THE IMPACT OF A DROUGHT ON KEY FRESHWATER PEARL MUSSEL *MARGARITIFERA MARGARITIFERA* POPULATIONS IN SCOTLAND

PETER COSGROVE[1], DONALD SHIELDS[1], DAWN ANDERSON[1], KATE MASSEY[1], CAMERON COSGROVE[2] & IAIN SIME[3]

[1]Alba Ecology Ltd, Coilintra House, Grantown on Spey, Moray, UK, PH26 3EN
[2]Faculty of Forestry, University of British Columbia, Vancouver, Canada, V6T 1Z4
[3]NatureScot, Great Glen House, Inverness, UK, IV3 8NW

Abstract *A prolonged period of high temperatures and low rainfall, created extremely low river levels across much of Scotland during summer 2018. At the time, there was anecdotal evidence that this drought caused significant ecological harm in several locations, including watercourses supporting internationally important pearl mussel populations. Given that the species is highly protected and also critically endangered in Europe, a study was undertaken to quantify the impact of the prolonged dry weather on four priority rivers. The evidence from this study, although mixed, demonstrates that significant drought mortalities can and do occur in Scotland, and by extension could happen elsewhere in the species' northern range. Previous studies on the impact of drought have taken place in populations at the southern edge of the species' range, and we recommend restorative actions that should help pearl mussel populations better adapt to the likelihood of increased drought events in the future.*

Key words *Freshwater pearl mussel, drought, climate change,* Margaritifera margaritifera

INTRODUCTION

The freshwater pearl mussel *Margaritifera margaritifera* (hereafter 'pearl mussel') is threatened throughout its Holarctic range and is classified by the International Union for the Conservation of Nature (IUCN) as Critically Endangered in Europe (Moorkens, 2011). The largest remaining populations in Scotland, Ireland, Norway, Finland, Sweden and northwest Russia are of international importance (Cosgrove *et al.,* 2014). The species has a complex lifecycle, which makes them vulnerable to a number of pressures and threats, one of which is from climate change (e.g. Hastie *et al.*, 2003; Cosgrove *et al.,* 2012a).

All known rivers in Scotland with recent records of pearl mussels were surveyed in 2013–2015 using a standard methodology (Cosgrove *et al.,* 2016). Pearl mussel populations were classed as: (i) apparently extinct in 11 rivers, (ii) not successfully recruiting in 44 rivers, and (iii) evidence of recent successful recruitment in 71 rivers. On a regional basis, a high proportion of extant populations were located in north and west Scotland. The status of pearl mussels in Scotland is of international importance, but their continued decline since the first national survey in 1998 is of great concern. The key threats identified by Cosgrove *et al.*, (2016) were: (i) pearl fishing, (ii) low host fish densities, (iii) pollution/water quality, (iv) climate change and associated habitat loss, (v) hydrological management/river engineering and (vi) 'other factors', such as non-native invasive species.

A prolonged period of high temperatures and low rainfall, creating historically low river levels were experienced across much of Scotland during summer 2018. June-July 2018 in particular saw notably or exceptionally low river levels across northern and western Scotland, and the lowest levels on record in a number of rivers (Hannaford, 2018). At the time, there was anecdotal evidence that this drought caused significant ecological harm in several locations, including watercourses that supported internationally important pearl mussel populations.

There has recently been evidence published of both the impact of a drought in the Iberian peninsula on pearl mussel populations at the southern limit of their range (Sousa *et al.*, 2018; Nogueira *et al.,* 2019) and that climate warming may be a possible trigger for declines in pearl mussel populations more widely (Bolotov *et al.,* 2018). The present study aimed to quantify, where possible, the impact of the prolonged period of dry weather in 2018 on four pearl mussel populations in the north of Scotland. Four rivers designated

Contact author : petercosgrove@albaecology.co.uk

as Special Areas of Conservation (SACs), under the EU Habitats Directive, within the drought affected area were selected for study because these watercourses held existing long-term baseline monitoring datasets, which was considered important to allow as robust a 'before and after drought' comparison as possible. Furthermore, the United Kingdom (UK) has legal obligations towards protected habitats and species and NatureScot commissioned this study to assess the impact of the 2018 drought on four of these important populations.

METHODOLOGY

This study aimed to survey discrete sections of the four SAC rivers to establish the current density, status and distribution of pearl mussels in reaches where they were considered to be of particular risk from damage during low flows in summer 2018. Despite being fully legally protected for over two decades, large numbers of pearl mussels are illegally killed every year in Scotland (Cosgrove *et al.*, 2012b). Consequently, because of the on-going illegal pearl-fishing threat, the watercourse names and locations are treated as confidential and are coded Rivers 1–4 to maintain site confidentiality.

The survey technique followed national standard 50m×1m transect methodology (running parallel to the bank) used in all Scottish pearl mussel monitoring since 1998. At each watercourse, a minimum of 300m of river length was surveyed. This equates to, at least, a total of six 50m×1m transects in each watercourse. These were focussed wherever possible around existing long-term SAC monitoring 50m transect sites, known as Site Condition Monitoring (SCM) locations. Whilst the 50m transect width was always 1m wide, its distance out from the bank sometimes varied according to where the most suitable habitats were found. For example, in the results this may be reported as 1–3m or 3–5m out, i.e. the 1m wide transect was situated in the river between 1 to 3m or 3 to 5m out from the bank.

Three of the four rivers were resurveyed in 2019 at SCM transects locations (one river was resurveyed in January 2020). Additionally, we present the results of an opportunistic survey in River 1 during the drought showing the clear mortality caused by the drought.

Table 1 The mussel abundance classifications and for 50m×1m transects

Mussels in 50m transect (N)	Abundance code	Term used in text
≥1000	A	Abundant
500–999	B	Common
50–499	C	Scarce
1–49	D	Rare
0	E	Absent

The abundance terms reported (Table 1) are based on the number of pearl mussels found in a standard 50m×1m transect. These categories are based on visible, i.e. part-buried, mussels.

At each of the SAC rivers identified for survey, there were a number of transects that had previous pearl mussel survey data. Between six and ten transect locations were selected for each SAC river. The transect site selection for each river was based a desk-based exercise, which identified previous SCM locations holding live pearl mussels during the most recent previous survey.

RIVER DESCRIPTIONS

The River 1 is a medium sized watercourse in the north of Scotland. It is typically ca. 10–20m wide and under summer flows ca. 0.5m deep. The lower reaches of the catchment are dominated by rough sheep and cattle grazing and the middle reaches are within plantation forestry before opening out into heathland and blanket bog in the upper reaches. The dominant catchment soil type is peat.

The River 2 is a medium-sized upland, regulated river in north of Scotland. It is typically ca. 5–10m wide and under summer flows ca. 0.3m deep. The catchment ranges from farmland/pasture/woodland in the lower reaches to heather moorland/scrub and blanket bog in the upper reaches, dominated by rough sheep and cattle grazing. The dominant catchment soil type is peat.

The River 3 is a very large and long watercourse in the north of Scotland. It is typically ca. 20–30m wide and under summer flows ca. 0.5–1.0m deep (with many deeper areas throughout the middle and lower reaches – but these have never been part of SCM). The catchment ranges from high altitude mountains with heathland, blanket bog and native woodland in the upper reaches through to farmland/pasture and commercial woodland in the middle and lower reaches. The dominate soil type in the upper reaches is peat, with non-peaty soils dominating the mid-lower reaches.

The River 4 is a large sized and relatively long watercourse in the north of Scotland. It is typically ca. 20–45m wide and under summer flows is ca. 0.4m deep and is dominated by a series of contrasting shallow riffle and glide areas, with occasional slow flowing, deeper peaty sections through heathland, blanket bog and rough pasture. The dominant catchment soil type is peat.

LIMITATIONS & ASSUMPTIONS

When comparing surveys undertaken in different years, it is important to recognise the assumptions and limitations (Table 2). Some of these are common to all pearl mussel surveys, some are common to between year or season comparisons and others only to a particular transect or river. Where these were considered important they have been highlighted in the individual SAC river accounts.

RESULTS

River gauges on three of the four SAC rivers indicated that 2018 water levels reached close to historic lows experienced over the past 50 years.

River 1

Direct observation during the drought

Prior to the 2018 drought the River 1 had been systematically surveyed twice (in 2009 and 2014). Uniquely within this study, direct pearl mussel mortality was assessed at the time of the 2018 drought by Donald Shields and Cameron Cosgrove on 27/07/18. Within a 100m section of the river channel a large number of dead shells were seen lining the banks, with many more pearl mussels half submerged, drying out and overheating (e.g. Figs 1–2) directly as a result of historically low water levels exposing high density mussel beds. Consequently, it was considered important to record, and if possible obtain, quantitative data to estimate the scale of the summer 2018 mortality at the peak time of the drought.

Four 50m×1m transects were conducted during July 2018 (T1–T4; Table 3) to count visible mussels (two transects by the left bank and two by the right bank of the river) and three quadrats were surveyed to quantify the ratio of hidden to visible mussels present. It was considered inappropriate to conduct more quadrat searches as this would likely have further stressed the pearl mussels. This location did not form part of the existing River 1 SCM dataset, so no previous population estimates for these July 2018 transect locations were available.

The transect metrics were extrapolated over the entire river width as mussel density and mortality appeared broadly homogenous throughout the wetted survey section. The ratio of hidden to visible mussels was approximately 1:1 (based around a series of quadrat searches) so the extrapolated transect numbers were doubled to give the estimated total number of mussels present. The 100m reach surveyed was estimated to contain 20,000 live mussels with 20% of these being juvenile (≤65mm in length) and 10% in flowing water <5cm deep (mussels considered to be at imminent risk of drying out). The same ratio of hidden to visible mussels was used for the number of dead shells found, increasing the estimated number of dead mussels found to 2,200.

In addition to these estimates, a stagnant pool had formed nearby on a newly exposed island in the river, which contained an additional ca. 1,500 mussels that were either already dead or at severe risk of death (Figs 3–4). Therefore, in total, the 100m section of river contained 2,200 dead mussels and an estimated 21,500 live mussels, of which ca. 1,500 were at imminent risk in <5cm of flowing water and a further ca. 1,500 mussels at severe risk in shallow stagnant water in July 2020. As well as moving hundreds of drying out pearl mussels into the remaining water flows, the surveyors dug a small channel with their heels to direct small flows into the stagnant pool which contained 1,500 pearl mussels already dead, exposed or at severe risk of death (small dug channel pictured in the bottom left of Fig. 4).

Post-drought monitoring

In 2019, T1–4 and three other transects which formed part of the existing River 1 SCM dataset were resurveyed (Table 3).

Table 2 Potential limitations, sources of bias and measures taken to address them

Potential limitation/source of bias	Measures taken to address limitation
Our sample of four rivers is not necessarily representative of all UK rivers with pearl mussels. Sites selected were those considered to be of particular risk to drought by NatureScot.	This is recognised sampling bias, but we do consider these rivers are a good representation of northern Scottish rivers.
Different surveyors undertook the transect surveys in different years.	Observer variability is an inherent and recognised limitation of such comparisons. Each survey team was led by a highly experienced surveyor, which included a surveyor who had previously surveyed the SAC river under investigation. Surveyors followed the same standard SCM survey methods across all sites.
Despite using GPS to relocate transect locations it was not possible for surveyors to follow the exact same route taken when surveying a 50m transect by previous surveyors. Potential sources of error would include slightly different start and end transect locations, surveying slightly different transect routes and the position of the transect out from the riverbank.	Original field sheets and transect photos (where available) were examined to determine approximate transect route previously taken. Where possible, two parallel 50m transects undertaken, one relatively close to bank edge and one slightly further out to try and account for a slightly different route taken between surveys. GPS readings from previous SCM surveys were used to relocate transect locations.
Water depth can make some transects inaccessible depending upon conditions at the time of survey.	Surveys were only conducted when water levels were considered suitable for comparable counts to be undertaken. In some instances, surveys were abandoned due to high water levels.
Surveys undertaken were sampling techniques, not absolute censi. Results give an indication of relative numbers of pearl mussels recorded at the particular times that surveys were carried out. This can be influenced by factors such as turbidity and levels of silt, macrophytes or filamentous algae on the riverbed.	These are recognised limitations of the standard survey methodology. Where factors such as silt, macrophytes or filamentous algae were considered to have substantially affected results, this is reported in the relevant river account. Turbidity was not a problem during any of the current or previous SCM transect surveys.
The gap between summer 2018 drought mortalities and the subsequent surveys was approximately one year and high water/spates in the intervening period may have moved dead shells away from former locations.	There was no obvious way to address this. It is recognised that dead shells recorded during 2019 surveys may not reflect 2018 drought mortality numbers at transect locations. It is highly likely that dead shells may have been washed away and conversely that upstream dead shells may have been washed downstream into 2019 transect locations. The approximate age of mortalities was assessed, based on shell condition to at least determine whether they came from 2018 or not.
Additional adverse factors may have affected pearl mussel numbers recorded between 2018 and 2019 surveys.	When it was possible to determine that additional adverse factors had impacted on pearl mussel occurrence this was reported e.g. an illegal pearl fishing kill.

50m transect comparisons between 2009, 2014, 2018 and 2019 surveys are provided in Table 3.

Table 3 demonstrates a trend in decreasing visible pearl mussel numbers between surveys since 2009. The minor increase in T1/T2 between 2018 and 2019 is best explained as part of the normal limitations of between years and surveyor variability. Juvenile pearl mussels were recorded in all but one of the 2019 transects, meaning that the River 1 population was still functional with successful juvenile recruitment despite the impacts of the 2018 drought. Using the standardised letter codes for recording visual pearl mussel relative abundance in transect counts between

Figure 1 A ca. 5m wide exposed mussel bed, River 1, July 2018. As an emergency conservation measure, hundreds of live stranded pearl mussels were moved into deeper water by the authors.

previous and current surveys, results also show a downward trend in status categories (Table 3).

The direction of change in five (TS20 L, TS19 R, TS12 L, T1/T R, T3/T4 R) of these seven transect comparisons is towards a substantial decline (>25% abundance change), with one slight decline (T3/T4 L) and one transect comparison showing a slight increase in pearl mussel abundance (T1/T2 L). Where there are slight changes in pearl mussel abundance this may relate to the residual limitations of the survey method or movement of individual pearl mussels in the riverbed as a result of changing conditions/flows (Table 2).

During the 2019 surveys of the River 1, a large and recent illegal pearl fishing kill was also identified. The size of the pearl fishing kill was estimated at ca. 150 individual pearl mussels. Based on the evidence from dead shells discarded on the bank, the pearl fishers had targeted larger, and easier to find adult mussels. It was not possible to know where the pearl mussels that were illegally killed came from as the pearl fishers tend to gather them from a wide area and sit on the bankside and kill them before examining them for pearls (*pers obs.*).

The surveys during the drought in July 2018 reported direct evidence that ca. 10% of the population had already recently died and a further 14% was at risk of immediately drying out and were dying based on relative abundance estimates made at T1-T4. One slightly optimistic finding from post drought 2019 studies was that the large stagnant pool (illustrated in Figs 3–4) with ca. 1,500 pearl mussels, surrounded by dried out mussel beds in 2018 did not fully dry out. In 2019 it contained hundreds of both dead and live pearl mussels. Many of those alive in 2019 may well have survived as the result of the

Figure 2 A typical dried out pearl mussel bed, River 1 with many dead shells in situ, July 2018.

Table 3 Direct comparisons of River 1 50m transects between 2009 and 2019

	2009		2014		2018 drought		2019	
SCM Transect Code	Visible in 50m transect	Abund. Code	Visible in 50m transect	Abund. Code	Visible in 50m transect	Abund. Code	Visible in 50m transect	Abund. Code
TS20	790 L**	B	681 L	B			470 L	C
							1,740 R	A
TS19	2,460 R	A	2,050 R	A			505 R	B
							750 L	B
TS12	247 L	C	165 L	C	*		182 L	C
							13 R	D
T1/T2					600 L	B	625 L	B
					720 R	B	136 R	C
T3/T4					630 L	B	590 L	B
					1,300 R	A	410 R	C

*Although no standard 50m transect was undertaken at TS12 in 2018, NatureScot staff visited the transect location on 14/09/18 and reported "*No exposed live pearl mussels found, although some live mussels remaining in <5cm of water. Numerous dead shells seen along river edge and fresh shells >100m from river, presumably indicating bird predation*". **L and R refer to the left or the right bank of the river when looking downstream.

Figure 3 Pearl mussels at severe risk of death in stagnant pool River 1, July 2018.

emergency measures enacted to create a small channel which directed modest fresh flows into the stagnant pool. Thus, a worse-case assessment that all pearl mussels in the stagnant pool at risk of drying out in 2018 subsequently died is not borne out by the 2019 survey evidence.

The best estimate of overall drought mortality in River 1 is that by 27 July 2018, ca. 10% of pearl mussels counted had died directly as a consequence of the drought. Combining all mussels still alive in T1–T4 on 27 July 2018 provided a total of 3,250 pearl mussels. In 2019, repeat counts at transects T1–T4 recorded 1,761 live pearl mussels, a decline of 46% at these locations. Therefore, based around the results of repeat transects (and all the assumptions associated with that) on a representative section of river typical of reaches containing pearl mussels, the survey evidence suggests the River 1 pearl mussel population declined by 51.4% at SCM sites as a consequence of the 2018 drought. Given numbers of both live and dead mussels were sometimes estimated in tens/hundreds, the population decline is probably better described as approximately 50%.

There is a need to further caveat this 50% metric because the results apply to shallow water reaches, as the survey transects were located along river banks. However, survey experience on the River 1 shows that the pearl mussel population tends to be located in areas of riverbed that are closer to the river banks, rather than the middle of the channel and therefore the result is considered broadly applicable to the whole river.

The evidence collected during repeat transect shows an observed loss of ca. 50% in the pearl mussel population, likely as a direct consequence of the summer 2018 drought. We think the whole river suffered similar magnitude losses, with the few deeper reaches present perhaps remaining largely unaffected. The SAC population prior to

Figure 4 Stagnant pool, River 1 with ca. 1,500 pearl mussels, surrounded by dried out mussels, July 2018. Note the small channel dug by the author's heels in the bottom left of the photo, as an emergency measure to increase water flows into the shrinking pool.

that was already declining due to other factors, including mortality associated with an extreme flood (2014), unauthorised river works, and illegal pearl fishing. The evidence of the recent (2019) pearl fishing kill shows other detrimental factors continue to adversely affect and threaten this vulnerable and declining north of Scotland SAC pearl mussel population.

River 2

Unfortunately no directly comparable 50m transects were undertaken during the 2018 drought, but a series of six spot checks were undertaken by NatureScot staff within the River 2 in summer 2018. NatureScot reported that "*No new mussel mortality was recorded within the original* (SCM) *survey section. Within a river section c. 150m upstream of the monitoring stretch, >750 mussels were visible. Of these, 15–20 were moved to deeper water, with around 15 found to be fresh dead. This indicates that at least 5% were being adversely affected by the low water conditions. The SCM locations assessed in July 2018, recorded an overall total of 10% affected, for comparison. Following inspection of the outflow from an upstream loch, it was clear that during these times of low water, such compensation flows are very important to the survival of mussel beds in shallow marginal zones of the SAC*". Direct 50m transect comparisons between 1997 and 2019 are provided in Table 4.

The evidence collected in 2019 revealed a substantial decline in relative abundance densities from earlier surveys in 1997, 2001 and 2013 for several transects. There is no way of directly attributing this decline to drought mortalities for methodological reasons (e.g. other factors may

Table 4 Direct comparisons of River 2 50m transects between 1997 and 2019

	1997/2001		2013		2018		2019	
SCM Transect Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code
EX4	520 (2001)	B	342 R	C			7 R	D
							51 L	C
EX5	137 (1997)	C	380 R	C			3 R	D
							17 L	D
EX6	1 (2001)	D	7 R	D			7 R	D
							0 L	E
SNH Pt 2					40+		64 R	C
							140 L	C
SNH Pt 4 & 5					400+ R		20 R	D
							21 L	D

have involved in the gap between surveys) and that very few recently dead pearl mussel shells (that could be directly attributed to 2018 mortality) were recorded. However, there has clearly been a decline in the abundance of pearl mussels in this part of the River 2 over the last ca. 20 years. The reasons behind this decline remain unclear but amongst detrimental factors, the 2018 drought seems likely to have had an adverse effect locally and may be reflected in the further reduction in the density of mussels recorded in 2019. Although, unlike some other rivers (e.g. River 1) dead shells did not cover the riverbed at the time of the 2019 survey; noting that despite low levels compensating flows from a headwater loch may possibly have helped. Moving some '*at risk*' live pearl mussels (as NatureScot staff did in summer 2018) may have resulted in greater survival than would otherwise be the case. An alternative explanation is that flow rates since the 2018 drought in the River 2 might have been such that many dead shells were washed away from the riverbed and were, therefore, undetected. This seems plausible because surveyors in 2019 saw no large groups of dead shells washed out or littering other parts of the River 2 when walking between SCM monitoring sites.

River 3

Given the potential changes to river flows and pearl mussel occurrence recorded during the drought of 2018, surveyors conducted paired or parallel 50m transects counts different distances out from banks at previous SCM locations throughout the River 3. It was not always clear from some of the SCM transects, at precisely what distance out from the bank previous surveys were conducted. In those circumstances, two parallel transects were undertaken within potentially suitable pearl mussel habitat, one close into the bank and one further out. A total of fifteen 50m transects were undertaken in 2019 (Table 5). Luxuriant non-native weed growth (*Ranunculus spp*) was a feature at one transect, making visual counts challenging in 2019. It should be noted that *Ranunculus* can smother and kill pearl mussels when it establishes itself within existing mussel beds (Laughton *et al.*, 2008).

Directly comparable 50m transects (previous and 2019 data) were undertaken at seven locations (Table 5), with assessments of live and dead pearl mussels made at two new 50m transects where no previous transect data had been collected. At TSC1 and TSC2, both repeat transect counts which were in relatively shallow water (<0.5m deep) had decreased substantially between 2013 and 2019 (Table 5). At TSA1 and TSA2, both repeat transect counts were in relatively moderate depth water (ca. 0.7m deep) had not appreciably changed between 2014 and 2019 (Table 5). It should be noted that extremely low water in 2013 previously killed many hundreds of pearl mussels at this location, so many vulnerable pearl mussels in shallow water had already died relatively recently, prior to the 2018 drought.

At TSG1 and TGS2 both repeat transect counts in relatively deep water had not appreciably changed in abundance between 2018 and 2019 (Table 5). The TSD1 2019 count was clearly affected by the presence of non-native *Ranunculus*

Table 5 Direct comparisons of River 3 50m transects between 2013 and 2019

	2013		2014		2018		2019	
SCM Transect Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code
TSC1	1,350 (4–5m out)	A					343 (2–3m out)	C
							422 (3–5m out	C
TSC2	1,870 (4–5m out)	A					350 (2–3m out)	C
							872 (3–5m out)	B
TSA1			380 (3–5m out)	C			20 (1–2m out)	D
							384 (3–4m out)	C
TSA2			1,640 (distance out not recorded)	A			187 (1–3m out)	C
							1,500 (3–4m out)	A
TSD1					250 (distance out not recorded)	C	56 (2–3m out)	C
TSG1					108 (2m out)	C	129 (2m out)	C
TSG2					29 (2m out)	D	44 (2m out)	D

fluritans and R. penicillatus psueudofluritans covering almost all substrates and presumably pearl mussels; a known conservation issue within this river (Laughton *et al.*, 2008).

River 4

During the 2018 drought, the river bailiff, along with a team of local volunteers moved a large number of live pearl mussels (estimated at around ca. 10,000 individuals) within River 4 from shallow beds that were either drying out or being cut off from river flows into areas of deeper water.

Site selection for the current study (which took place in January 2020) was centred at locations where previous SCM took place (thereby having relatively up to date comparative status information). During the survey, surveyors were accompanied by the river bailiff who had co-ordinated the movement of ca. 10,000 pearl mussels into deeper water in 2018. This allowed for direct consideration of the 2018 pearl mussel drought pearl mussel relocations, i.e. the surveyors knew where shallow water pearl mussels within SCM transects had been moved.

Directly comparable 50m transects (2003 and 2015 data) were undertaken at five locations (Table 6). On four of the five transect counts, pearl mussel numbers had decreased from those recorded in 2015 (Table 6). A single transect showed a small increase in the number of pearl mussels from 2015 (TS61). However, this was from 2 to 9 and could easily be attributed to methodological limitations e.g. individual survey route taken or the visibility of mussels. The largest decrease in numbers was at TS58 (Table 6).

While the number of pearl mussels recorded has decreased, in some transects substantially, the number of dead would very likely have been much greater were it not for direct emergency efforts during the drought to translocate pearl mussels in danger of drying out or being 'cut off' from river flows. These efforts were led by a small team of local volunteers during the middle of the drought period in the summer of 2018 and it seems reasonable to assume from

Table 6 Direct comparisons of River 4 50m transects between 2003 and 2020

	2003		2015		2020	
SCM Transect Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code	Visible in transect	Abund. Code
TS15	213	C	44	D	N/A*	N/A*
TS29	47	D	10	D	3	D
TS31	55	C	40	D	6	D
TS37	196	C	72	C	8	D
TS58	2,380	A	1,150	A	320	C
TS61	39	D	2	D	9	D

*Not completed due to rising water levels during survey.

Table 7 Mean number of pearl mussels found per transect and standard deviation (SD) and standard error (SE) for each rivers and all rivers combined before and after the drought event (note – for each transect, the most recent population count used)

River	Pre-drought	Post drought	SD pre-drought	SD post drought	SE pre-drought	SE post drought
River 1	878.00	416.86	568.53	176.47	214.89	66.70
River 2	233.80	20.20	173.03	22.64	77.38	10.13
River 3	803.86	486.71	727.53	492.72	274.98	186.23
River 4	254.80	69.20	448.28	125.42	200.48	56.09
All rivers	592.33	282.17	619.78	352.87	126.51	72.03

their first-hand accounts that most of the 10,000 pearl mussels moved would likely have dried out and died without intervention. The majority of these were in the upper catchment, with the areas around TS58 having the greatest numbers of live pearl mussels moved into the middle of the river (though the translocation efforts were not only limited to this area). Therefore, the very substantial decline in relative abundance does not directly translate to pearl mussel drought mortalities as some can be attributed to the emergency movement of mussels out of shallow areas within SCM locations into deeper water.

The number of dead pearl mussels recorded during the 2020 survey (only 5 individuals) was not considered to be unusual for a typical river survey, which often record a few natural mortalities. Some potential downstream wash out locations were searched, but no further dead shells were recorded. When compared to other rivers, such as the nearby, adjacent River 1, where several thousand dead shells were recorded (particularly in natural washout areas), the difference is stark. There could be several reasons for this. The River 4 is a larger river with more areas for dead shells to be moved to. The depth of some parts of the River 4 would make a more thorough search of the riverbed difficult. However, the lack of dead shells found *in-situ* anywhere (they were common in River 1) suggests that the River 4 may have entirely avoided the large-scale mortalities associated with other northern Scottish rivers, perhaps at least partly as a consequence of effective emergency translocation efforts.

Overall river comparisons

The mean number of all pearl mussels found before and after the 2018 drought is provided in Table 7 and illustrated in Fig. 5. The mean number of pearl mussels found on transects pre

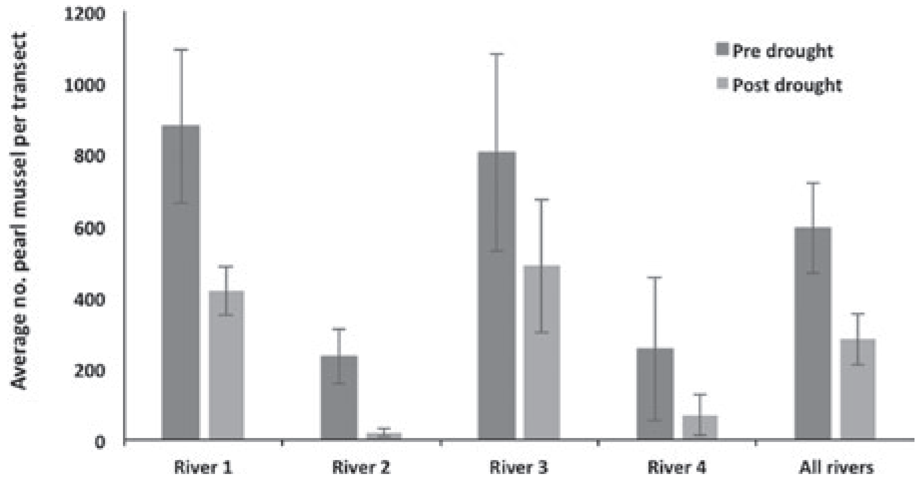

Figure 5 Mean number of pearl mussels recorded per transect for each river before and after the drought (note – for each transect, the most recent SCM population count used) – standard error bars are illustrated.

drought on the four rivers was 592, falling significantly to an average of 282 post drought (paired t-test p=0.0018, 23 d.f.). The paired t test was carried out in Excel using the most recent number of pearl mussels per transect pre drought available (for full details refer to Tables 3 to 6).

Discussion

The evidence from this study in four Scottish pearl mussel SACs demonstrates that significant drought mortalities can and do sometimes occur in northern European rivers and they are not just a feature of southern populations at the edge of their range. Nevertheless, with the time gaps between pre and post 2018 drought data there is uncertainty that drought was the primary case of mortalities in some of the survey rivers studied. Sousa *et al.*, (2018) assessed the mortality of pearl mussels in the Mente, Rabaçal and Tuela rivers (northwest of the Iberian Peninsula) during an extreme summer drought in 2017. Mortality occurred as a result of low river flow, which led to pearl mussel stranding near the banks (mussels drying out).

The Sousa *et al.* (2018) study recorded most moralities associated with stranding, but also increased opportunistic predation and scavenging by wild boar *Sus scrofa* and birds. Little has been published on the natural predation of pearl mussels, although Cosgrove *et al.*, (2007) summarised evidence of natural predation of pearl mussels in Scottish populations from over 300 detailed river studies between 1996–2007. Cosgrove *et al.*, (2007) recorded opportunistic predation by hooded crow (*Corvus corone cornix*), oystercatcher (*Haematopus ostralegus*), American mink (*Muslela vison*), and European otter (*Lutra lutra*), but found no direct evidence to suggest natural predation caused substantial mortalities in any Scottish populations studied. The local river bailiff in River 2 within this study noted that as water levels dropped in July 2018 and pearl mussels became stranded and/or vulnerable, opportunistic predation by crows and gulls increased substantially (*pers comm.*). Droughts in Portugal and Scotland do appear to make pearl mussel populations susceptible to opportunistic predation.

Nogueira *et al.*, 2019 undertook a detailed before/after comparison in two Portuguese river basins (Rabaçal and Tuela) to assess the possible effects of an extreme drought in 2017 on the abundance and size structure of two pearl mussel populations. One year after the drought, a significant reduction in abundance was observed (i.e. 27.6% for the Rabaçal and 38.7% for the Tuela basin populations). However, no differences were detected in the size structure of the two pearl mussel populations.

The comparisons between the four Scottish rivers in this study show contrasting results. Pearl mussel densities in River 1 (which was the most shallow watercourse studied) have declined to such an extent that the 2018 drought was considered to have caused a ca. 50% decline in the pearl mussel population at the SCM sites. By contrast, the ongoing declines in pearl mussel populations in Rivers 2 and 3 have been driven by other factors and there is little evidence for substantial drought related mortalities, but noting that a drought in 2013 killed large numbers in River 3 which would otherwise have likely died in 2018.

One of the most interesting findings was in River 4, where although a decline in abundance was recorded, due to concerted local emergency conservation efforts, the mortality was lower compared to the adjacent river catchment (River 1). We are unaware of other examples where a local community took it upon themselves to rescue stranded pearl mussels as the water levels dropped, as occurred in 2018. This undoubtedly made a difference by rescuing and moving ca. 10,000 pearl mussels into deeper water.

An issue not investigated by our study was the decline in water quality associated with the drought. During 2018 there was lots of death and decay of pearl mussels within and around the remaining low flows. The impact on water quality of the decomposition of tens of thousands of pearl mussels was very likely detrimental on those pearl mussels that survived, but we have no way of quantifying this.

In the face of the current climate emergency, conservation actions for endangered species can sometimes seem futile. Perhaps, the actions of the local community on River 4 could form the basis of some future emergency conservation action. Local communities are well placed to identify and respond to climate driven droughts and so could their actions be supported in and around other important remnant pearl mussel populations? In Ireland, protocols for similar situations have recently been developed (Moorkens, 2019) and could form the basis for such future action.

Whilst such emergency actions can prevent large numbers of pearl mussels from dying, the long-term consequences of increasing droughts predicted under most climate change scenarios means that in some catchments formerly permanently wetted river habitats become ephemeral. As pearl mussels require a constant flow of water, these shallow, ephemeral habitats can no longer support pearl mussels. In the long-term, this suggests that shallow edge habitats will be lost and pearl mussels may increasing be found only in the deeper parts of channels. There is also the issue of ensuing that rescued pearl mussels are put into suitable habitats.

Stochastic losses are part of natural population dynamics, but the increase in severity and frequency of droughts could have a major impact on many key pearl mussel rivers. Recent research indicates that this risk will increase considerably, as the number of extreme drought events in Scotland (at least as large as experienced in 2018) could increase from an average of one every 20 years to one every three years (Kirkpatrick Baird *et al*., 2021).

As part of large-scale, wider catchment management to restore important peatlands and blanket bog habitats, hundreds of kms of drainage ditches are being blocked in pearl mussel catchments as part of efforts to restore Scotland's peatlands and tackle climate change under the auspices of Peatland ACTION. The Peatland ACTION project is helping to restore damaged peatlands in Scotland (e.g. www.nature.scot/climate-change/nature-based-solutions/peatland-action-project). Since 2012, over 25,000 hectares have been restored with funding provided by the Scottish Government. In February 2020, the Scottish Government announced a substantial, multi-annual investment in peatland restoration of more than £250 million over the next 10 years. Similar conservation work is now being undertaken for pearl mussels in Ireland where efforts in pearl mussel peatland catchments are being directed towards restoring the water level (so called 're-wetting') across catchments to improve catchment water storage, slower peak flows and higher water availability from the catchment to the river during low flows (Evelyn Moorkens, *pers comm.*).

It is now widely recognised that restoring peatlands is one of the most effective ways of locking in carbon; offering a nature-based solution to the climate crisis. Ditch blocking, which forms part of these peatland restoration measures, slows down the speed of water flowing off drained upland habitats, thereby retaining water within the catchment for longer. These peatland restoration efforts can now be seen as directly helping climate change threatened pearl mussel populations.

Furthermore, there is also strong evidence that riparian woodlands contribute to climate change adaptation by regulating water temperature via shading, given the right location and design (Jackson *et al.,* 2018). While there is not such strong evidence that riparian woodlands will retain water within catchments during drought periods, they can under certain circumstances mitigate the secondary pressure during droughts of high river temperatures that can damage host salmonids (Jackson *et al.*, 2018), and potentially pearl mussels themselves (Cosgrove *et al.*, 2012a). Nevertheless, care needs to be taken and should be informed by an investigation into the range of near bed velocities relative to the locations of pearl mussels. In more southern/hotter regions pearl mussels tend to live in steep gradients and trees can mitigate higher temperatures, but where gradients are lower there is a much heavier reliance on near bed velocity. Riparian trees, and also excessive trees as a percentage in a catchment can mitigate high flows very well, but may add to and thus potentially exacerbate, the decline in low flows (Iacob *et al.*, 2017).

Low flows, such as illustrated in Figs 3 and 4, can lead to the release of iron ochre and occasionally to dense growths of iron bacteria. This occurs when the water table lowers to below the acid influence of the peat, and acidic water with high concentrations of dissolved iron meets less acidic mineralized water which causes the iron to precipitate out of solution, which in turn can cause and be exacerbated by growths of iron depositing bacteria. Iron ochre precipitate can be toxic to both juvenile and adult pearl mussels (Evelyn Moorkens, *pers comm*).

Under the CEN standard (British Standards Institution, 2017) the levels of loss of pearl mussels identified in this study should initiate investigative monitoring. In Ireland, as flows reduce and near-bed velocity decreases, juvenile pearl mussels pull themselves out of the riverbed and adult mussels become stressed, if there is a long period of low flow before patches dry out, mussels are much less able to move to deeper water. Drying of the riverbed in mussel habitat is rarely sudden, the more prolonged low flow conditions (while the mussels are in the wet) before the drying out has implications for the possibility of mussels being able to rescue themselves. Near bed velocity measurements during "normal" low flows (Q85 and lower) would assist with an understanding of whether the ongoing loss of mussels may be due to chronic low flow stress, which is considered to be the biggest problem in peat catchments in Ireland. (Moorkens & Killeen, 2014).

Taken together, carefully planned riparian woodland and peatland restoration at the landscape scale have the potential to help our rivers, and their important pearl mussel populations, better adapt to the increasing frequency of droughts they will experience in the coming years.

Recommendations

- Extreme droughts are predicted to increase under practically all climate change modelling scenarios, both in number and intensity in the future, and so practical human intervention (as shown in this study) may become necessary if preventable drought related mortalities are to be avoided.
- Physically moving live pearl mussels from vulnerable shallow water areas into deep water undoubtedly prevented many thousands of pearl mussels from dying in River 1 and 4. We consider that the direct intervention by volunteers could offer a practical local community-based emergency solution during exceptional drought conditions.
- During droughts when isolated pools with live pearl mussels are created as water levels drop, where possible efforts should be directed to direct river flows into the isolated pools as occurred in River 1.
- Many pearl mussel rivers have regulated flows and so called 'compensation flows'[1] could play an important role in the survival of downstream pearl mussel beds in shallow/marginal areas during drought conditions.
- Peatland/blanket bog restoration measures should be recognised as directly contributing towards protecting climate change threatened pearl mussel populations.
- Further investigative monitoring is needed in order to better understand the undoubted declines that have recently occurred on the four SAC catchments. The UK has legal obligations in relation to protecting these internationally important pearl mussel populations and such monitoring should be used to inform restorative conservation measures.

Acknowledgements

We would like to thank numerous landowners for allowing access to the four rivers for the purpose of this NatureScot funded research. Several local NatureScot staff provided useful baseline

[1]Denotes a flow that is required to remain in a river when a dam is constructed.

information and also helped move drought-stranded pearl mussels into deeper water in 2018. Special thanks are due to Richard Wright who mobilised considerable local support on one SAC and moved an estimated 10,000 stranded pearl mussels into deeper water in 2018; undoubtedly these would have died without this intervention. We are grateful to Evelyn Moorkens who provided valuable comments and highlighted important work in Ireland that we may otherwise have missed.

References

British Standards Institution 2017 Water quality – Guidance standard on monitoring freshwater pearl mussel (*Margaritifera margaritifera*) populations and their environment. *BS EN* **16859**:*2017*. London: BSI.

Bolotov I, Makhrov A, Gofarov M, Aksenova O, Aspholm P, Bespalaya Y, Kabakov M, Kolosova Y, Kondakov A, Ofenböck T, Ostrovsky A, Popov I, Proschwitz T, Rudzīte M, Rudzītis M, Sokolova S, Valovirta I, Vikhrev I, Vinarski M & Zotin A 2018 Climate Warming as a Possible Trigger of Keystone Mussel Population Decline in Oligotrophic Rivers at the Continental Scale. *Scientific Reports*: 8, 35.

Cosgrove P, Hastie L, Watt J, Sime I & Boon P 2012a Scotland's freshwater pearl mussels: the challenge of climate change. In: Boon, P. & Raven, P. (eds) *River conservation and management*. Wiley-Blackwell, Chichester, pp 121–132.

Cosgrove P, Hastie L & Sime I 2012b Wildlife crime and Scottish freshwater pearl mussels. *British Wildlife* **24**: 10–13.

Cosgrove P, Watt J, Hastie L, Sime I, Shields D, Cosgrove C, Brown L, Isherwood I & Bao M 2016 The status of the freshwater pearl mussel *Margaritifera margaritifera* (L.) in Scotland: extent of change since 1990s, threats and management implications. *Biodiversity and Conservation* **25**: 2093–2112.

Hannaford J 2018 UK Hydrological Status Update – early August 2018. UK Centre for Ecology and Hydrology. https://www.ceh.ac.uk/news-and-media/blogs/uk-hydrological-status-update-early-august-2018.

Hastie L, Cosgrove P, Ellis N & Gaywood M 2003 The threat of climate change to freshwater pearl mussel populations. *Ambio* **32**: 40–46.

Iacob, O, Brown, I & Rowan, J 2017 Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland. Hydrological Sciences Journal **62**: 1931–1948.

Jackson F, Fryer R, Hannah D, Millar C & Malcolm I 2018 A spatio-temporal statistical model of maximum daily river temperatures to inform the management of Scotland's Atlantic salmon rivers under climate change. *Science of the Total Environment* **612**: 1543–1558.

Kirkpatrick Baird F, Stubbs Partridge J & Spray D 2021 Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland, 2021–2040. *NatureScot Research Report No. 1228.*

Laughton R, Cosgrove P, Hastie L & Sime I 2008 Effects of aquatic weed removal on freshwater pearl mussels and juvenile salmonids in the River Spey, Scotland. *Aquatic Conservation: Freshwater and Marine Ecosystems* **18**: 44–54.

Moorkens E 2011 *Margaritifera margaritifera*. In: IUCN 2013. IUCN Red List of Threatened Species. Version 2013.2.

Moorkens E 2019 Monitoring Populations of the Freshwater Pearl Mussel *Margaritifera margaritifera* 2017–2019. Protocol for the assessment of risk of mortality of Margaritifera in drought and choice of action. *Report for the Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs*.

Moorkens E & Killeen I 2014 Assessing near-bed velocity in a recruiting population of the endangered freshwater pearl mussel (*Margaritifera margaritifera*) in Ireland. *Aquatic Conservation: Marine Freshwater Ecosystems.* **24**: 853–862.

Nogueira J, Lopes-Lima M, Varandas S, Teixeira A & Sousa R 2019 Effects of an extreme drought on the endangered pearl mussel *Margaritifera margaritifera*: a before/after assessment. *Hydrobiologia*. https://doi.org/10.1007/s10750-019-04103-1.

Sousa R, Ferreira A, Carvalho F, Lopes-Lima M, Varandas S & Teixeira A 2018 Short communication: Die-offs of the endangered pearl mussel *Margaritifera margaritifera* during an extreme drought. *Aquatic Conservation: Marine Freshwater Ecosystems* **28**: 1244–1248.