing practices among Mongolian anglers, a comprehensive community engagement project is essential. Any efforts should not only focus efforts on rural anglers that reside in the Onon or Kharaa river basins, but also urban anglers in Ulaanbaatar, as they have been revealed to be responsible for a significant part of the increasing fishing pressure in the more remote, and thus pristine, river reachers (Chapter 4). As has already been successful in the Onon River basin, fishing clubs should be created across other Mongolian river basins that experience considerable fishing pressure, including an urban chapter in Ulaanbaatar. Regular fishing club meetings could provide an avenue to train and support anglers to increasingly adopt catch and release practices, while also providing a platform to install compliance for the existing and new fishing regulations recommended in this thesis. Such a community project could work to create a sense of ownership and responsibility for a specific region, in addition to helping drive a shift in long held environmentally unfriendly habits (Cooke et al., 2013; Freed et al., 2016).

9.6 Preserving Hydrological Connectivity and River Integrity in the Face of Imminent Threats

As hydroelectric dam construction on the Selenge, Orkhon and Eg (Egiin) rivers in Mongolia wait for final approval, the government remains eager to increase its power production and meet the rising demands of urbanisation and the powerful mining sector (Rapoza, 2017). However, the extensive environmental impacts that such dams typically inflict on the river continuum, including ecological processes, regional habitats and aquatic communities are often widespread and long lasting (Morita et al., 2009). Dam construction is one of the major causes of fish population declines (Dudgeon et al., 2006; Vörösmarty et al., 2010); especially for many riverine species that move large distances between spatially distinct habitats to complete their life cycles (Liermann et al., 2012). Thus the impacts of dam construction on Mongolian river basins will add substantial pressure to the already threatened *H. taimen*, *B. lenok* and *T. bacicalensis* populations (Chapter 6, 7 & 8). If these dams are constructed, then it is imperative that all necessary measures are taken to mitigate their ecological effects.

Fish Passages

Fish passages including ladders, lifts and ramps, are incorporated in, or added on, to river barriers such as dams and weirs so migrating species can move past these obstacles and access critical habitats to complete their life cycles (Agostinho et al., 2002). In a recent workshop that focused on the Eg River dam construction, a trap-and-transport method was proposed as a viable option to facilitate both up and downstream fish movements past the planned 90 m high dam wall (FAO, 2015). This method would involve trapping migrating individuals in a chamber at the bottom of the dam and periodically transporting them via truck more than 60 km upstream to a free-flowing river reach to be released. However such a proposal would likely only provide minimal success as a number of potential limitations appear to exist. These include the duration and frequency of the upstream fish release trips, increased fish stress during transportation, water quality issues in the transport chamber and the potential for increased predation during the extended time in a limited space. There is also likely to be problems in maintaining funding for the continuation of such a program over the life of the dam (decades). Thus more suitable options for fish passages may include an automatic vertical fish lift or an extensive fish bypass channel around the dam wall, although even these methods are likely limited with such a large dam height. They do however; present alternative options for inclusion on other smaller dams constructed in Mongolia. For the Eg River dam, the best solution in terms of fisheries management, conservation and sustainability would be to not build the dam at all. Authorities should first exhaust all other renewable energy options that could be capable of increasing power demands, before constructing a dam that would undoubtedly have a severe impact on the health of the Eg River, one of the few remaining Mongolian rivers with robust *H. taimen* populations (Jensen et al. 2009).

Implementing Environmental Flows

The implementation of a suitable environmental flows regime as part of a dam's management procedure would be crucial to the survival of local fish populations. Environmental flows are a relatively new concept that are aimed at mitigating the ecological impacts of a dam by intentionally releasing water in a way that mimics the river's natural flow variability in terms of magnitude, frequency, timing, duration, rate of change and predictability (Arthington et al., 2006; Olden & Naiman, 2010). Dammed rivers without appropriate environmental flows suffer from a myriad of changes with regards to the quality and quantity of water available downstream, reduction of sediment transportation and nutrient input, and loss of aquatic habitat and biodiversity (Ligon et al., 1995; Kingsford, 2000). For many riverine fish species, the extent and timing of river discharge, along with water temperature, can trigger key movements and behaviours such as the timing of spawning runs.

Thus a major transformation or the complete loss of the natural flow regime can have significant impacts on river dynamics as well as fish populations (Bunn & Arthington, 2002). Appropriate environmental water releases can also help to maintain hydrological connectivity during low flows, which is increasingly important considering the expected impacts of climate change, which include lower annual rainfall, increased air temperatures and elevated evapotranspiration across the region (Batimaa, 2006; Bardach et al., 2009; Preiss et al., 2011; Karthe et al., 2014). While environmental flows, in conjunction with suitable fish passages, can help to lower the overall impact of dam construction on freshwater communities, by no means can these measures completely replicate all of the lost benefits of an unimpacted, free-flowing ecosystem and thus should in no way been seen as justification for dam construction. The inclusion of appropriate fish passages and environmental flows within the management of any proposed hydroelectric dam in Mongolia is highly recommended, and should be legally mandated if dam construction is deemed to be unavoidable.

Climate Change Impacts

Alteration of stream thermal regimes is likely to be one of the most important environmental changes that aquatic organisms experience, given the strong control that temperature has on distribution, abundance, growth, and population persistence (Isaak et al., 2010). Already in northern Mongolia, air temperatures are increasing three times faster than the rest of the northern hemisphere and thus resident fish populations, including *B. lenok* and *T. baicalensis*, are currently experiencing water temperatures close to their upper levels for normal growth during the summer months (Hartman & Jensen, 2016). With a further 2˚C rise in mean temperatures, *B. lenok* would experience a reduction in growth of 59 %, while *T. baicalensis* would suffer from a complete inability to grow (if food levels remain unchanged; Hartman & Jensen, 2016). Thus these imminent climate change impacts pose a significant threat to Mongolia's fish populations, particularly the more thermally sensitive salmonid species (Rieman et al., 2007). As well as impacts on individual growth, there will likely be large scale distributional shifts as well as an increased loss of suitable habitat including critical spawning and early juvenile rearing sites in the colder headwaters (Isaak et al., 2010). Therefore, along with the need to maintain riparian vegetation via FPAs, which can strongly influence near-stream microclimates (Moore et al. 2005), and preserving natural river flows *e.g*. minimising dam constructions, authorities need to conserve the highest genetic potential for evolutionary adaptations which can better facilitate population survival amid these future environmental perturbations (Chapter 8). Steps need to be taken to ensure as many priority populations (those that have been identified to have above average genetic diversity or differentiation) as possible are protected across Mongolia (refer to Figure 27).

9.7 Management Avoidances

Stocking Programs

In freshwater recreational fisheries, often the default action by managers when stocks have become depleted (either perceived or actual) has been to supplement the wild population through a stocking program of artificially produced conspecifics (Cooke & Cowx, 2006; Hunt et al., 2014). While such releases can temporarily compensate for population declines and help to maintain or increase local catch rates, there are also potentially longer lasting negative ecological implications which can have significant impacts on the recipient populations (Einum & Fleming, 2001). Hatchery reared fish typically differ from wild individuals in regards to both their genotype and phenotype due to propagation using non-local brood stock and the artificial rearing environment, which exposes fish to unnatural selection pressures and conditions. Studies on the impacts of these differences have shown that wild fish population abundances are often reduced due to density dependent mortality from the increased competition for habitat and food resources, as well as the genetic introgression from maladapted stocked individuals (Frankham et al., 2002; Kostow, 2009; Araki & Schmid, 2010). In Mongolia, the artificial propagation and stocking of threatened fish species, particularly *H. taimen*, is seen in some circles as a suitable solution or easy fix for the current widespread population declines, and as a result, there has already been preliminary efforts focused on their captive breeding for restocking purposes (Dulmaa, 1999; Hogan & Jensen, 2013). However, while the inter-basin genetic differentiation was found to be low for *H. taimen*, *B. lenok* and *T. baicalensis* populations (Chapter 8), and thus potentially conducive for basin specific stocking programs, the perceived ecological impacts of introducing large numbers of individuals, especially of the highly aggressive *H. taimen*, into Mongolia's rivers would likely be highly detrimental for the resident fish communities. This is due to the effects of increased competition and predation as the natural densities of this top predator are naturally very low (Holćík et al., 1988; Matveyev et al., 1998). Thus it is recommended that the future direction for Mongolian authorities and fish conservation organisations is to prioritize the protection, conservation and recovery of remaining wild populations and riverine habitats before resorting to stocking programs and captive breeding and rearing activities which would further jeopardize these already threatened species.

9.8 Transferability of Research Methods, Results and Recommendations

The current scientific research conducted in Mongolia utilised common fisheries techniques and state-of-the-art technologies to investigate several key, yet previously missing, aspects of the country's fish and fisheries. While these methods are in regular use in contemporary fisheries science around the world, their implementation under

Mongolia's extreme environmental conditions and across such remote and isolated regions was not as common in some of these fields. With the main analyses of both the heavy metal biocontamination (Chapter 5) and the population genetic structure (Chapter 8) projects conducted in modern laboratories in Germany, the transferability of this research should be straight forward, as only the samples would need to be collected in the study site. However the use of passive acoustic telemetry in free-flowing, highly connected lotic systems has not been extensively trialled previously under such extreme conditions. Thus the success of the current tagging projects have clearly demonstrated that this method can be effectively implemented in these harsh environments in order to gather detailed fish movement data, as long as potentially problematic issues were adequately addressed (Chapters 6 and 7). This method has already been successfully transferred across river basins and species within Mongolia, *i.e. H. taimen* in the Onon/Balj rivers (Amur drainage) and *B. lenok* in the Eroo River (Arctic drainage), and thus the possibility to remotely track other medium and large bodied riverine fishes such as *T. baicalensis*, the Siberian sturgeon (*Acipenser baerii*) or the blunt-snouted lenok (*B*. sp.) across river basins in northern and Central Asia and Siberia or beyond, is highly possible and achievable.

Many of the challenges facing Mongolian salmonid populations are also impacting these species across their entire range; however, in many parts of Russia and China these challenges are occurring at a far greater intensity due to the higher human population densities, a more established fishing culture and past large-scale infrastructure development projects (Tong et al., 2013; Zolotukhin, 2013). As a result, populations of these species are suffering from even more dramatic losses with *H. taimen* having gone locally extinct or suffered from significant declines in 39 out of the 57 river basins assessed in Russia (M. Skopets unpubl. data, in Hogan & Jensen, 2013), while in China, *H. taimen* populations in the Heilongjiang (Amur) River have declined by 95 % over the past 50 years (Tong *pers. comm*s., in Hogan & Jensen, 2013). Thus even more urgent actions are needed in these countries to avoid continued widespread declines and more local extinctions. The potential to effectively transfer the current Mongolian research results and recommendations to help guide such changes is highly plausible and necessary as long as regionally specific conditions are also considered. By establishing additional FPAs in the remaining intact regions, immediate impacts could be made to secure the surviving populations and last riverine habitats. In addition, legislating for prohibited species, implementing sufficient spawning season closures (specific to the local climates), introducing minimum size limits and commencing a focused angler education program would all also help immensely in those countries.

9.9 Future Research and Management Priorities

The likelihood of securing the long-term survival and recovery of Mongolia's threatened fish populations in parallel to safeguarding the sustainability and resilience of the emerging recreational fishery, will depend largely on the successful implementation and enforcement of the current and proposed management recommendations. However, there are also additional key research questions that need to be addressed across a range of topics.

Future Research Priorities

With recent legislation prohibiting the intentional killing of *H. taimen* across Mongolia, incidences of their catch and release are now fortunately increasing among local anglers (Chapter 4; G. Balbar *pers. comm*.). However, the physiological impacts associated with this practice and the potential for post-release mortality or sub-lethal effects resulting from the mishandling of individuals (*pers. observations*.), which is critical to the success of this management tool, has not yet been investigated in detail. This information is urgent considering previous computer modelling has indicated that even a small level of harvest, or in this case post-release mortality, could have significant impacts on the resident *H. taimen* population (Jensen et al., 2009). There may also be hidden effects such as increased predations of smaller individuals following release or sub-lethal effects including elevated stress, impaired reproductive output, reduced energy levels, increased infections and / or reduced growth rates (Davie & Kopf, 2006; Halttunen et al., 2010; Smit et al., 2016). Such research is essential given that there are a number of international fishing tour operators that specifically target *H. taimen* along the same river reach on multiple occasions during a season, and year after year. A comprehensive research project would need to entail analyzing blood plasma for concentrations of glucose, cortisol and lactate to determine the effects of angling duration, air exposure and water temperature on individuals stress post capture, while longer term effect studies may require observing post-release mortality of individuals in tanks or *in situ* cages over a period of hours or days. Examining post-release behavioural impairments and mortality over for a longer period of months or years could be investigated using biotelemetry methods (Donaldson et al., 2008).

There are also a number of other important research topics that should be considered including investigating the physiological effects of mining induced heavy metal contamination on resident fish species, particularly in relation to the survival and development of the more sensitive younger life stages (Jezierska et al., 2009; Barbee et al., 2014). Such an experiment would require only a basic laboratory setup to expose embryos and larvae collected from the field, to different concentrations and mixtures of heavy metals in the water and sediment. Mortality and deformity rates could then be observed over a specific period of time (hours and days). Additional research should focus on climate change effects as it will be a significant factor for the region in the near future. The physiological stress (thermal ecology) of various fish species under higher water temperatures needs to be determined, including across all life stages. With preliminary research having already begun (Hartman & Jensen, 2017) and indicating that *B. lenok* and *T. baicalensis* are already experiencing temperatures near their upper levels for growth during summer, this research is urgent for other species including *H. taimen* and blunt-snouted lenok. Experiments can be run streamside with the metabolic rate of individual fish measured under different water temperatures so bioenergetics models can be derived to assess fish responses and impacts on growth and maturity (Hartman & Jensen, 2017).

Long-term Monitoring and Assessment of Mongolian Fisheries

As well as future research, authorities need to implement a multi-faceted, long-term fisheries monitoring and population assessment program to be able to track species abundance, recruitment rates and population size structures in selected river basins. Information obtained from such monitoring can be compared to creel survey results to better evaluate and manage the fishery by setting appropriate sustainable harvest limits for *B. lenok* and *T. baicalensis*. Building on from the current creel surveys (Chapter 4), further angler interviews should be performed both within the Kharaa, Eroo and Onon river basins, to allow for comparisons, and across additional river basins that are a concern due to increasing fishing pressure (*e.g.* Delgermoron, Tuul, Eg-Uur, Orkhon, *etc*.). These surveys must record important details regarding the fish caught (and released) each trip, including species, lengths and quantity. A 'catch log book' could be provided to regular anglers or those who are fishing club members to get a more complete idea of the annual fishing activities. At the same time, fishery observers (*e.g.* trained university students) could follow specific anglers or closely monitor a particular area to obtain regular catch data. Ideally these creel surveys should be done annually or in alternate years so a long-term data set can be collected and trends can be identified and managed appropriately.

Merging Fish Ecology and River Basin Management

The increased human demand for freshwater has placed severe pressure on inland fisheries productivity and aquatic biodiversity (Dudgeon et al., 2006; Cooke et al., 2013). One factor that has contributed to this current situation is the historical lack of consideration for ecological issues within water resource management plans, as preference has often been given to economically beneficial water allocations that tend to receive much wider political or public support (Brummett et al., 2013; Cooke et al., 2016). Although priorities have slowly shifted in many regions and countries towards more environmentally friendly policies and regulations (*e.g.* the European Water Framework Directive), fundamental changes are still urgently required to better integrate ecological priorities into river basin management plans particularly in many developing and transitional countries. Such changes could result in better functioning ecosystems and more robust inland fisheries, while still maintaining water security for human needs (Cooke et al., 2016). As Mongolia is already a water scarce country, it faces many challenges with regards to water security (Karthe et al., 2015). Even though the Mongolian government has selected an IWRM concept as the legally binding national water resource management plan, within the National Water Law of Mongolia, there are substantial shortcomings (Karthe et al., 2015). Currently, the implementation of the IWRM plan falls behind political aspirations due to limited funding and capacities both at the regional and river basin level, and as fisheries ecology and aquatic biodiversity in general is remarkably absent from these legal provisions, fundamental changes are still urgently required.

Transboundary Coordination of Fisheries Conservation and Management

Many exploited inland fisheries often cross geopolitical boundaries, therefore increased coordination of conservation and management between countries in essential (Welcomme et al., 2010; Cooke et al., 2016). However, such watershed-wide management has not been broadly adopted by national fisheries plans due to the complexities and challenges associated with coordinating the governance of fish stocks across different jurisdictions (Nguyen et al., 2016; Guzmán Mandonado et al., 2017). Nevertheless, the large number of transboundary rivers in Mongolia make it an important concept to develop with its neighbors, especially as *H. taimen*, *B. lenok* and *T. baicalensis* display extensive individual movements (Chapter 6 & 7) and large scale genetic interconnectedness across 1000's of km (Chapter 8). Thus developing transboundary fisheries and river basin management regulations through increased communication, cooperation and collaboration between countries and departments would be highly advantageous for these fish population going forward. Species ESUs could be managed as a single entity and incongruent domestic policies could be streamlined to better protect habitats, fight illegal fishing and cross border trading while maintaining large scale river connectivity (Nguyen et al., 2016). In addition, the inclusion of *H. taimen* and potentially other threatened salmonid species, on to a binding international agreement such as the Convention of Migratory Species would be a positive step forward to help raise the profile of the current accelerated declines of freshwater fish populations in general, while providing an avenue for greater international awareness and support for conservation activities and coordination of one of the most imperiled group of vertebrates in the world (Dudgeon et al., 2006; Vörösmarty et al., 2010; Hogan & Jensen, 2013).

10 References

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Appendix 1

Overview of the Current Fishing Laws in Mongolia

The existing laws and regulations as pertaining to extractive fishing activities in Mongolia are included within the 'Mongolian Law on Hunting' (Compendium of Environmental Law and Practice in Mongolia, Ulaanbaatar, Mongolia, 2000). Within this document, all fish are defined as *game animals* (Article 3.1) and all citizens who hunt or trap them, other than *rare animals*, for household purposes must obtain a permit from the Soum (regional council) Governor (Articles 7.1; 10.1). The permit shall list the names and surnames of the authorized citizen, the species, quantity, season, location and payment amount (Article 10.2). A onetime permit to hunt or trap *game animals* for household purposes issued to citizens of Mongolia shall be valid for up to three (3) days to fish a total of two *Hucho taimen*, although this has amended in 2012 and is now prohibited, and not more than ten (10) other fish (Article 10.3.1; 10.4). Fishing for species other than those specified in 13.2.1 to 13.2.7 (including Siberian whitefish, *Coregonus lavaretus*; fish in Lake Buir; Baikal Omul, *Coregonus autumnalis*; Omul, *Coregonus peled*; Siberian Ide, *Leuciscus leuciscus*), must be conducted from June 15th to April 1st (Article 13.2.8). Article 14 lists prohibited hunting and trapping methods (encompassing fishing activities) and includes the use of chemical substances and explosives (Article 14.1.1) as well as nets to fish for household purposes (Article 14.1.7).

For violations of the hunting legislation, administrative penalties shall be applied by judges, environmental inspectors or rangers to guilty persons (Article 16). Penalties should be applied to citizens using an expired permit < 10 000 ₮ (Article 16.1.1), for using a net to fish < 5000 ₮ (Article 16.1.4), for violations of hunting season provisions and exceeding the amount of animals fished < 15 000 ₮ (Article 16.1.5), and for fishing for household purposes without a permit < 25 000 ₮ (Article 16.1.6). For repeat violations of these laws or for hunting or trapping *rare animals* there shall be a criminal penalty applied to the person found guilty (Article 16.2). Environmental inspectors shall confiscate all equipment and all animals from those responsible for illegal hunting / trapping / fishing (Article 16.3). All guilty persons may also be deprived of their driving license for a period of up to two (2) years (Article 16.4). Article 17 states the citizens who reveal persons liable for violations of legislation and provide information shall be rewarded by the Governor of the Soum to the amount of 15% of the fine imposed or reimbursements for the losses by those liable for the violations.

Appendix 2

Table A2- 1. Summary of the demographic characteristics of surveyed anglers from three river basins in northern Mongolia between June and October 2012.

Section 1: Angler Demographics	**Kharaa**	**Eroo**	**Onon**	**Total**
Number of fishing groups	17	18	23	58
Number of anglers	27	59	68	154
Nationality	Mongolian = 27	Mongolian = 56 Russian = 3	Mongolian = 68	Mongolian =151 Russian = 3
Mean age of anglers	35.5 years (16 – 55 years)	41.8 years (27 – 71 years)	37.4 years (17 – 70 years)	38.2 years
Age began to fish?	Av. 22 years	Av. 26 years	Av. 22 years	Av. 23.3 years
Year began to fish?	Av. 1999	Av. 1999	Av. 1992	Av. 1996
Father/ grandfather fished?	Yes = 7 No = 10	Yes = 6 No = 11	Yes = 6 No = 13	Yes = 19 No = 34
Residence	Kharaa basin = 12 Ulaanbaatar = 5 Darkhan = 2	Ulaanbaatar = 10 Kharaa basin = 4 Russia = 3	Onon basin = 15 Ulaanbaatar = 3	Ulaanbaatar = 18 Onon basin = 15 Kharaa basin = 12
Occupation	Working = 12 Retired / un = 4 Student = 3 Herder = 1	Working = 22 Retired / un = 1 Student = 1 Herder = 0	Working = 13 Retired / un = 4 Student = 2 Herder = 1	Working = 47 Retired / un = 9 Student = 6 Herder = 2
Transport	Car = 6 Foot = 9 Train = 2	Car = 16 Foot = 0 Train = 0	Car = 17 Foot = 3 Other = 2	Car = 39 Foot = 12 Other = 4

Table A2- 2. Summary of the fishing practices of anglers from three river basins in northern Mongolia between June and October 2012.

Section 2: Fishing Practices	**Kharaa**	**Eroo**	**Onon**	**Total**
Fish every year?	Yes = 14 No = 3	Yes = 7 No = 11	Yes = 17 No = 3	Yes = 38 No = 17
Fishing trips in 2011? **Frequency = > 10** **Occasionally = 4 - 9** **Rarely = 0 - 3**	Frequently = 7 Occasionally = 4 Rarely = 3	Frequently = 0 Occasionally = 1 Rarely = 16	Frequently = 3 Occasionally = 12 Rarely = 5	Frequently = 10 Occasionally = 17 Rarely = 24
Fishing trips in 2012? **Frequency = > 10** **Occasionally = 4 - 9** **Rarely = 0 - 3**	Frequently = 5 Occasionally = 5 Rarely = 3	Frequently = 1 Occasionally = 2 Rarely = 13	Frequently = 1 Occasionally = 8 Rarely = 11	Frequently = 6 Occasionally = 15 Rarely = 27
What season?	Summer = 10 Autumn = 9 Winter = 0 Spring = 2	Summer = 11 Autumn = 8 Winter = 0 Spring = 1	Summer = 29 Autumn = 8 Winter = 0 Spring =0	Summer = 50 Autumn = 25 Winter = 0 Spring =3
How much time do you typically spend fishing?	>7 hrs = 5 4 - 6 hrs = 3 < 3 hrs = 4	>7 hrs = 12 4 - 6 hrs = 2 < 3 hrs = 0	>7 hrs = 12 4 - 6 hrs = 4 < 3 hrs = 2	>7 hrs = 29 4 - 6 hrs = 9 < 3 hrs = 6
Do you fish in other rivers?	Yes = 7 No = 9	Yes = 11 No = 4	Yes = 12 No = 8	Yes = 30 No = 21
Which rivers do you also fish?	Eroo = 4 Orkhon = 4 Tuul = 1 Selenge = 1	Orkhon = 5 Kharaa = 3 Kherlen = 3 Tuul = 4	Eg-Uur = 4 Kherlen =2 Tuul = 2 Eroo = 1	Orkhon = 9 Tuul = 7 Kherlen = 5 Eroo = 5
What do you do with the fish you catch?	Keep = 15 Release = 2 Give away = 2	Keep = 13 Release = 3 Give away = 3	Keep = 22 Release = 5 Give away = 0	Keep = 50 Release = 10 Give away = 5
What do you do with taimen /small fish if you catch?	Release = 12 Keep = 6	Release = 14 Keep = 1	Release = 21 Keep = 2	Release = 47 Keep = 9
Fish consumption, month^{-1}? **Frequently = >10** **Occasionally = 4 - 9** **Rarely = 0 - 3**	Frequently = 7 Occasionally = 2 Rarely = 7	Frequently = 0 Occasionally = 2 Rarely = 13	Frequently = 1 Occasionally = 3 Rarely = 16	Frequently = 8 Occasionally = 7 Rarely = 36

Table A2- 3. Summary of the current fishing trip in the three river basins, northern Mongolia, between June and October 2012.

Section 3: Surveyed fishing trip	Kharaa	Eroo	Onon	Total
Did you buy a fishing permit for this trip?	Yes = 5 No = 1 Never = 13	Yes = 12 No = 1 Never = 4	Yes = 13 No = 2 Never = 5	Yes = 30 No = 4 Never = 22
Mean length of fishing trip? (mean ± SD)	1.29 ± 0.59 d / trip	3.06 ± 1.51 d / trip	1.43 ± 0.79 d /trip	1.90 ± 1.28 d / trip
Mean hours fishing per day? (mean ± SD)	5.6 ± 3.6 hrs/ day	5.2 ± 1.7 hrs / day	5.19 ± 2.8 hrs / day	5.34 ± 2.8 hrs / day
Intended target species this trip?	Lenok = 10 Grayling = 7 Taimen = 3 No matter = 5	Lenok = 8 Grayling = 5 Taimen = 3 No matter = 7	Lenok = 14 Grayling = 2 Taimen = 8 No matter = 2 Pike = 2	Lenok = 32 Grayling = 14 Taimen = 14 No matter = 14 Pike = 2
How many fish do you want to catch?	≥10 fish = 4 4 - 9 fish = 8 ≤ 3 fish = 6 No matter = 0	≥10 fish = 5 4 - 9 fish = 5 ≤ 3 fish = 2 No matter = 2	≥10 fish = 2 4 - 9 fish = 6 ≤ 3 fish = 13 No matter = 3	≥10 fish = 11 4 - 9 fish = 19 ≤ 3 fish = 21 No matter = 5
Number of fish caught per species?	Lenok = 12 Grayling = 1 Taimen = 0 Dace = 4 Total fish = 17	Lenok = 34 Grayling = 31 Taimen = 1 Dace = 0 Total fish = 66	Lenok = 30 Grayling = 1 Taimen = 7 Dace = 0 Total fish = 38	Lenok = 76 Grayling = 33 Taimen = 8 Dace = 4 Total fish = 121
Have you released a fish alive this trip?	Yes = 3 No / Not yet = 15	Yes = 10 No / Not yet = 6	Yes = 17 No / Not yet = 6	Yes = 30 No / Not yet = 27
Mean fish total length (cm)?	Lenok = 34.5 ± 4.7 Grayling = 32 Taimen = 0 Dace = 20 ± 3.8	Lenok = 32.3 ± 7.9 Grayling = 21.4 ± 5.3 Taimen = 60 Dace = 0	Lenok = 36.4 ± 7.5 Grayling = 0 Taimen = 71.7 ± 2.9 Dace = 0	Lenok = 34 ± 7.3 Grayling = 21.8 ± 5.6 Taimen = 68.8 ±6.3 Dace = 20 ± 3.8

Table A2- 4. Summary of fishing gear and trip costs of anglers in the three river basins, northern Mongolia, between June and October 2012.

Section 4: Fishing gear and trip costs	Kharaa	Eroo	Onon	Total
Fishing gear used?	Rod = 16 Net = 1	Rod = 17	Rod = 22	Rod = 55 Net = 1
Bait used / preferred?	Artificial lures = 15 Everything = 1 Netting = 1	Artificial lures = 4 Everything = 7 Grasshopper = 1 Live fish = 1	Artificial lures = 18 Grasshopper = 5 Rain-worm = 3 Fly fishing = 2 Live fish - 1 Mouse – 1	Artificial lures = 37 Everything = 8 Grasshopper = 6 Rain-worm = 3 Live fish = 2 Fly fishing = 2
Where do you buy your fishing gear?	Black-market = 12 UB fishing shop= 4 International = 2	Black-market = 9 UB fishing shop= 8 International = 1	Black-market = 4 UB fishing shop = 9 International = 3 From Friend = 4	Black-market = 25 UB fishing shop = 21 International = 6 From Friend = 4
How much money do you spend on fishing gear per year? (per angler)	61.000₮ ($24.6 US) Median: 40 000 ₮ Range:15 000 – 250 000 ₮	158.462₮ ($63.9 US) Median: 100 000 ₮ Range:10 000 – 550 000 ₮	68.409₮ ($27.6 US) Median: 37 500 ₮ Range:10 000 – 300 000 ₮	89.600₮ ($36.1 US) Median: 40 000 ₮ Range: 10 000 – 550 000 ₮
How much money have you spent on this fishing trip? (per angler)	45 313₮ ($18.3 US) Median: 5000 Range: 0 – 125 000 ₮	291 000₮ ($117.3 US) Median: 300 000 Range: 10 000 – 850 000 ₮	43 260₮ ($17.4 US) Median: 30 000 Range: 0 – 200 000 ₮	112 685₮ ($45.4 US) Median: 45 000 Range: 0 – 850 000 ₮

Table A2- 5. Summary of the angler knowledge and opinion in the three river basins, northern Mongolia, between June and October 2012.

Section 5: Angler knowledge and opinion	**Kharaa**	**Eroo**	**Onon**	**Total**
Is fishing getting better?	Better = 0 No change = 2 Worse = 15 Don't know = 1	Better = 0 No change = 5 Worse = 6 Don't know = 3	Better = 1 No change = 7 Worse = 11 Don't know = 1	Better = 1 No change = 14 Worse = 32 Don't know = 5
What do you think is the main reason?	Overfishing = 6 Flooding = 3 Pollution = 2	Flooding = 1 Pollution = 1	Overfishing = 2 Flooding = 1	Overfishing = 8 Flooding = 5 Pollution = 3
Have you seen illegal fishing? What?	Yes = 11 No = 7 *e.g.* netting, dynamite	Yes = 3 No = 14 *e.g.* netting	Yes = 15 No = 2 *e.g.* netting, no permission	Yes = 29 No = 23
Do you know the Mongolian fishing regulations?	Yes = 5 No = 2 Not Sure = 10	Yes = 12 No = 0 Not Sure = 3	Yes = 16 No = 2 Not Sure = 5	Yes = 33 No = 4 Not Sure = 18
Do you know taimen are endangered?	Yes = 17 No = 0 Not Sure = 0	Yes = 15 No = 2 Not Sure = 0	Yes = 20 No = 1 Not Sure = 1	Yes = 52 No = 3 Not Sure = 1
Do you release fish alive? Why?	Yes = 18 No = 0 Too small = 14 Conserve = 3	Yes = 15 No = 2 Too small = 6 Conserve = 1	Yes = 23 No = 0 Too small = 2 Conserve = 6	Yes = 56 No = 2 Too small = 22 Conserve = 10
Would you support new fishing laws?	Yes = 5 No = 1 Unsure = 11	Yes = 13 No = 1 Unsure = 1	Yes = 14 No = 1 Unsure = 6	Yes = 32 No = 3 Unsure = 18

Appendix 3

Table A3- 1. Generalised linear model (GLM) results table per species with heavy metal contents as the response variable and fish length, fish tissue, fish age, site sediment content and site water concentrations added as predictor variables.

				L. baicalensis				
	Cr	**Zn**	**As**	**Cd**	**Ni**	**Cu**	**Hg**	**Pb**
Fish length	0.004	Not Sig	0.005	0.000	0.005	Not Sig	0.000	Not Sig
Fish tissue	0.000	0.004	0.000	0.000	Not Sig	0.000	0.000	0.009
Fish age	Not Sig	0.005	0.000	0.000	0.015	0.033	0.000	Not Sig
Site sediment	0.000	0.009	0.000	0.001	Not Sig	0.028	0.000	Not Sig
Site water	NA	NA	0.000	NA	NA	NA	0.000	NA
Length/tissue	0.000	0.009	0.002	0.000	0.006	0.000	0.023	0.000
Length/age	Not Sig	0.009	0.016	0.000	0.003	Not Sig	Not Sig	Not Sig
Length/sediment	0.003	0.089	0.002	Not Sig	0.024	Not Sig	0.001	Not Sig
Length/water	NA	NA	0.001	NA	NA	NA	0.001	NA
Tissue/age	Not Sig	0.001	0.019	0.000	Not Sig	0.002	Not Sig	0.010
Tissue/sediment	0.000	0.004	0.000	0.006	Not Sig	0.010	0.000	Not Sig
Tissue/water	NA	NA	0.000	NA	NA	NA	0.000	NA
Age/sediment	Not Sig	0.007	0.002	0.000	Not Sig	Not Sig	Not Sig	Not Sig
Age/water	NA	NA	0.000	NA	NA	NA	0.001	NA
Sediment/water	NA	NA	0.000	NA	NA	NA	Not Sig	NA
				T. baicalensis				
	Cr	**Zn**	**As**	**Cd**	**Ni**	**Cu**	**Hg**	**Pb**
Fish length	0.000	0.048	0.007	0.000	0.005	Not Sig	0.000	Not Sig
Fish tissue	Not Sig	0.003	0.000	0.001	Not Sig	0.000	0.000	0.024
Fish age	0.005	0.004	0.000	0.000	0.011	0.021	0.000	0.027
Site sediment	Not Sig	0.007	0.000	0.002	Not Sig	0.014	0.000	0.046
Site water	NA	NA	0.000	NA	NA	NA	0.000	NA
Length/tissue	0.001	0.007	0.004	0.000	0.004	Not Sig	0.014	0.000
Length/age	Not Sig	0.006	0.016	0.000	0.003	Not Sig	Not Sig	Not Sig
Length/sediment	0.000	Not Sig	0.020	Not Sig	0.022	Not Sig	0.001	Not Sig
Length/water	NA	NA	0.013	NA	NA	NA	0.003	NA
Tissue/age	0.000	0.000	0.001	0.001	Not Sig	Not Sig	Not Sig	Not Sig
Tissue/sediment	Not Sig	0.003	0.000	Not Sig	Not Sig	Not Sig	0.000	Not Sig
Tissue/water	NA	NA	0.021	NA	NA	NA	0.000	NA
Age/sediment	Not Sig	0.006	0.001	0.001	Not Sig	Not Sig	Not Sig	Not Sig
Age/water	NA	NA	0.000	NA	NA	NA	0.000	NA
Sediment/water	NA	NA	0.002	NA	NA	NA	0.000	NA
				B. lenok				
	Cr	**Zn**	**As**	**Cd**	**Ni**	**Cu**	**Hg**	**Pb**
Fish length	0.002	0.043	0.000	0.000	Not Sig	0.003	0.000	Not Sig
Fish tissue	0.003	0.002	0.000	0.001	Not Sig	Not Sig	0.000	0.042
Fish age	0.000	0.004	0.000	0.000	0.000	0.002	0.000	0.045
Site sediment	Not Sig	0.007	0.000	0.002	0.043	0.010	0.000	Not Sig
Site water	NA	NA	0.000	NA	NA	NA	0.000	NA
Length/tissue	0.000	0.006	0.000	0.000	Not Sig	0.001	0.013	0.000
Length/age	Not Sig	0.005	0.000	0.000	0.007	0.002	Not Sig	Not Sig
Length/sediment	0.001	Not Sig	0.000	Not Sig	Not Sig	Not Sig	0.001	Not Sig
Length/water	Not Sig	NA	0.000	NA	NA	NA	0.003	NA
Tissue/age	0.000	0.000	Not Sig	0.001	0.002	0.000	Not Sig	Not Sig
Tissue/sediment	Not Sig	0.003	Not Sig	0.012	Not Sig	Not Sig	0.000	Not Sig
Tissue/water	NA	NA	Not Sig	NA	NA	NA	0.000	NA
Age/sediment	0.000	0.006	Not Sig	0.001	0.005	0.020	Not Sig	Not Sig
Age/water	NA	NA	Not Sig	NA	NA	NA	0.000	NA
Sediment/water	NA	NA	0.000	NA	NA	NA	0.000	NA

	L. lota							
	Cr	**Zn**	**As**	**Cd**	**Ni**	**Cu**	**Hg**	**Pb**
Fish length	0.000	0.032	0.000	0.000	0.015	Not Sig	0.028	0.016
Fish tissue	0.000	Not Sig	0.000	0.000	0.012	0.000	0.026	0.001
Fish age	Not Sig	0.032	0.000	0.000	Not Sig	0.017	0.009	Not Sig
Site sediment	0.000	0.029	0.000	0.000	Not Sig	0.019	0.010	Not Sig
Site water	NA	NA	0.000	NA	NA	NA	0.010	NA
Length/tissue	0.000	0.042	0.001	0.000	0.001	0.000	Not Sig	Not Sig
Length/age	Not Sig	0.010	0.011	0.000	0.009	0.048	0.018	0.028
Length/sediment	0.000	Not Sig	0.001	Not Sig	Not Sig	Not Sig	0.031	Not Sig
Length/water	NA	NA	0.001	NA	NA	NA	0.031	NA
Tissue/age	Not Sig	0.022	Not Sig	0.000	Not Sig	0.002	0.017	0.000
Tissue/sediment	0.000	Not Sig	0.001	0.005	Not Sig	0.011	0.029	Not Sig
Tissue/water	NA	NA	0.000	NA	NA	NA	0.029	NA
Age/sediment	Not Sig	0.043	0.007	0.000	Not Sig	Not Sig	0.011	Not Sig
Age/water	Na	NA	0.000	NA	NA	NA	0.010	NA
Sediment/water	NA	NA	0.000	Na	NA	NA	0.012	NA

	P. asotus							
	Cr	**Zn**	**As**	**Cd**	**Ni**	**Cu**	**Hg**	**Pb**
Fish length	0.028	0.000	0.020	0.000	Not Sig	0.013	0.003	Not Sig
Fish tissue	0.007	0.000	0.000	0.000	0.000	0.000	0.001	Not Sig
Fish age	Not Sig	0.000	0.046	0.002	0.000	0.038	0.000	0.011
Site sediment	0.042	0.000	0.021	Not Sig	Not Sig	0.017	0.014	Not Sig
Site water	NA	NA	0.031	NA	NA	NA	Not Sig	NA
Length/tissue	0.014	0.001	Not Sig	0.000	0.000	Not Sig	0.011	0.000
Length/age	Not Sig	Not Sig	0.022	0.000	0.005	Not Sig	Not Sig	Not Sig
Length/sediment	0.020	0.000	0.013	0.000	Not Sig	Not Sig	0.006	Not Sig
Length/water	NA	NA	0.015	Not Sig	NA	NA	NA	NA
Tissue/age	0.000	0.000	0.007	0.000	Not Sig	Not Sig	Not Sig	Not Sig
Tissue/sediment	0.005	0.000	Not Sig	Not Sig	Not Sig	0.044	0.016	Not Sig
Tissue/water	NA	NA	Not Sig	NA	NA	NA	NA	NA
Age/sediment	Not Sig	Not Sig	0.039	0.005	Not Sig	Not Sig	Not Sig	Not Sig
Age/water	NA	NA	0.039	NA	NA	NA	NA	NA
Sediment/water	NA	NA	0.004	NA	NA	NA	NA	NA

Results for single and one-way interactions are displayed from full models.

Not Sig indicates a nonsignificant result ($p > 0.05$) for that variable and contaminate, *NA* represents all water values for that heavy metal were below the analytical detection limits and thus excluded from the model.

Appendix 4

mtDNA sequencing

Sequencing was conducted in a total volume of 20 μL including 5 pMol Primer LRBT-25, 10 pMol Primer LRBT-1195 (Uiblein et al. 2001), 200 μM dNTP, 2 μL 10x Dream Taq-buffer, 0.8 U Dream Taq-Polymerase and appr. 5 ng DNA. The PCR program involved 3 minutes at 95˚C, then 40 cycles of 95˚C for 30 seconds, 64˚C for 40 seconds, 72˚C for 1 minute and a final 10 minutes of 72˚C. PCRs products were purified by centrifuging for 3 minutes at 2800 rpm through cross linked dextran gel (Sephadex G-50 Superfine, GE Healthcare Life Sciences, Germany). PCR-products were directly cycle-sequenced using the ABI BigDye Terminater v3.1 cycle sequencing Kit using the same primers. Products were sequenced on an Applied Biosystems 3130xl Genetic Analyser (Applied Biosystems, Foster City, USA).

Microsatellite PCR

We used a PCR protocol with CAG/M13R-tagged forward primers and GTTT-"pigtailed" reverse primers following Schuelke (2000). Microsatellites primers were combined and amplified in either a multiplex or singleplex polymerase chain reactions (PCR) and were fluorescently labelled with FAM, NED, PET or VIC for genotyping (see Tab. S1). The PCR amplification was conducted in 5 μL of 2x Qiagen Multiplex PCR kit solution, 0.6 pMol tagged (CAG/M13R) forward primer, 2.4 pMol untagged reverse primer, 2.5 pMol CAG/M13 oligo, and approximately 3 ng DNA. The PCR program conditions consisted of 15 mins at 95˚C, followed by 20 cycles of a touchdown PCR with 94˚C for 30 s, 60˚C for 30 s minus 0.5˚C per cycle, and 72˚C for 90 s; then 20 cycles of 94˚C for 30 s, 50˚C for 30 s and 72˚C for 90 s, and a final period of 10 mins at 72˚C (Faircloth et al. 2009). The PCR product was diluted 1:100 H_2O and 2 μL were added to 7 μL of formamide including size standard mix (1.5 ml FA + 40 1 μL LIZ 500). Samples were denatured at 95˚C for 3 minutes and placed immediately on ice. Fragment analysis was conducted using an Applied Biosystems 3130xl Genetic Analyser (Applied Biosystems, Foster City, USA) with genotyping conducted in GeneMapper 4.0 (Applied Biosystems, Foster City, USA).

Table A4- 1. Microsatellite primers used for *H. taimen* (HT), *B. lenok / B. sp.* (BL / Bsp) and *T. baicalensis / T. nigrescens* (TB / TN) with details including repeat motif, size range of alleles in study, forward / reverse sequence, tags added to 5' end of F primer, pigtail sequence added 5' to R primer, florescence dye with superscript M indicating multiplex sets, Genebank accession number and source reference (* CAG: CAGTCGGGCGTCATCA; M13R: GGAAACAGCTATGACCAT).

Locus	Species	Repeat Motif	Range of alleles	F / R Sequence	Tag*	Dye	pigtail	Accession No.	Publication
BleTri2	HT BL/Bsp	$(CAT)_{11}$	132-145 122-165	CCAGGACATATTCCCTTCTAG / CCACAGCTCAGGGCAGGGAGT	CAG	VIC	GTTT	AY48448	Froufe et al. 2004
BleTri4	HT BL/Bsp	$(CAT)_5$	106-196 94-164	CTCCTGGAGAGGACACCACTG / CCAGCTTCCTCTGGTGGGATG	CAG	FAM	GTTT	AY48450	Froufe et al. 2004
OMM1007	HT BL/Bsp	$(TCA)_{15}$	165-194 170-222	CATCGTTTTCCTGGTTCAC / CCCTTAACTGACGCTATT	M13R	PET	GTTT	AF346669	Jia et al. 2008
OMM1011	HT BL/Bsp	$(TGA)_8$	204-210 193-333	CAAGGATTCGGGACAT / CACCCCTAAAGTAGAGCA	CAG	NED	GTTT	AF346672	Jia et al. 2008
OMM1105	HT BL/Bsp	$(AGAC)_{23}(GATA)_{16}$	109-127 116-233	GCACACTGTCTGGGTAAGAGA / GCAGAGCCACACTAAACCA	CAG	NED	GTTT	AF352768	Jia et al. 2008
OMM1077	HT BL/Bsp	$(GATA)_9$	292-399 291-376	GGCTGACCAGAGAAAGACTAGTTC / TGTTACGGTGTCTGACATGC	M13R	VIC	GTTT	AF352748	Jia et al. 2008
OMM1039	HT	$(GA)_{20}$	140-179	GGGGTAGGAGTAGACTAGACA / ATCTTTCCCTCCTTGCAC	CAG	VIC	GTTT	AF346689	Jia et al. 2008
BleTet2	HT	$(CAGA)_5$	139-180	TGTCAGAGGCCTTGACTGCGT / GCTAGGCTGTTTACTCTAGGT	M13R	VIC	GTTT	AY484452	Froufe et al. 2004
BleTet5	HT	$(TGTC)_5$	179-182	CTTCTTCACCCGCCTGAGTGT / TTGAATGGGCTATCTGGCTGT	CAG	FAM	GT	AY484455	Froufe et al. 2004
BleTet6	HT	$(CCTG)_7$	175-322	AGACAGCATGACAGCACAACG / GGCAGACAGACAGGCAAACAG	M13R	FAM	GTTT	AY484456	Froufe et al. 2004
BleTet9	HT	$(TATC)_2(TGTC)_{12}(TATC)_3$	167-373	ACTGGATAGAAAGACCTGTGG / AGATTCTTGGTAAAAGTGAAG	CAG	FAM	GTTT	AY486103	Froufe et al. 2004
BleTri3	BL / Bsp	$(CAT)_7$ $(CATT)_7$	129-161	CAGACGTGGCGCTTGTTTGGT / CTAGTCAGGAAGCAAGTGATG	M13R	FAM	GTTT	AY48449	Froufe et al. 2004
OMM1008	BL / Bsp	$(GAT)_{11}$	270-333	GATCCTTTGGGAGATTAACAG / CACCACAGTTGCTACTGCC	CAG	NED	GTTT	AF346670	Jia et al. 2008
Tar100	TB /TN	$(CTTT)_{23}$	238 - 350	TTTGGATGTGTCAGACCTG / GAGAAAGCAAGGAGAAATCAC	M13R	FAM^{M2}	GTTT	EF694937	Diggs and Ardren 2008
Tar101	TB /TN	$(CTTT)_{22}$	252-452	CAGAGCACACCAAGCAGAG / AGGGCAAGTCATTCCAGTC	M13R	VIC^{M3}	GTTT	EF694938	Diggs and Ardren 2008
Tar103	TB /TN	$(ATCC)_7$	176-252	CGGGGATCAATAAAGTATCC / CTTCACTGTCGCTGTGAGTAC	M13R	VIC^{M3}	GTTT	EF694939	Diggs and Ardren 2008
Tar108	TB /TN	$(ATAC)_{27}$	179-203	GGGCTTTACCTGGAAACTAGC / CCATGAAATTCTTTGGAGTGG	CAG	PET	GTTT	EF694943	Diggs and Ardren 2008
Tar112	TB /TN	$(TATC)_7$	361-542	CCTGGGAATCAACAAAGTATC / AGGAGGTTCAGTGAGTGTTTC	M13R	PET^{M1}	GTTT	EF694946	Diggs and Ardren 2008
Tth419a	TB /TN	$(CAGA)_{24}$	107-119	CAATTCCCTCTCAATACTTC / CACCAGCCGAGAGTC	CAG	PET^{M1}	GTTT	GU225722	Junge et al. 2010
Tth419b	TB /TN	$(CAGA)_{24}$	138-162	CAATTCCCTCTCAATACTTC / CACCAGCCGAGAGTC	CAG	PET^{M1}	GTTT	GU225722	Junge et al. 2010
Tth447	TB /TN	$(TG)_{19}$	170-206	CTTGATTGCCATTGGATTGT / CAACATCCTTGTCGCCTCTA	M13R	FAM^{M2}	GTTT	GU225727	Junge et al. 2010

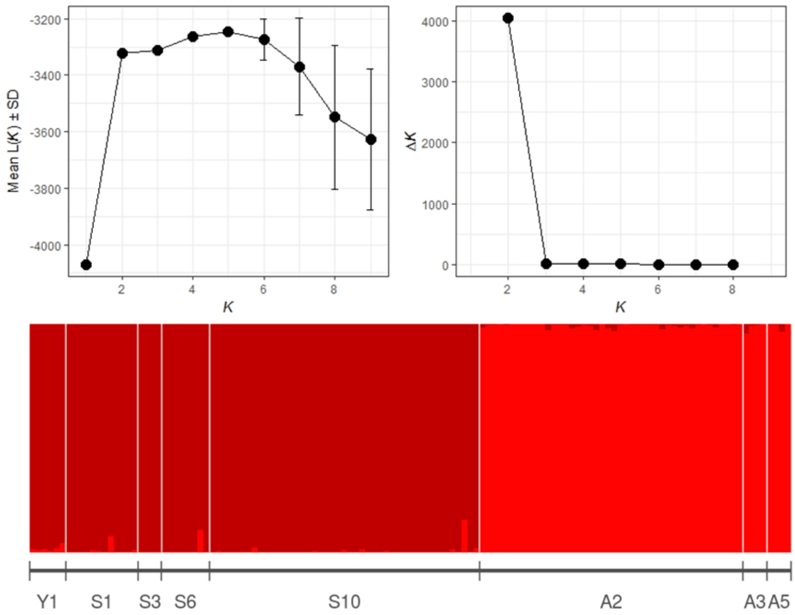


Figure A4. 1. Bayesian cluster analysis with STRUCTURE for the microsatellite data of *H. taimen* sampled from eight populations from the Yenisei, Selenge and Amur river basins, Mongolia. Two genetic clusters were identified using the Evanno et al. (2005) method (top). Individual proportional membership at $K = 2$ (bottom). Each identified cluster was again run separately and both displayed K = 1 (Results not shown).

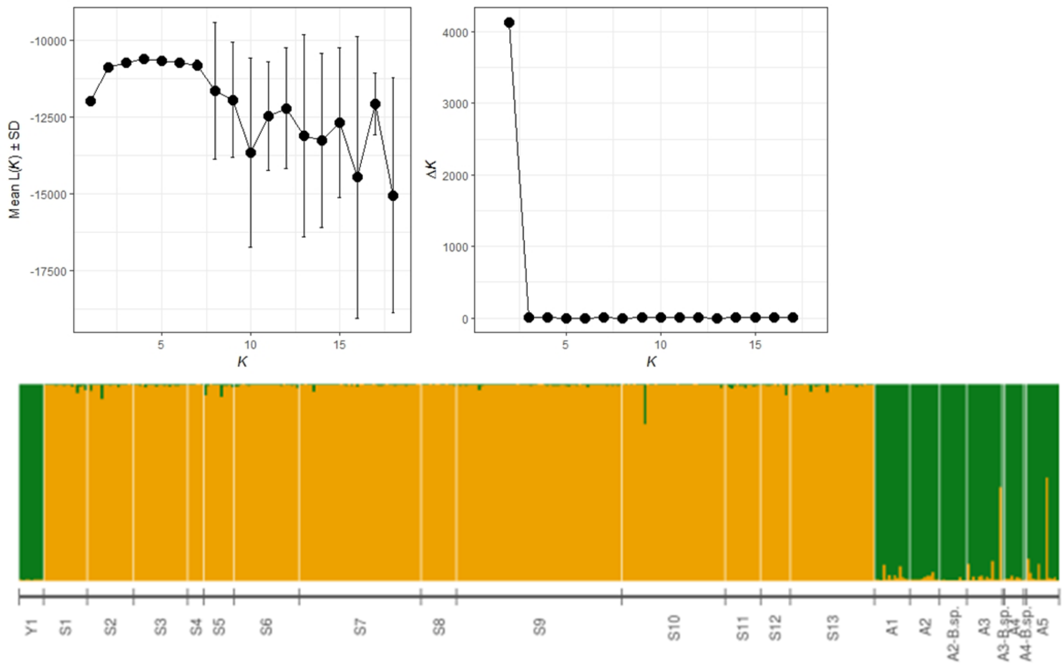


Figure A4. 2 a. STRUCTURE analysis for microsatellite data of all *B. lenok* and blunt-snout lenok (*B. sp.*) populations collected from 19 rivers across the Yenisei (Y1), Selenge (S1 – S13) and Amur river basins (A1 – A5) in Mongolia. When all populations were included in the analysis, two genetic clusters were identified; ➔ K=2. These two clusters are further analysed in Fig. A4. 2b and A4. 2c-A4. 2e.

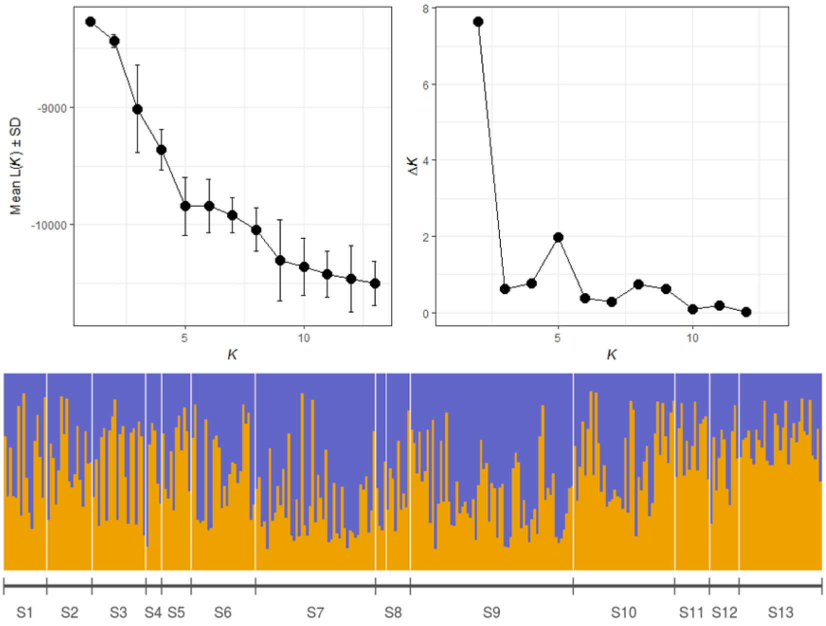


Figure A4. 2 b. Following the reanalysis of the *B. lenok* "Orange Cluster" from the Selenge River basin (S1 – S13), L(K) is highest at K= 1 and decreases with increasing K. Thus, the peak of ΔK at K=2, resulting from the Evanno et al. (2005) method is misleading. The plot of individual cluster membership for K=2 shows no biologically meaningful pattern. Overall this indicates that there was only a single cluster across the basin ➔ K=1.

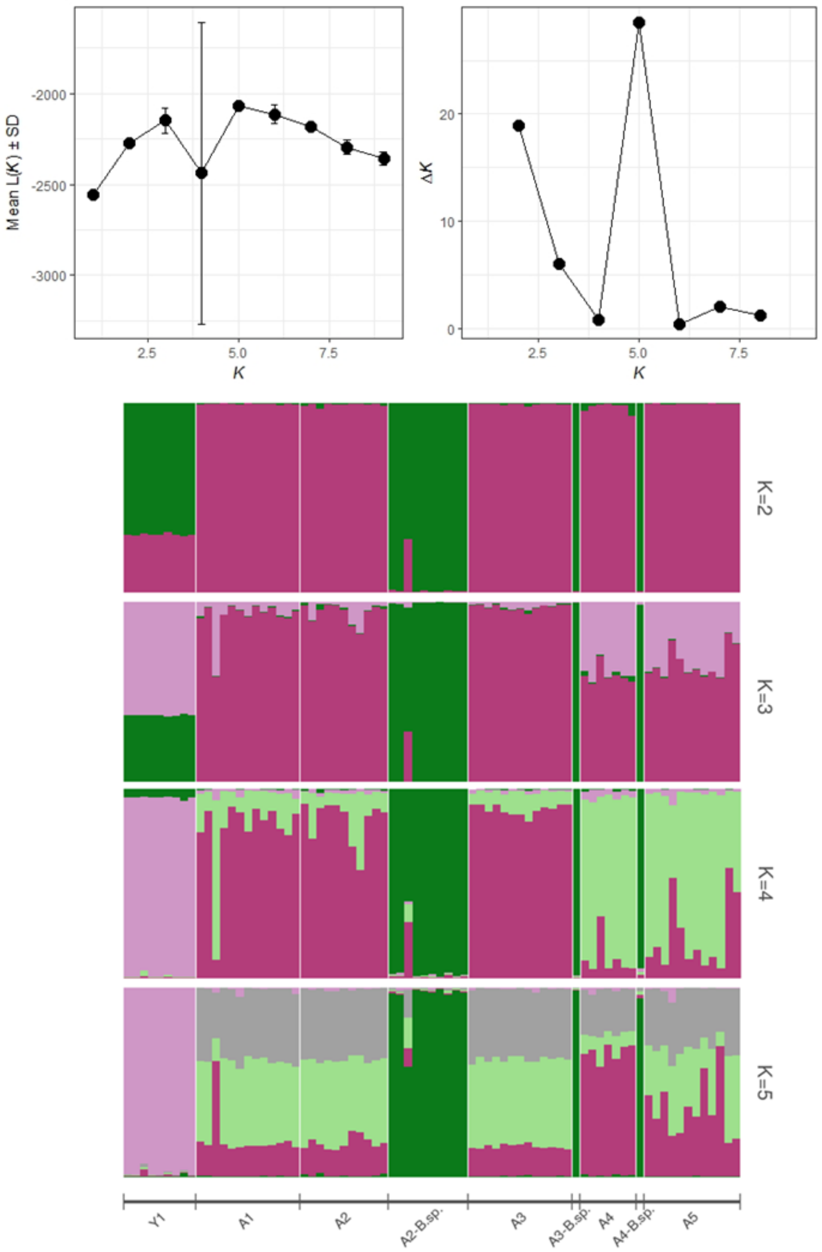


Figure A4. 2 c. After a separate analysis of the "Green Cluster", which included *B. lenok* from the Shishged River (Y1) and Amur River basin (sites A1-A5), plus blunt-snouted lenok (*B.* sp.) from A2, A3 and A4 populations, K=2 was identified as the most parsimonious solution, splitting blunt-snouted lenok (dark green individuals in sites A2, A3, A4) from *B. lenok*, with *B. lenok* from Y1 appearing admixed of these two groups. We consider the ΔK peak at K=5 as an artefact and biologically irrelevant. The peak is due to the low variability of L(K) at K= 5 together with the a rather large increase of L(K) from K=4 to K=5, which however is due to individual runs with particularly low L(K) at K=4. Therefore, K=2 is the most biologically meaningful solution of the genetic clustering present. This conclusion is supported by further analyses with different subsets of these two groups (see figures below).

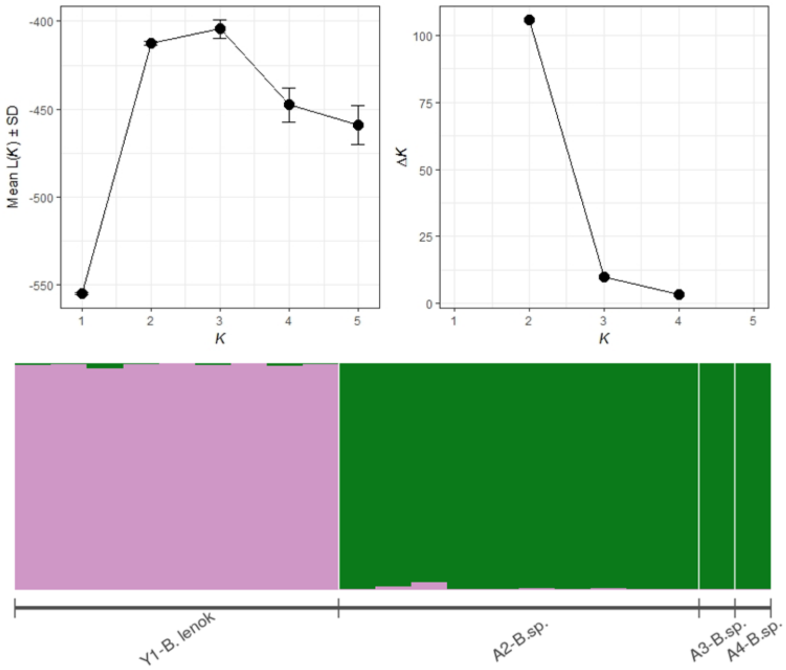


Figure A4. 2 d. The Shishged River *B. lenok* population (Y1) and blunt-snouted lenok (*B. sp.*) individuals collected from the Onon (A2), Balj (A3) and Kherlen (A4) rivers also were clearly separated into two genetic clusters ➔ K = 2.

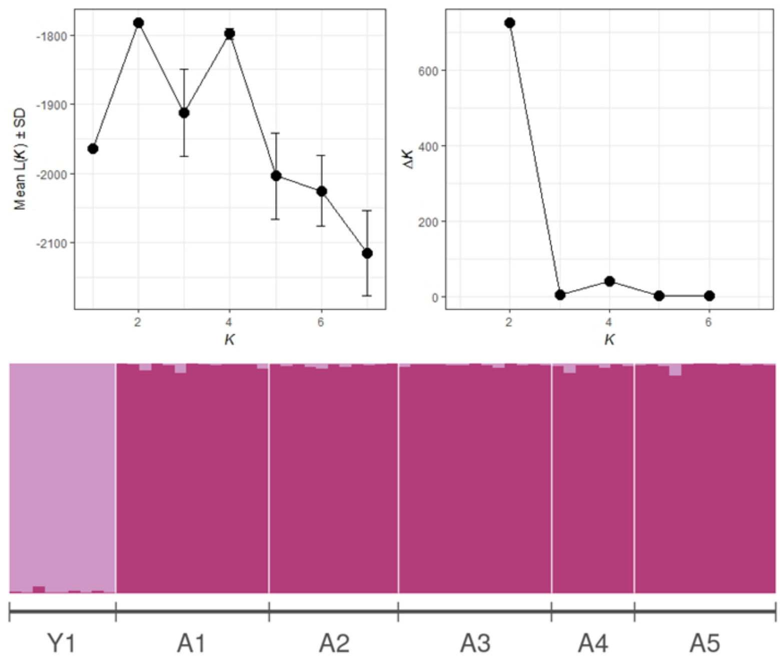


Figure A4. 2 e. *B. lenok* from the Shishged River (Y1) and the Amur River basin populations (A1-A5) with all blunt-snouted lenok (*B. sp.*) excluded, also displayed two genetic clusters; ➔ K = 2.

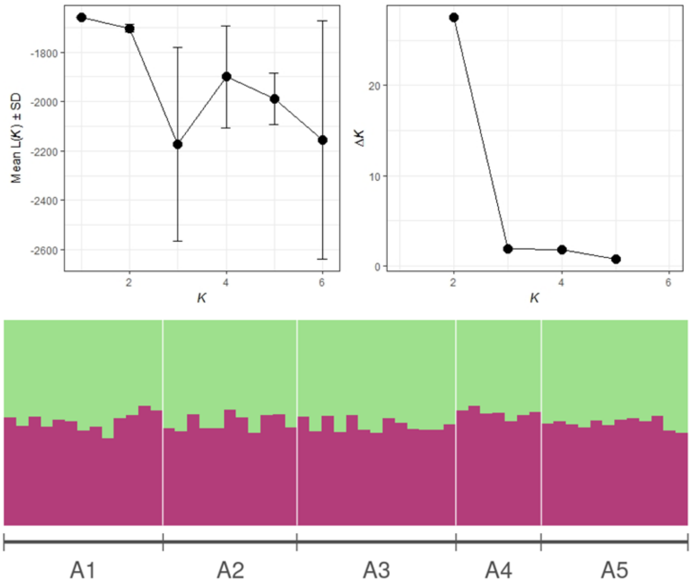


Figure A4. 2 f. For *B. lenok* populations sampled from across the Amur River basin (A1 – A5) excluding all blunt-snouted lenok (*B. sp.*) and the Shishged population, the Evanno method indicated K=2; but this is wrong as clearly, L(K) is highest at K=1 resulting in K = 1 as the most parsimonious and biologically meaningful solution ➔ K=1. Overall the STRUCTURE runs of *Brachymystax*, including both *B. lenok* and *B*. sp., revealed four genetic clusters: 1. Selenge *B. lenok* (Fig. A2a, A2b); 2.1. Amur *B*. sp. (Fig. A2c, A2d); 2.2. Shishged *B. lenok* (Fig. A2c, A2d, A2e); 2.3 Amur *B. lenok* (Fig. A2c, A2e, A2f).

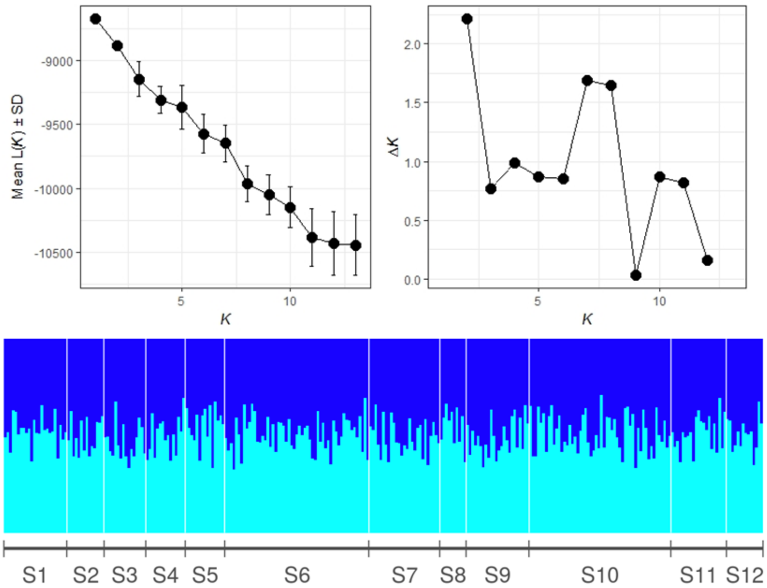


Figure A4. 3. STRUCTURE analysis of the microsatellite data of *Thymallus baicalensis* (including *T. nigrescens*, S5) in the Selenge River basin Mongolia, according to the Evanno et al. (2005) method. Note that for the Kharaa River (S9), not all, but only 24 randomly drawn samples were used (see Fig. A4.4 for an analysis including all samples). The reported ΔK is highest at K=2; however, the method is unable to detect the correct number of clusters which is K=1, as L(K) is clearly the highest solution at K=1.

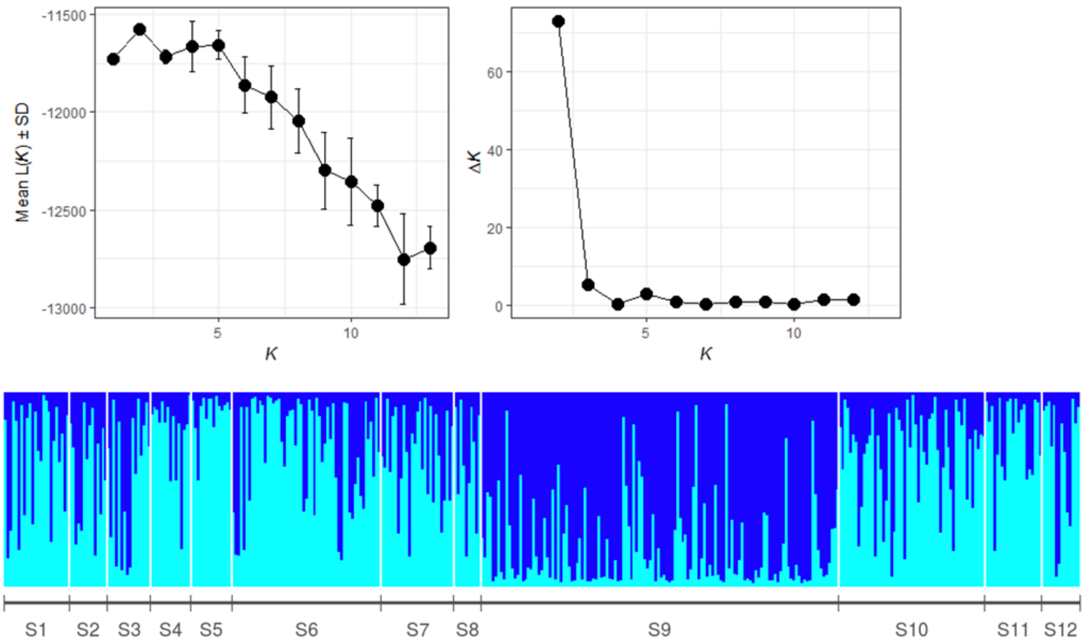


Figure A4. 4. STRUCTURE analysis of the microsatellite data of *Thymallus baicalensis* (including *T. nigrescens*, S5) in the Selenge River basin, Mongolia, according to the Evanno et al. (2005) method. Note that for the Kharaa River (S9), all 132 samples were used. The analysis indicates two gene pools (K = 2), however is very likely an artefact of unequal sample size in S9, which can be seen from the comparison with the analysis with only 24 samples from this site (Fig. A4. 3).

Table A4- 2. Pairwise estimates of F_{ST} values for the eight populations of *Hucho taimen* sampled in the Yenisei, Selenge and the Amur River basins, Mongolia. F_{ST} values are below the diagonal and probability (P (rand >= data) based on 999 permutations) is shown above the diagonal.

Pop.	Y1	S1	S3	S6	S10	A2	A3	A5
Y1		**0.004**	**0.010**	**0.007**	**0.002**	**0.001**	**0.001**	**0.001**
S1	0.083		0.421	0.443	0.214	**0.001**	**0.001**	**0.001**
S3	0.118	0.000		0.423	0.423	**0.001**	**0.001**	**0.001**
S6	0.090	0.000	0.000		0.436	**0.001**	**0.001**	**0.001**
S10	0.122	0.005	0.000	0.000		**0.001**	**0.001**	**0.001**
A2	0.238	0.293	0.301	0.279	0.319		0.187	**0.008**
A3	0.305	0.361	0.396	0.355	0.384	0.016		0.378
A5	0.257	0.327	0.335	0.306	0.364	0.088	0.006	

Table A4- 3. Pairwise estimates of F_{ST} values for the 19 populations of *Brachymystax lenok* sampled in the Yenisei, Selenge and the Amur River basins and blunt-snout lenok (*B.* sp.) sampled from the Amur basin only (including individuals from A2, A3 and A4). F_{ST} values are below the diagonal and probability (P (rand >= data) based on 999 permutations) is shown above diagonal.

	Y1	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	A1	A2	A3	A4	A5	*B.* sp.
Y1		**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S1	0.339		0.323	0.068	0.167	0.150	0.468	**0.016**	**0.028**	**0.005**	**0.003**	0.260	0.127	**0.017**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S2	0.326	0.002		0.009	0.119	**0.010**	0.182	**0.012**	**0.002**	**0.001**	**0.006**	0.066	**0.007**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S3	0.320	0.011	0.019		0.388	0.100	0.053	**0.001**	**0.002**	**0.001**	**0.001**	0.108	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S4	0.336	0.014	0.017	0.002		0.129	0.106	0.099	**0.008**	**0.006**	**0.003**	0.059	**0.007**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S5	0.331	0.009	0.029	0.012	0.016		0.059	**0.003**	**0.003**	**0.001**	**0.019**	0.270	0.141	**0.008**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S6	0.346	0.000	0.005	0.010	0.015	0.013		**0.001**	**0.009**	**0.001**	**0.002**	0.309	**0.018**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S7	0.317	0.014	0.015	0.023	0.016	0.029	0.019		**0.001**	**0.006**	**0.001**	**0.008**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S8	0.385	0.019	0.044	0.032	0.045	0.034	0.023	0.036		**0.001**	**0.001**	**0.007**	**0.002**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S9	0.326	0.017	0.026	0.032	0.035	0.025	0.024	0.009	0.045		**0.001**	**0.012**	**0.004**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S10	0.358	0.021	0.020	0.037	0.038	0.019	0.018	0.027	0.051	0.029		0.249	**0.021**	**0.003**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S11	0.375	0.005	0.016	0.011	0.027	0.005	0.003	0.019	0.030	0.017	0.004		0.376	0.064	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S12	0.402	0.011	0.033	0.048	0.049	0.012	0.020	0.037	0.048	0.028	0.019	0.002		0.406	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
S13	0.364	0.017	0.032	0.046	0.051	0.025	0.024	0.032	0.034	0.022	0.023	0.012	0.000		**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
A1	0.344	0.133	0.162	0.141	0.141	0.147	0.147	0.134	0.176	0.127	0.182	0.150	0.152	0.155		0.441	0.344	**0.001**	**0.004**	**0.001**
A2	0.313	0.137	0.156	0.135	0.137	0.145	0.148	0.142	0.181	0.139	0.186	0.158	0.162	0.166	0.000		0.346	**0.001**	**0.001**	**0.001**
A3	0.340	0.126	0.159	0.128	0.143	0.133	0.136	0.130	0.170	0.118	0.172	0.136	0.143	0.144	0.002	0.004		**0.001**	**0.001**	**0.001**
A4	0.369	0.183	0.207	0.166	0.191	0.167	0.182	0.181	0.224	0.179	0.212	0.189	0.191	0.191	0.125	0.121	0.146		**0.001**	**0.001**
A5	0.364	0.159	0.189	0.173	0.167	0.161	0.166	0.159	0.190	0.149	0.203	0.173	0.150	0.165	0.036	0.058	0.055	0.131		**0.001**
B. sp.	0.448	0.305	0.329	0.320	0.310	0.329	0.322	0.323	0.357	0.333	0.369	0.344	0.358	0.359	0.307	0.273	0.301	0.344	0.342	

Table A4- 4. Pairwise estimates of F_{ST} values for the eleven populations of *Thymallus baicalensis* sampled in the Selenge River basins and *T. nigrescens* from Lake Khovsgol (S5). F_{ST} values are below the diagonal and probability (P (rand >= data) based on 999 permutations) is shown above diagonal.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1		0.197	**0.050**	0.063	**0.001**	**0.003**	0.101	0.175	**0.001**	**0.002**	0.074	0.075
S2	0.006		0.117	0.180	**0.001**	**0.002**	**0.001**	0.061	**0.001**	**0.009**	**0.047**	0.120
S3	0.011	0.010		0.453	**0.002**	0.417	**0.012**	**0.013**	0.082	0.446	0.205	0.084
S4	0.011	0.007	0.000		**0.009**	0.154	0.074	**0.039**	**0.012**	0.145	0.260	0.420
S5	0.036	0.045	0.034	0.024		**0.001**	**0.001**	**0.034**	**0.001**	**0.001**	**0.005**	**0.036**
S6	0.015	0.023	0.000	0.005	0.024		**0.004**	**0.003**	**0.001**	0.438	0.252	**0.006**
S7	0.006	0.031	0.015	0.009	0.039	0.013		**0.012**	**0.001**	**0.001**	**0.041**	0.112
S8	0.007	0.019	0.026	0.022	0.024	0.025	0.029		**0.001**	**0.007**	**0.042**	**0.046**
S9	0.033	0.031	0.009	0.018	0.061	0.015	0.035	0.053		**0.009**	**0.005**	**0.002**
S10	0.014	0.015	0.000	0.005	0.030	0.000	0.017	0.025	0.010		0.180	**0.022**
S11	0.008	0.013	0.005	0.003	0.030	0.002	0.010	0.018	0.019	0.003		0.078
S12	0.010	0.011	0.012	0.000	0.021	0.016	0.008	0.022	0.033	0.012	0.010	

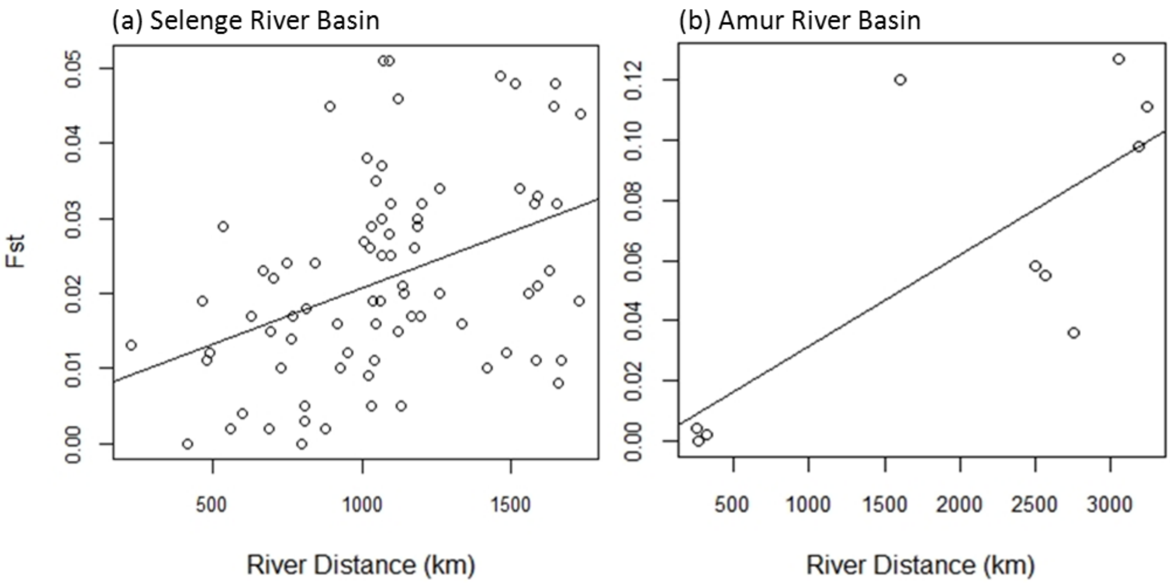


Figure A4. 5. Correlation between the distance along the river and genetic distance of sampled *Brachymystax lenok* populations (a) Selenge River Basin (Mantel's test statistic = 0.41, p = 0.004); and (b) Amur River Basin (excluding blunt-snouted lenok *B*. sp., Mantel's test statistic = 0.76, p = 0.045).

Table A4- 5. Summary results for the Analyses of Molecular Variance (AMOVA) (a) All *H. taimen* (F_{ST} = 0.302), (b) *H. taimen* from the Selenge (F_{ST} = 0.027), (c) *H. taimen* from the Amur basin (F_{ST} = 0.052); (d) All *Brachymystax* individuals including both *B. lenok* and blunt-snouted lenok (*B. sp.*; F_{ST} = 0.177), (e) *B. lenok* only (F_{ST} = 0.181), (f) *B. lenok* from the Selenge (F_{ST} = 0.049), and (g) Amur (F_{ST} = 0.056) basins; and (h) *T. baicalensis* / *T. nigrescens* (F_{ST} = 0.014) from the Selenge River basin. NA indicated that no p value was calculated.

	df	SS	MS	Est. Var.	%	p
(a) All *H. taimen*						
Among Basins	2	165.75	82.88	1.15	29%	0.001
Among Pop. within basins	5	18.80	3.76	0.04	1%	0.060
Among Individuals	119	349.33	2.94	0.19	5%	0.003
Within Individuals	127	325.50	2.56	2.56	65%	NA
Total	253	859.39		3.94	100%	
(b) Selenge *H. taimen*						
Among Populations	4	16.29	4.07	0.07	3%	0.004
Among Individuals	70	178.10	2.54	0.1	4%	0.058
Within Individuals	75	176.00	2.35	2.35	93%	NA
Total	149	370.39		2.51	100%	
(c) Amur *H. taimen*						
Among Populations	2	11.9	5.95	0.17	5%	0.008
Among Individuals	49	171.23	3.49	0.31	9%	0.002
Within Individuals	52	149.50	2.88	2.88	86%	NA
Total	103	332.63		3.36	100%	
(d) All *Brachymystax spp.*						
Among Basins	2	135.78	67.89	0.49	15%	0.001
Among Pop. within basins	16	113.27	7.08	0.10	3%	0.001
Among Individuals	364	1089.76	2.99	0.24	7%	0.001
Within Individuals	383	963.00	2.51	2.51	75%	NA
Total	765	2301.81		3.35	100%	
(e) *B. lenok* (only)						
Among Basins	2	124.44	62.22	0.52	16%	0.001
Among Pop. within basins	16	96.95	6.06	0.08	2%	0.001
Among Individuals	352	1019.94	2.90	0.18	5%	0.001
Within Individuals	371	940.00	2.53	2.53	76%	NA
Total	741	2181.34		3.32	100%	
(f) Selenge *B. lenok*						
Among Populations	13	114.81	8.83	0.14	5%	0.001
Among Individuals	301	860.42	2.86	0.17	6%	0.001
Within Individuals	315	795.50	2.53	2.53	89%	NA
Total	629	1770.7		2.83	100%	
(g) Amur *B. lenok* (only)						
Among Populations	4	27.67	6.92	0.17	6%	0.001
Among Individuals	51	159.59	3.13	0.27	9%	0.001
Within Individuals	56	144.50	2.58	2.58	85%	NA
Total	111	331.69		3.03	100%	
(h) All *Thymallus spp.*						
Among Populations	11	51.02	4.64	0.04	1%	0.001
Among Individuals	277	785.05	2.83	0.19	8%	0.001
Within Individuals	289	709.00	2.45	2.45	91%	NA
Total	577	1545.07		2.68	100%	

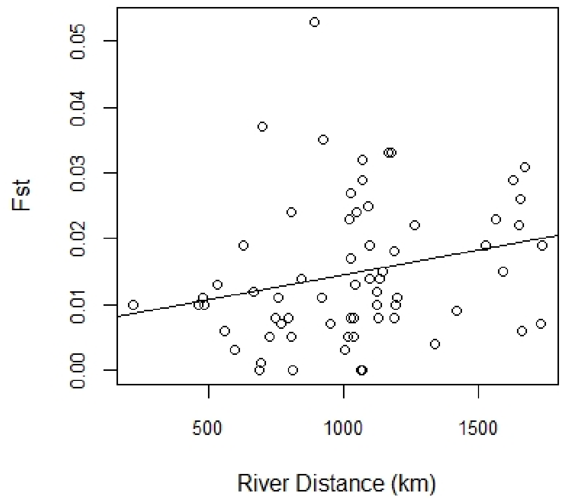


Figure A4. 6. Correlation between the distance along the river and genetic distance of sampled *Thymallus baicalensis* populations (excluding *T. nigrescens* from Lake Hovsgol) in the Selenge River basin (Mantel's test statistic = 0.24, p = 0.12.

Table A4- 6. Additional genbank accessions used for inferring haplotype networks in *Hucho taimen* and *Brachymystax* spp.

Hucho taimen	*Brachymystax* spp.			
AY230447	AY230451	DQ017067	EU395728	JN680735
AY230448	AY230452	DQ017068	EU395729	JN680736
AY230449	AY230453	DQ017069	EU395730	JN680737
AY230450	AY230454	DQ017070	EU395731	JN680738
AY862343	AY230455	DQ017071	EU395732	JX227987
AY862344	AY230456	DQ017072	EU395733	KC136268
AY862345	AY230457	DQ017073	EU395734	KC136269
AY862346	AY230458	DQ017074	EU395735	KC136270
AY862347	AY230459	DQ017075	EU760490	KF647837
AY862348	AY230460	DQ017076	EU760491	KF647838
AY862349	AY230461	DQ017077	FJ713570	KF647839
AY862350	AY230462	DQ017078	FJ713571	KF647840
AY862351	AY230463	DQ017079	FJ713572	KF647841
AY862352	AY230464	EU395717	FJ713573	KF647842
AY862353	AY230465	EU395718	FJ713574	KF647843
AY862354	AY230466	EU395719	FJ713575	KF647844
AY862355	AY230467	EU395720	FJ713576	KF647845
AY862356	AY230468	EU395721	FJ713577	
AY862357	AY230469	EU395722	FJ713578	
AY862358	AY230470	EU395723	JN680730	
AY862359	AY230471	EU395724	JN680731	
EU395715	AY230472	EU395725	JN680732	
EU760489	AY960113	EU395726	JN680733	
KF703543	DQ017066	EU395727	JN680734	

Appendix 5

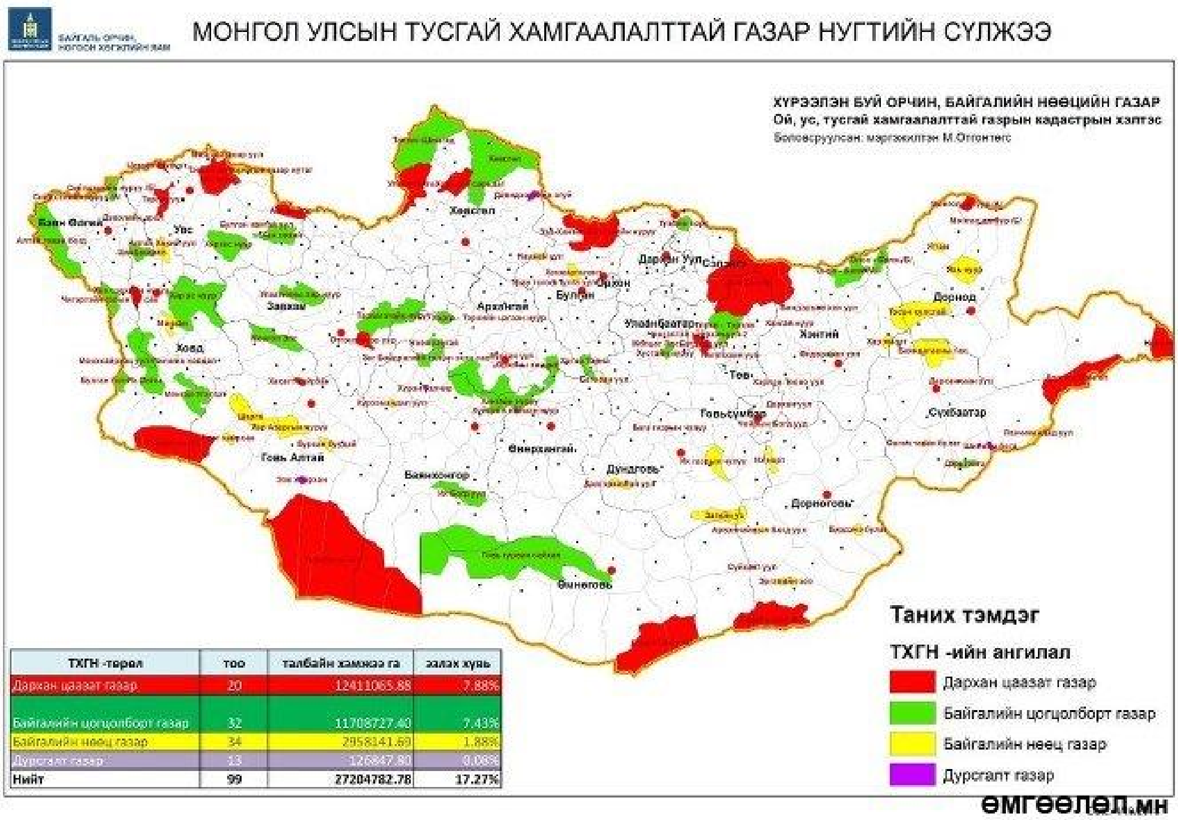
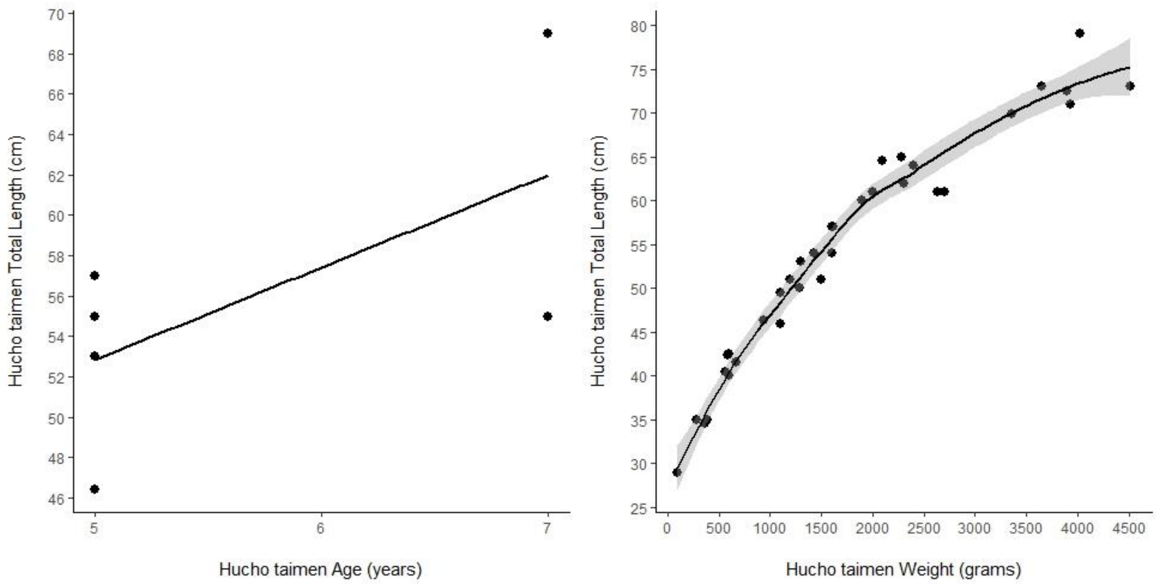


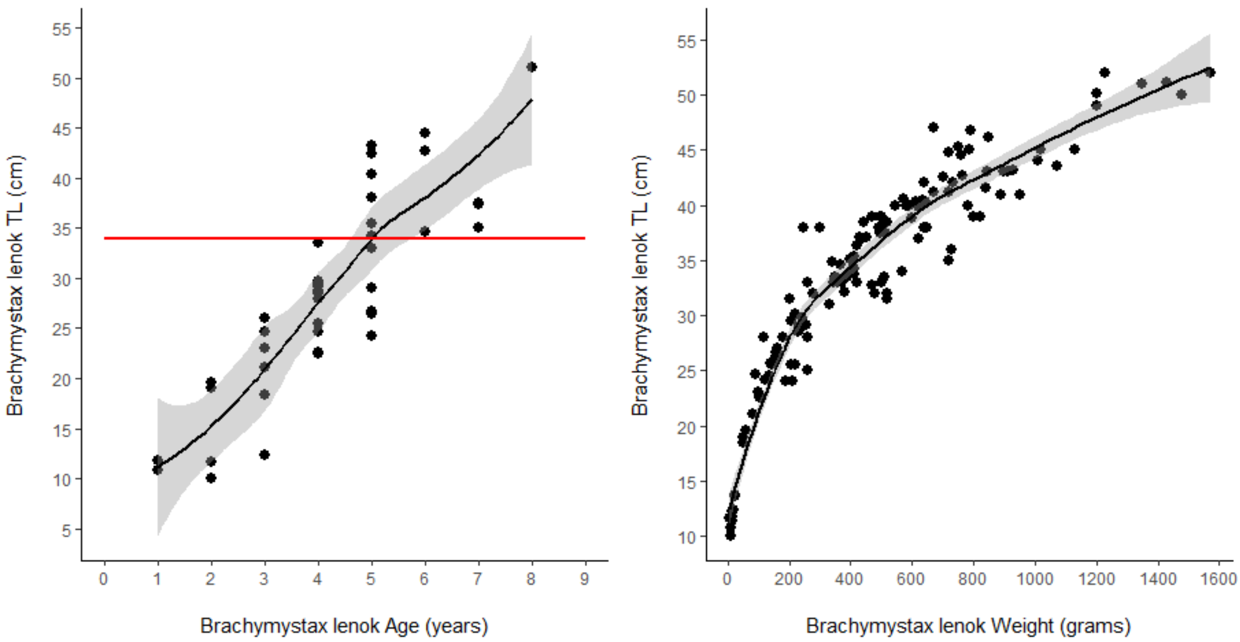
Figure A5. 1 Map of Mongolia's Protected Areas in 2015 covering 17.27 % of the total land area. Red indicates Strictly Protected Areas (n = 20), green represents National Parks (n = 32), yellow are Nature Reserves (n = 34), and purple is a National Monument (n = 13). Source: Political Review Bulletin 10.12.2015 (http://vip76.mn/content/35658).

Appendix 6

a)



b)



c)

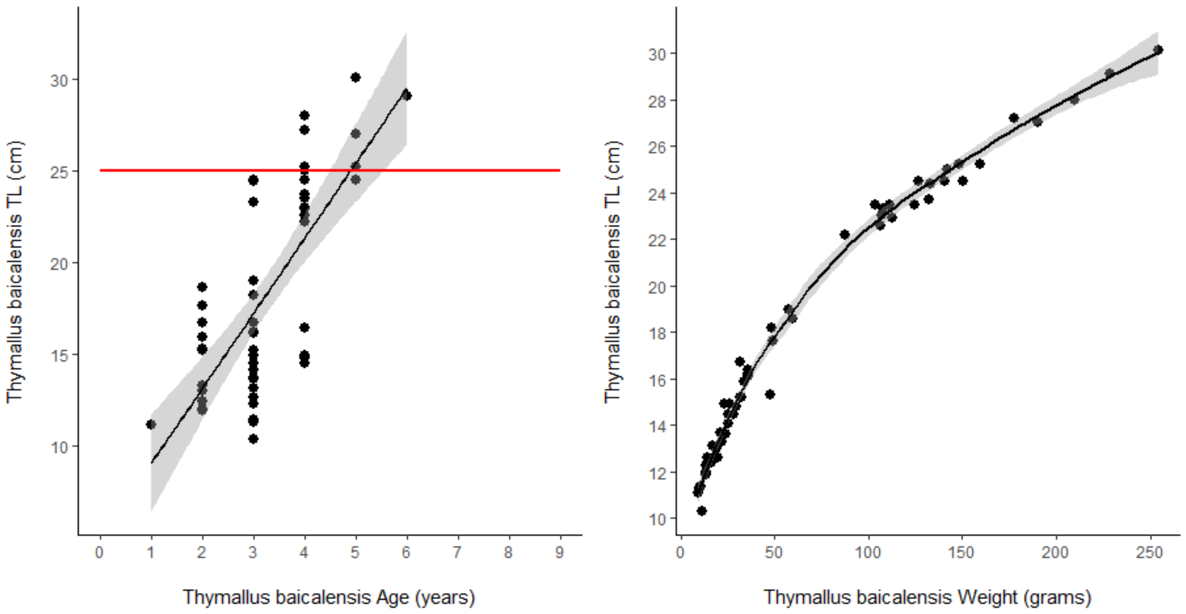


Figure A6. 1. Biometric data collected from the three salmonid species a) *Hucho taimen*, b) *Brachymystax lenok* and c) *Thymallus baicalensis*, during the current research in the Kharaa River basin (*B. lenok* and *T. baicalensis*) and Eroo River basin (All species). The horizontal red line represents the proposed minimum size limit for *B. lenok* and *T. baicalensis* respectively. Total lengths were measured in centimetres, total weights in grams and ages were counted in years. Otoliths were extracted from sampled individuals (*B. lenok* and *T. baicalensis* only) or from recreational catches / poaches (*H. taimen*) that were encountered. The grey shading represents the 95 % confidence interval (CI).

Appendix 7

Figure A7. 1. A copy of a poster (in Mongolian) that was developed to help educate anglers of the key fishing laws, the originally proposed minimum size limits (28 cm TL), best practices for catching, handling and releasing *H. taimen* and some general advice environmental to address some key issues that have been observed *e.g.* disposal of rubbish, use of soap in rivers and the dangers of throwing cigarette butts near to or in rivers.

11 References to Own Published / Submitted Manuscript in the Present Thesis

Chapter 4 (*Under Review*)

Kaus, A., Schäffer, M., Karthe, D., Borchardt, D., "An emerging recreational fishery in Mongolia's urbanising society: a threat to its pristine fish stocks?" *Fisheries Management and Ecology*

Chapter 5 (*Published*)

Kaus, A., Schäffer, M., Karthe, D., Büttner, O., von Tümpling, W., Borchardt, D. (2016). Regional patterns of heavy metal exposue and contamination in the fish fauna of the Kharaa River basin (Mongolia). Regional Environmental Change, 16(4), doi: 10.1007/s10113-016-0969-4

Chapter 6 (*Published*)

Kaus, A., Büttner, O., Karthe, D., Schäffer, M., Borchardt, D. (2017). Migration and movement profiles of a potadromous fish (*Brachymystax lenok* Pallas 1773) in a highly connected river system (Mongolia). Ecology of Freshwater Fish, 1- 15. doi: 10.1111/eff.12390.

Chapter 7 (*Published*)

Kaus, A., Büttner, O., Schäffer, M., Balbar, G., Surenkhorloo, P., Borchardt, D. (2016). Seasonal home range shifts of the Siberian taimen (*Hucho taimen,* Pallas 1773): Evidence from passive acoustic telemetry in the Onon River and Balj tributary (Amur River basin, Mongolia). International Review Hydrobiology, 101, 1-13. doi:10.1002/iroh.201601852

Chapter 8 (*Under Review*)

Kaus, A., Michalski, M., Karthe, D., Hänfling, B., Borchardt, D., Durka, W. "Fish conservation in the land of steppe and sky: evolutionary significant units of threatened salmonid species in Mongolia mirror major river basins". *Ecology and Evolution*

12 Individual Contributions to the Current Thesis

CHAPTER 4 - An emerging recreational fishery in Mongolia's urbanising society: a threat to its pristine fish stocks?

Andrew Kaus (first author)	Developed concept and hypothesis Organised and conducted creel surveys Data analysis and interpretation of results Prepared figures and tables Composed and edited manuscript
Michael Schäffer	Assisted with creel surveys Corrected manuscript
Daniel Karthe	Produced map Corrected manuscript
Dietrich Borchardt	Developed concept and hypothesis Corrected manuscript

CHAPTER 5 - Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia)

Andrew Kaus (first author)	Developed concept and hypothesis Organised and conducted field sampling and dissections Organised and conducted laboratory analysis Data analysis and interpretation of results (GLM) Prepared figures and tables Composed manuscript
Michael Schäffer	Assisted with field sampling and dissections Assisted with laboratory analysis Assisted with data analysis and interpretation of results Prepared figures Corrected manuscript
Daniel Karthe	Produced map Corrected manuscript
Olaf Büttner	Assisted with preliminary data analysis Corrected manuscript
Wolf von Tümpling	Advised laboratory analysis methods Conducted statistical analysis Corrected manuscript
Dietrich Borchardt	Developed concept and hypothesis Corrected manuscript

CHAPTER 6 - Movements and behaviour of an archaic trout, Brachymystax lenok (Pallas, 1773), under extreme environmental conditions in Mongolia

Andrew Kaus (first author)	Developed concept and hypothesis Organised and conducted field sampling, fish surgeries and logger retrieval Data analysis and interpretation of results Prepared figures and tables, conducted statistical analysis Composed manuscript
Olaf Büttner	Database management and analysis Prepared figures, statistical analysis, modelling Corrected manuscript
Michael Schäffer	Assisted with field sampling and logger retrieval Corrected manuscript

Daniel Karthe	Produced map Corrected manuscript
Dietrich Borchardt	Developed concept and hypothesis Corrected manuscript

Chapter 7- Seasonal home range shifts of the Siberian taimen (Hucho taimen Pallas 1773): Evidence from passive acoustic telemetry in the Onon River and Balj tributary (Amur River basin, Mongolia)

Andrew Kaus (first author)	Developed concept and hypothesis Organised and conducted field sampling, fish surgeries and logger retrieval Data analysis and interpretation of results Prepared figures and tables, conducted statistical analysis Composed manuscript
Olaf Büttner	Database management and analysis Prepared figures, statistical analysis, modelling Corrected manuscript
Michael Schäffer	Assisted with field sampling and logger retrieval Corrected manuscript
Ganna Balbar	Organised field sampling, Assisted with field sampling and logger retrieval Corrected manuscript
Puje Surenkhorloo	Developed concept and hypothesis Organised field sampling, Assisted with field sampling and logger retrieval Prepared map Corrected manuscript
Dietrich Borchardt	Developed concept and hypothesis Corrected manuscript

Chapter 8 - Fish conservation in the land of steppe and sky: evolutionary significant units of threatened salmonid species in Mongolia mirror major river basins

Andrew Kaus (first author)	Developed concept and hypothesis Designed, organised and conducted field sampling Conducted laboratory work for microsatellites Conducted data analysis for microsatellites Prepared figures for microsatellites Interpretation of results, prepared tables Composed manuscript
Stefan Michalski	Conducted laboratory work for mtDNA Conducted data analysis for mtDNA Prepared figures for mtDNA
Daniel Karthe	Prepared map Corrected manuscript
Bernd Hänfling	Developed concept and hypothesis Assisted with the interpretation of results Corrected manuscript
Dietrich Borchardt	Developed concept and hypothesis Corrected manuscript
Walter Durka	Developed concept and hypothesis Advised laboratory work for microsatellites Advised statistical analysis and interpretation Corrected manuscript
Other personal: Andrea Voigt (HiWi)	Assisted with the laboratory analysis – DNA extraction and microsatellites sequencing

13 Note on the Commencement of the Doctoral Procedure

(1) I hereby assure that I have produced the present work without inadmissible help from third parties and without other than those stated. Ideas taken directly or indirectly from external sources are identified as such.

(2) When selecting and evaluating the material and also when producing the manuscript, I have received support from the following persons:

Prof. Dr. Dietrich Borchardt

(3) No further persons were involved in the intellectual production of the present work. In particular, I have not received help from a commercial doctoral adviser. No third parties have received monetary benefits from me, either directly or indirectly, for work relating to the content of the presented dissertation.

(4) The work has not previously been presented on the same or a similar format to another examination body in Germany or abroad, nor has it – unless it is a cumulative dissertation – been published.

(5) If this concerns a cumulative dissertation in accordance with Section 10 Para.2, I assure compliance with the conditions laid down therein.

(6) I confirm that I acknowledge the doctoral regulations of the Faculty of Environmental Sciences of the Technische Universität Dresden.

Dresden, September 22nd 2017

14 Curriculum Vitae

Tertiary Qualifications

2010 – current **PhD Candidate** Department of Aquatic Ecosystem Analysis and Management, Helmholtz Centre for Environmental Research, Magdeburg, Germany and Technical University of Dresden, Dresden, Germany.

PhD Supervisor: - Prof. Dr. Dietrich Borchardt. Thesis title: - Ecological assessment of salmonid populations in a country undergoing rapid environmental and socioeconomic transitions (Mongolia).

2003 - 2004 **Master of Applied Science** (Tropical Marine Ecology and Fisheries Biology), School of Marine Biology and Aquaculture, James Cook University, Australia

Masters Supervisor: - Assoc. Prof. Dr. Geoffrey Jones. Master's thesis title: - Chemical marking embryonic *Amphiprion melanopus* otoliths using barium (^{137}Ba) incorporated via maternal transmission. Master's thesis result: - High Distinction.

2000 - 2002 **Bachelor of Science** (Aquaculture and Zoology) School of Marine Biology and Aquaculture and School of Tropical Biology, James Cook University, Australia

Employment History

2014 - 2017 **Scientific Researcher,** Department of Aquatic Ecosystem Analysis and Management, Helmholtz Center for Environmental Research, Magdeburg, Germany

2009 – 2010 **Aquatic Fish Ecologist,** Arthur Rylah Institute for Environmental Research, Melbourne, Australia

2007 **Aquaculture Researcher** with the Australian Youth Ambassadors for Development Project funded by Ausaid within the Department of Foreign Affairs and Trade to Can Tho University, Vietnam.

2006 - 2007 **Fisheries Technician** for the reef fish research hatchery team at the Aquaculture and Stock Enhancement Facility of the Northern Fisheries Centre, Cairns, Australia.

2005 - 2006 **Fisheries Technician** with the Long-term Monitoring Project for the Assessment and Monitoring division at the Northern Fisheries Centre, Cairns, Australia.

2004 **Research Assistant** for Assoc. Prof. Geoffrey Jones, Adjunct Lecturer Dr Phillip Munday, Marine and Aquaculture Research Facility, School of Marine Biology and Aquaculture, James Cook University, Townsville, Australia.

Licences and Training Courses

- Recreational Ship Masters License, 2002
  - Coxswains Coastal Maritime Operations (Certificate II in Transport and Distribution), 2009.
  - Elements of Ship Board Safety Course, 2009
- Open Water PADI Diver Certification, 2008
- Open Manual Drivers Licence, 2000
  - Advanced 4WD operations, maintenance and recovery course, 2006
- First Responder Refresher Course, 2016, Germany
  - Remote Area First Aid Specific, 2004 (St Johns First Aid)
- Graphical Visualisations in R 2016

- Statistics for Ecologists using R 2015
- Introduction to Environmental Ecotoxicology 2011
- Introduction to Hydrobiology, Water Research and Management 2011

Conferences and Workshops

- UFZ Seminar Series, Oral Presentation 2016, Magdeburg, Germany
- HIGRADE Graduate Students Conference 2015, Oral Presentation, Leipzig, Germany
- Lake Baikal and Selenge Basin Workshop, 2014, Irkutsk, Russia
- 2nd International Fish Telemetry Conference 2013, Oral Presentation, Grahamstown, South Africa
- Mongolia Project Update Conference, 2012, Oral Presentation, Darkhan, Mongolia
- Biodiversity Research in Mongolia Conference 2012, Oral Presentation, Halle, Germany
- World Fisheries Congress 2012, ePoster Presentation, Edinburgh, Scotland
- 6th World Recreational Fishing Conference 2011, Poster Presentation, Berlin, Germany
- IWA Central Asian Young Water Professionals Conference 2011, Oral Presentation, Almaty, KZ
- Australian Society of Fish Biology Conference 2010, Poster Presentation, Melbourne, Australia

Authored Reports

Kaus, A., Büttner, O., Schäffer, M., Balbar, G., Surenkhorloo, P., Borchardt, D. (2015). *Hucho taimen* movements in the Onon and Balj Rivers, Mongolia 2013 / 2014. World Wildlife Fund for Nature Mongolia and IWRM MoMo Project / Helmholtz Centre for Environmental Research, Germany

Kaus, A., Völker, J., Bärlund, I., Büttner, O., Katterfeld, C., Malsy, M., Borchardt, D. (2015) Sensitivity of Inland Fisheries to Water Quality (Milestone M5.1, Product 5.1): Assessment of World Water Quality to Meet the Global Water Quality Challenge. UFZ / CESR

Karthe, D., Borchardt, D., **Kaus, A.** (2011). Towards an Integrated Water Resources Management for the Kharaa Catchment, Mongolia. (Ed.) (2011) Proceedings of the IWA 1st Central Asian Regional Young and Senior Water Professionals Conference, Almaty/Kazakhstan, pp. 79–93

Kaus, A., Karthe, D., Borchardt, D. (2011). Incorporating fish ecology into water resource management: Current research in northern Mongolia. Proceedings of the IWA 1st Central Asian Regional Young and Senior Water Professionals Conference, Almaty/Kazakhstan

Kaus, A., Crook, D. (2010). Lake Condah Restoration Project – Biodiversity Assessment 2010. Internal Report. Arthur Rylah Institute for Environmental Research, Melbourne, Australia

Kaus, A., Fairweather, C., Rose, D. (2008). Fisheries Long Term Monitoring Program - Summary of the Gulf of Carpentaria Developmental Finfish Trawl Fishery survey results: 2004 – 2006. Department of Primary Industries and Fisheries, Brisbane, Australia

Referees

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15 List of Publications

ISI Publications

Kaus, A., Büttner, O., Karthe, D., Schäffer, M., Borchardt, D. (2017) Migration and movement profiles of a potadromous fish (*Brachymystax lenok* Pallas 1773) in a highly connected river system (Mongolia). Ecology of Freshwater Fish, 1- 15. doi: 10.1111/eff.12390.

Kaus, A., Schäffer, M., Karthe, D., Büttner, O., von Tümpling, W., Borchardt, D. (2016a). Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia). Regional Environmental Change, 16(4) doi: 10.1007/s10113-016-0969-4

Kaus, A., Büttner, O., Schäffer, M., Balbar, G., Surenkhorloo, P., Borchardt, D. (2016b). Seasonal home range shifts of the Siberian taimen (*Hucho taimen,* Pallas 1773): Evidence from passive acoustic telemetry in the Onon River and Balj tributary (Amur River basin, Mongolia). International Review Hydrobiology, 101: 1-13. doi: 10.1002/iroh.201601852

Karnaukhov, D.Y., Bedulina, D.S., **Kaus, A.**, Prokosov, S.O., Sartoris, L., Timofeyev, M.A., Takhteev, V.V. (2016). Behaviour of Lake Baikal Amphipods as part of the night migratory complex in the Kluevka settlement region (South-Eastern Baikal). Crustaceana, 89(4): 419-430. doi: 10.1163/15685403-00003530

Hofmann, J., Karthe, D., Ibisch, R., Schäffer, M., Avlyush, S., Heldt, S., **Kaus, A.** (2015). Initial Characterization and Water Quality Assessment of Stream Landscapes in Northern Mongolia. Water, 7(7): 3166-3205. doi: 10.3390/w7073166

Tokin, Z., Ramsey, D.S.L., Macdonald, J., Crook, D., King, A., **Kaus, A.** (2014). Does localized control of invasive eastern gambusia (Poeciliidae: *Gambusia holbrooki*) increase population growth of generalist wetlands fishes? Austral Ecology, 39(3): 355-366. doi: 10.1111/aec.12088

Macdonald, J.I., Tonkin, Z., Ramsey, D.S.L., **Kaus, A.**, King, A.K., Crook, D.A. (2012). Do invasive eastern gambusia (*Gambusia holbrooki*) shape wetland fish assemblage structure in south-eastern Australia? Marine and Freshwater Research, 63(8): 659 – 671. doi: 10.1071/MF12019

Submitted Manuscripts

Kaus, A., Schäffer, M., Karthe, D., Borchardt, D. "An emerging recreational fishery in Mongolia's urbanising society: a threat to its pristine fish stocks?"

Kaus, A., Michalski, M., Karthe, D., Hänfling, B., Borchardt, D., Durka, W. "Fish conservation in the land of steppe and sky: evolutionary significant units of threatened salmonid species in Mongolia mirror major river basins" *Ecology and Evolution*