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ORIGINAL PAPER

The status of the freshwater pearl mussel *Margaritifera margaritifera* in Scotland: extent of change since 1990s, threats and management implications

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Abstract All known rivers in Scotland with recent records of freshwater pearl mussels *Margaritifera margaritifera* were surveyed in 2013–2015 using a standard methodology. Freshwater 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. In all regions extant populations were characterised by low pearl mussel densities, with 97 of 115 extant Scottish populations defined as 'rare' (0.1–0.9 mussels per 1 m ^{2}) or 'scarce' (1.0–9.9 mussels per 1 m ^{2}). Only 18 Scottish rivers now hold pearl mussel populations in densities that are considered to be 'common' (10–19.9 mussels per 1 m ^{2}) or 'abundant' (>20 mussels per 1 m ^{2}). Based on survey evidence, the number of apparently extinct pearl mussel populations in Scottish rivers is now 73. The decline is particularly pronounced in the West Highlands and Western Isles strongholds. The key threats are: (i) pearl fishing, (ii) low host fish densities, (iii) pollution/water quality, (iv) climate change and habitat loss, (v) hydrological management/river engineering and (vi) 'other factors', such as non-native invasive species. Over the last 100 years this endangered species has been lost from much of its former Holarctic range. Scotland's extant *M. margaritifera* populations continue to be of international importance, but their continued decline since the first national survey in 1998 is of great concern.

Keywords Endangered species · Population decline · Aquatic conservation · Rivers

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Introduction

The freshwater pearl mussel *Margaritifera margaritifera* 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) having declined by 95 % in central Europe (Degerman et al. 2009). The largest remaining populations in Scotland, Ireland, Norway, Finland, Sweden and northwest Russia are of international importance (Cosgrove et al. 2014). The freshwater mussels (*Unionacea*) are among the most imperilled group of species in the world and have attracted much concern from conservationists because of the important role they play in freshwater ecosystems (Strayer et al. 2004).

To date there has been only one national survey of freshwater pearl mussels in Scotland. This Scottish Natural Heritage (SNH) funded research took place between 1996 and 1999, and produced the first overall picture of the species' status in Scotland. One hundred and fifty-five rivers with historical pearl mussel records in the previous 100 years were surveyed for the presence of freshwater pearl mussels and the results reported (Cosgrove et al. 2000a). Evidence of recent juvenile recruitment was found in only 52 rivers (34 % of the total surveyed) and these populations were classified as 'functional' on the basis of their continued ability to reproduce successfully. Approximately two-thirds of the 155 rivers occupied previously (101 rivers) were assessed as 'extinct' (no mussels present) or considered 'functionally extinct' (only adult mussels present with no evidence of juvenile recruitment in the previous ca. 15 years) (Cosgrove et al. 2000a).

The current survey was commissioned by SNH to update the 1996–1999 information, assess the present status of surviving *M. margaritifera* populations and determine changes in abundance, distribution and threats across Scotland. The results are intended to contribute to the Scottish Biodiversity Surveillance Strategy and to allow Scotland and the UK to adequately report on the status of *M. margaritifera* to the European Union. A number of new (previously unsurveyed) populations have been discovered since the first national survey was conducted and these too were included in the current survey.

Freshwater pearl mussel habitat requirements

The freshwater pearl mussel has a complex life-cycle, which makes it vulnerable to a number of threats. The species is found in fast flowing unpolluted rivers and streams, with detailed studies on Scottish freshwater pearl mussel populations suggesting that optimum water depths of 0.3–0.4 m and optimum current velocities of 0.25–0.75 ms^{-1} at intermediate water levels are most suitable (Hastie et al. 2000a). River bed substratum characteristics appear to be the best physical parameters for describing freshwater pearl mussel habitat in Scotland. Freshwater pearl mussels prefer stable cobble/boulder dominated substrate with some fine substrate that allows the mussels to burrow (Cosgrove et al. 2000b; Fig. 1). Adult and juvenile mussels tend to have similar habitat preferences, although adults are found over a wider range of physical conditions and juveniles appear to be more exacting in their habits requiring fine stable sediments, particularly clean sand and gravel (Hastie et al. 2000a). Of specific importance to freshwater pearl mussel survival are levels of silt, suspended solids, biochemical oxygen demand, calcium and chemical compounds generally associated with enrichment (eutrophication) i.e. nitrate and phosphate (Bauer 1983; Moorkens 2000; Degerman et al. 2009, 2013).

Fig. 1 Freshwater pearl mussel substrate habitat, West Highlands

Freshwater pearl mussel host requirements

Freshwater pearl mussels have a short parasitic larval phase on the gills of suitable native salmonid host fish. The larvae (glochidia) of *M. margaritifera* are host-specific and can only complete their development on Atlantic salmon *Salmo salar* or brown/sea trout *Salmo trutta*. Usually juvenile fish (fry and parr) are utilised (Young and Williams 1984). The presence of freshwater pearl mussels in any river therefore depends on salmonid host fish availability and there is some adaptive matching between species/races of fish and mussels (Geist et al. 2006). This complexity illustrates the many potential threats and pressures that operate on *M. margaritifera* and its habitat.

Objectives

The main objectives of the present survey were:

- To survey all known watercourses in Scotland with extant freshwater pearl mussel populations and report on their current status.
- To identify positive and negative factors that may be contributing to the present condition of populations in each watercourse.

Methods

The current survey was carried out in two separate phases. The first was a desk study conducted by SNH that collated all known records of rivers containing freshwater pearl mussel using previous survey reports. This desk assessment then provided the basis for a standardised survey of almost all rivers in Scotland with freshwater pearl mussel records. This was carried out in 2013–2015. A small number of rivers that had already recently been surveyed (post 2010) were not resurveyed, but their results are reported here as part of this updated assessment of the status of *M. margaritifera* in Scotland.

For the purpose of this study (and to repeat methods used in 1996–1999) a river was defined as a named watercourse on 1:25,000 Ordnance Survey maps. If, for example, a named tributary containing pearl mussels joined the main pearl mussel watercourse, then for the purpose of reporting and analysis both named watercourses were considered separate 'pearl mussel rivers'.

Site selection

The survey was based on a list of rivers provided by SNH. It included the majority of Scottish watercourses with known populations of freshwater pearl mussels (those rivers recorded with pearl mussels in the first national survey and new populations discovered since then). It also included a small number of rivers where there were recent anecdotal reports of freshwater pearl mussels, but for which no confirmed records existed.

As a consequence of the threat posed by illegal pearl fishing, the names and locations of specific pearl mussel rivers are treated as confidential and are not reported here, but are instead provided geographically, based on the hydrological regions defined by Maitland et al. (1994) (Fig. 2).

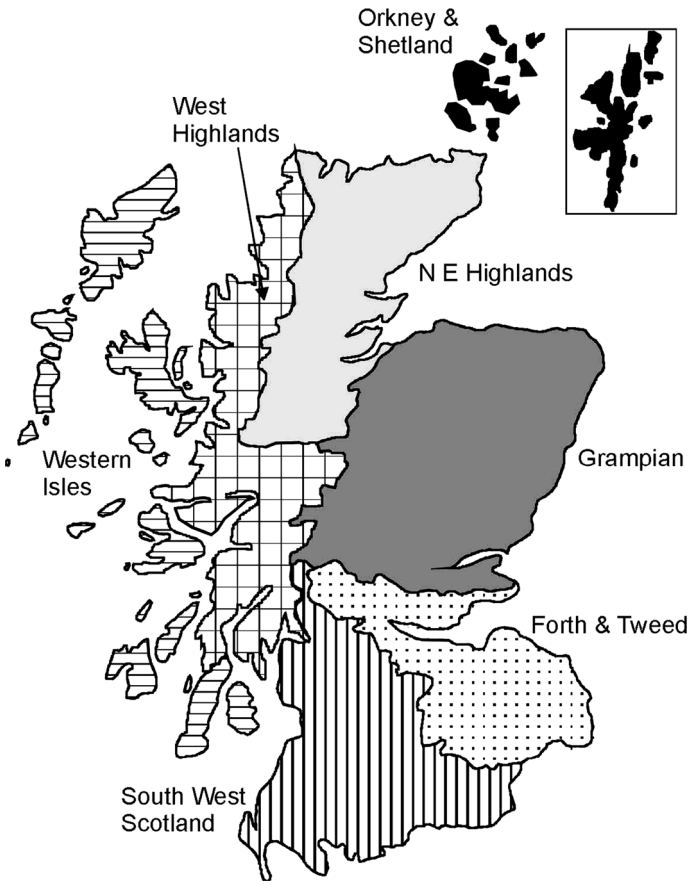

Fig. 2 Scottish Hydrological Regions (after Maitland et al. 1994)

Fig. 3 Typical large-sized Scottish pearl mussel river, Grampian

Fig. 4 Typical small-sized Scottish pearl mussel river, West Highlands

The Scottish rivers within this survey varied considerably in size from the largest, which averaged ca. 70 m in width and 2 m in depth (Fig. 3) to the smallest, which averaged ca. 2 m in width and 0.2 m in depth (Fig. 4).

Selection of specific locations to be visited in each river

The first national pearl mussel survey in 1996–1999 involved a significant element of searching, as the locations of pearl mussel populations were unknown (Cosgrove et al. 2000a). Selection of original transect locations in the first national survey was focussed on river reaches known, or believed, to have previously held pearl mussels. These were often where pearl fishers had been active and so other search areas were also chosen from a map study. Cosgrove et al. (2000a) reported that an attempt was made to include all main sub-divisions of the rivers.

As the current survey was largely intended to be a repeat of the 1996–1999 survey, it was clear that, where possible, the same transect locations should be revisited. However, were the current survey limited only to revisiting original transect locations this may not reflect the current status or distribution of the freshwater pearl mussel population in a catchment. This is for three main reasons. Firstly, research conducted by Hastie et al. (2001) in Scotland demonstrated that pearl mussels move and mussel habitats change over time, especially in relation to significant floods, which have occurred with greater frequency in recent years (Cosgrove et al. 2012a). Revisiting only the original transect locations would provide an assessment of status in formerly suitable locations. These are not necessarily the best or most representative current locations. Secondly, the first survey spent on average one day per river surveying at least three representative areas. This typically meant surveying in the lower, middle and upper river reaches. In several rivers however, some remote reaches were not surveyed at all. The element of seeking out further suitable habitat and areas populated by mussels, which was a key part of the first survey, was incorporated into the current survey as well as revisiting the previous transect locations. Thirdly, knowledge of freshwater pearl mussel distribution in some rivers has increased since 1996–1999 and it was judged important to incorporate new sites and areas where these were known—particularly where they extended mussel range beyond that identified in 1996–1999 or where their omission might be expected to alter the reported population status (e.g. known recruiting mussel beds). In practice, this meant that surveyors had to balance repeating all 1996–1999 transects against omitting one or more to (i) explore new areas of potential mussel habitat, or (ii) survey transects where significant numbers of mussels had been identified more recently.

As a result of the above considerations, not all previous transects were repeated in every river, but most were. Generally a larger number of transects were completed in 2013–2015 than in 1996–1999. The approach taken is likely to have resulted in a more complete picture of current status than would have resulted from an exact repeat of 1996–1999 survey locations.

Survey methodology for live mussels

The standard Scottish field survey protocol for freshwater pearl mussels was used to assess the distribution, age structure, and size of populations in each river (based on Young et al. 2003). The standard survey methodology, conducted by teams of highly experienced and licensed surveyors, involved the following:

- Searches were made using a glass-bottomed viewing bucket, under favourable conditions (i.e. bright light, clear water and a low flow regime) and in water sufficiently shallow for safe wading.
- Searches were made in an upstream direction, checking possible and potentially suitable areas of habitat (e.g. in the shelter of boulders or over-hanging banks).
- If no mussels were found, the search was continued until a range of potentially suitable locations had been searched within the area selected. An area was considered to not support pearl mussels after it had been searched for approximately two person hours or until no further suitable habitat could be identified.
- If mussels were found, a transect 50 m long by 1 m wide was laid out so as to traverse the main area of suitable habitat at a location. All mussels in a 1 m wide ‘corridor’ were counted.

- At 10, 20, 30, 40 and 50 m along each transect, 1 m × 1 m quadrats were laid on the substrate. Within these quadrats all visible *M. margaritifera* were counted, removed and measured along their maximum dimension to the nearest 1 mm using dial callipers (note, juvenile mussels defined as ≤65 mm in length). All loose stones and debris were then displaced in order to reveal any hidden mussels and to search for any juveniles.
- If it became clear that more than 250 visible mussels were present in the transect, a full count as above was abandoned. Instead, five 1 × 1 m quadrats were placed at 10, 20, 30, 40 and 50 m. Each was surveyed as for the standard placing of quadrats. An estimated total for the whole transect was extrapolated from the visible numbers in the five 1 × 1 m quadrats.
- All live mussels were returned to the river in the approximate locations where they were found.

Standard field sheets were completed for each transect. Transect locations were recorded using 12-figure grid references generated by hand-held GPS at the downstream end of transects. Transect locations were photographed and sketched in order to aid future site identification.

Standard criteria for describing the relative abundance of *M. margaritifera* populations

Mussel relative abundance in each survey transect is expressed using absolute numbers counted and standardised abundance codes/terms. The abundance classification (Table 1) is based on the number of live mussels found in a standard 50 m × 1 m transect. These relative abundance terms are based on visible, i.e. unburied mussels, and were also used in the 1996–1999 survey.

A single population classification was provided for each watercourse surveyed. Population status was categorised following Cosgrove et al. (2012a), based on the presence or absence of adult and juvenile mussels across all transects. The categories are directly comparable with those used by Cosgrove et al. (2000a) in the first national survey although different terminology was used (Table 2). The change in terminology was prompted by the

Table 1 The mussel abundance classifications for 50 m transects

Mussels in 50 m transect (N)	Visible mussel density per 1 m^2	Relative abundance code	Term used
≥1000	>20	A	Abundant
500–999	10–19.9	B	Common
50–499	1–9.9	C	Scarce
1–49	0.1–0.9	D	Rare
0	0	E	Absent

Table 2 Pearl mussel population status terminology used for watercourses, 1996–1999 and 2013–2015

Survey findings	Status term used 1996–1999	Status term used 2013–2015
Mussels absent	Extinct	Apparently extinct
Mussels present, juveniles absent	Functionally extinct	Not successfully recruiting
Mussels present, juveniles present	Functional	Recent successful recruitment

findings of Hastie et al. (2011), showing that small, adult only apparently non-recruiting populations retained capacity for reproduction.

Temporal trends in population status

Population status (Table 2) is used as the basis for comparison when comparing current survey results with those from the first national survey. A number of rivers were included in the current survey that were not assessed or known of during the first national survey. Where more than two consecutive and comparable surveys have taken place, these rivers are included in analyses of temporal trends.

Eighteen watercourses (15 %) with extant *M. margaritifera* populations were not surveyed during 2013–2015 because recent survey data already existed (defined as 2010 or later). These watercourses were included in regional and national analyses, using the most recent survey data (post 2010) to determine current status. Mussel populations in each watercourse for which there were baseline and current/recent data were defined as declined, unchanged or improved. Decline was defined as an observed change in population status, from '*not successfully recruiting*' to '*apparently extinct*' or from '*recent successful recruitment*' to either of the other two status categories. Improvement was defined as any change in the opposite direction. One new and previously unknown pearl mussel watercourse is included that was discovered after completion of the 2013–2015 SNH funded study.

Threat assessment

Where evidence was available, surveyors identified apparent threats to each river *M. margaritifera* population. In order to present these regionally and nationally, threats were categorised following the methods of Cosgrove et al. (2000a), who identified five broad categories of threat: (i) pearl fishing, (ii) pollution/water quality, (iii) hydrological management/river engineering (iv) 'other threats' and (v) unknown. A new sixth category—low host fish density or host fish decline—was defined and used for the current survey. This threat was identified using one or more of the following criteria: (i) recent survey data showing host fish density of less than 0.2 host fish per square metre in watercourse (after Zuiganov et al. 1994); (ii) reported declines of adult stocks of salmon or trout (using catch or fish counter data) suggesting potential stock collapse.

Results

The current status of *M. margaritifera* in Scotland

A total of 126 watercourses were surveyed as part of the current study. Fifty-eight rivers that were surveyed in the first national survey, but where pearl mussels were determined to be 'extinct' in 1996–1999 were not resurveyed in the current survey.

Based on current survey data, there were 115 Scottish watercourses with extant populations of freshwater pearl mussels (Table 3). Seventy-one (56 %) of the rivers included in the current survey showed some sign of recent recruitment. This represents 62 % of the watercourses with extant populations. Based on current data, a total of 44 rivers (approximately one-third of river populations) were not recruiting. Eleven apparent river

Table 3 Current Scottish freshwater pearl mussel status classification in surveyed watercourses 2013–2015

Region	Recruiting	Not recruiting	Extinct	Total rivers	Total extant rivers
SW Scotland	0	3	0	3	3
Grampian	10	4	4	18	14
NE Highlands	12	11	1	24	23
Orkney and Shetland	0	1	0	1	1
W Highlands	38	20	3	61	58
W Isles	11	5	3	19	16
Scotland	71	44	11	126	115

extinctions were recorded since the first national survey. These and other changes are considered further below.

Unsurprisingly the current regional status of extant populations largely matches that found during the first national survey, with a high proportion of sites located in the north and west of Scotland, including the Western Isles (Fig. 5). Many of the sites with evidence of recent recruitment were in the north and west of Scotland but high levels of recruitment were also recorded in some large east coast Grampian rivers.

An analysis was conducted of the relative abundance classifications across regional areas and nationally (Table 4). For this analysis, the abundance code used for each river was that of the highest scoring 50 m transect on the river. In all regions extant pearl mussel populations were dominated by relative abundance codes C and D (scarce-rare). Less than a third of pearl mussel populations in any region held relative abundance codes A and B (abundant-common). Despite there being 19 known mussel rivers in the Western Isles no transect exceeded abundance code C and three were assessed as apparently extinct since the first national survey. Nationally, 97 of the 115 extant Scottish populations (84 %) were classified as scarce-rare. In other words, only 18 of Scotland's rivers (16 % of those surveyed) now hold pearl mussel populations in densities that are considered to be common-abundant.

Figure 6 provides a breakdown of changes in population status by hydrological region. Of the 105 rivers for which current and previous baseline data are both available, mussel population status remained unchanged in 75 watercourses. A further 21 rivers showed evidence of decline while only nine showed some improvement. Improvements outnumbered declines only in the NE Highland region.

Of the eleven instances of apparent recent extinction (Table 4), ten occurred in rivers where no evidence of recruitment was found in the first national survey, and only one river previously defined as 'functional' (based on the presence of a single juvenile in first national survey) has become extinct. No particular regional trends are apparent, with extinctions in both east and west coast watercourses. In addition to the extinctions, ten rivers were recorded as declining due to failure of recruitment since they were first surveyed. Recent recruitment failure was recorded in all regions with the exception of Orkney and Shetland where there is only one known *M. margaritifera* population.

Apparent improvements in status arising from a record of recent recruitment occurred in nine watercourses (of which six were included in the first national survey and three were surveyed in the intervening period). The improved classifications of three of these were the result of finding a single large juvenile mussel in each river (65, 64 and 60 mm respectively), so these improved classifications may be considered weak or tenuous at best. The

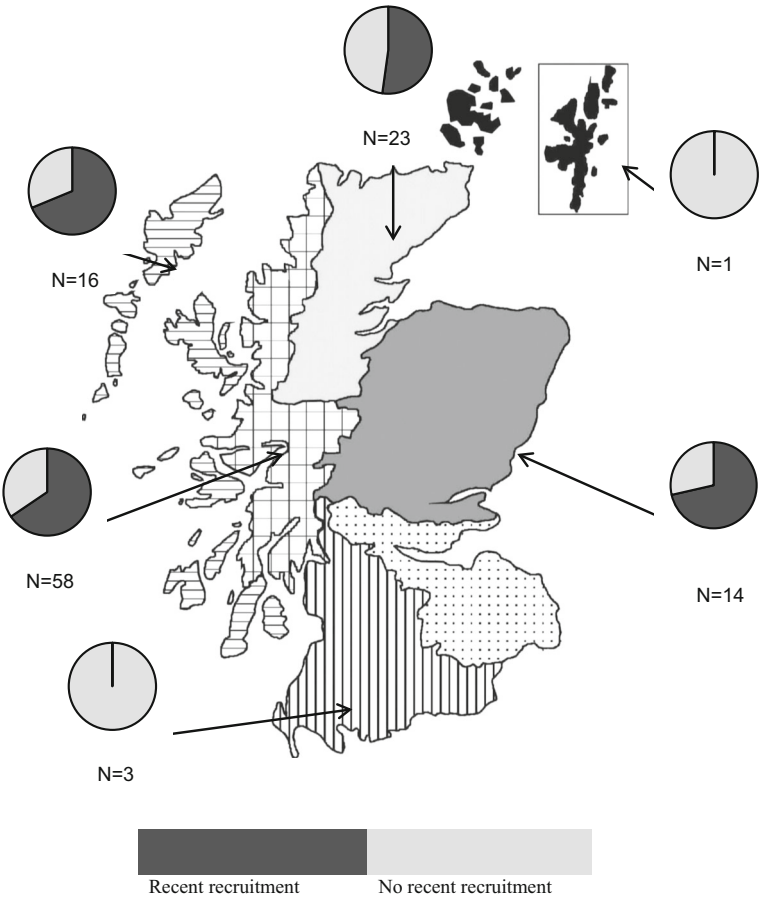

Fig. 5 The current status of *M. margaritifera* populations in Scottish Hydrological Regions

Table 4 The relative abundance status of freshwater pearl mussel populations in Scottish Hydrological Regions (proportion of extant regional populations only in parenthesis)

Hydrological region	Maximum abundance classification per transect					All rivers (n)
	A	B	C	D	E	
SW Scotland	0	0	1 (33.3)	2 (66.7)	0	3
Grampian	1 (7.1)	1 (7.1)	4 (28.6)	8 (57.1)	4	18
NE Highlands	4 (17.4)	2 (8.7)	5 (21.7)	12 (52.2)	1	24
Orkney and Shetland	0	0	0	1 (100)	0	1
West Highlands	6 (10.3)	4 (6.9)	26 (44.8)	22 (37.9)	3	61
Western Isles	0	0	6 (37.5)	10 (62.5)	3	19
Scotland	11	7	42	55	11	126

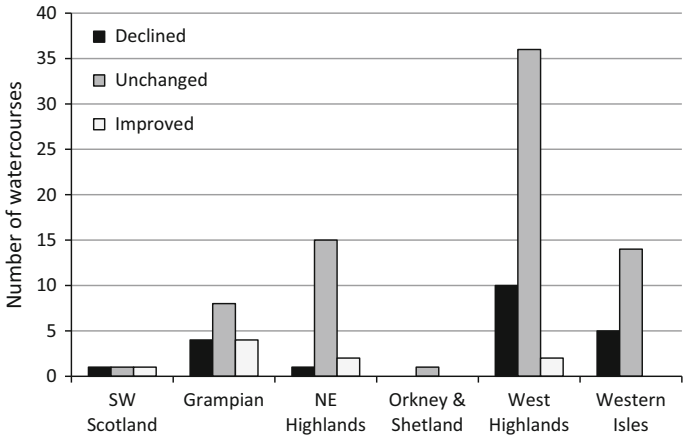

Fig. 6 Trends in pearl mussel status by Scottish Hydrological Region (data from rivers with 2 sets of data for comparative purposes)

original classification of one river (located in NE Highland) was based on a single 50 m transect and so the apparent improvement in mussel population status from this watercourse is likely to have been an artefact of increased sampling effort in the current survey, where five transects were undertaken in 2014.

Threats

In order to assess current threats and trends, it is important to consider changes that have occurred between the first and second national surveys (a period of 15 years). Using and expanding upon the categories listed by Cosgrove et al. (2000a), this report assesses specific threats, based on evidence of their occurrence at all the rivers surveyed in 2013–2015. Table 5 summarises threats identified in pearl mussel rivers in each hydrological region and these are considered further in the Discussion. The apparently recently extinct watercourses are included, as the extinctions have presumably occurred due to recent or ongoing pressures.

Discussion

Overall status of Scottish freshwater pearl mussel populations

Cosgrove et al. (2000a) reported that the pearl mussel population in 58 of the 155 rivers surveyed between 1996 and 1999 were extinct. These extinct rivers were not resurveyed in the current study and it is assumed that the former populations in these watercourses remain extinct, based on a sub-set being resurveyed for potential reintroduction in 2007 (ERA/Cosgrove and Hastie 2007).

Therefore, of the 126 known pearl mussel river populations, the evidence from 2013 to 2015 suggests that:

- Apparently extinct = 11 rivers;

Table 5 Specific threats identified in pearl mussel rivers in each Hydrological Region (percentage in parenthesis)

Region	Threat category						
	Rivers (N)	Pearl fishing	Pollution/ water quality	Hydro' impact/river engineering	Host fish	Climate change/river bed instability	Other
SW Scotland	3	2 (66.7)	3 (100)	0 (0)	0 (0)	0 (0)	0 (0)
Grampian	18	7 (38.9)	6 (33.3)	8 (44.4)	1 (5.6)	4 (22.2)	1 (5.6)
NE Highlands	24	5 (20.8)	6 (25)	10 (41.7)	0 (0)	9 (37.5)	4 (16.7)
Orkney and Shetland	1	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (100)
West Highlands	61	24 (39.3)	14 (23)	5 (8.2)	28 (45.9)	8 (13.1)	4 (6.6)
Western Isles	19	6 (31.6)	2 (10.5)	0 (0)	5 (26.3)	5 (26.3)	3 (15.8)
Scotland	126	44	31	23	34	26	13

- Not successfully recruiting = 44 rivers with no evidence of recent successful juvenile recruitment; and
- Recent successful recruitment = 71 rivers with evidence of successful juvenile recruitment.

It should be borne in mind that Cosgrove et al. (2000a) reported that pearl mussels had already become extinct from 58 Scottish rivers occupied in the previous 100 years. Between the first national survey and the current survey, an additional four former pearl mussel rivers were surveyed and populations were found to be extinct. Thus, combined survey evidence from surveys since 1996 indicates that the number of apparently extinct Scottish pearl mussel rivers known is now 73.

Based on the findings of the first national survey, Cosgrove et al. (2000a) provided estimates of historical extinction (i.e. disappearance) rates for Scottish *M. margaritifera* populations. It was apparent that, in Scotland, *M. margaritifera* declined throughout the twentieth century, and that the annual rate of population extinction accelerated during the latter 30 years of the last century, from an estimated 0.5 extinctions/year during the period 1901–1970 to an estimated 2 extinctions/year during the period 1971–2000 (Cosgrove et al. 2000a). The results of the current survey indicate that the extinction rate may have slowed since then. Although this reduction in rate is to be welcomed, a further 15 population extinctions in Scotland during the past 15 years represents a significant loss to one of the remaining global strongholds of *M. margaritifera*. To continue conserving the species every effort must be made to arrest any further losses.

Threats to Scottish freshwater pearl mussel populations

Pearl fishing

During the first national survey 99 % of Scottish pearl mussel populations were considered to have been affected by pearl fishing (Cosgrove et al. 2000a). Illegal pearl fishing is still a threat to all Scottish pearl mussel populations. Annual pearl fishing mortality levels as high

as 5–10 % (representing 25–50 % of total mortality) were estimated for a sample of exploited Scottish *M. margaritifera* populations (Hastie 2006). These levels are clearly unsustainable in the long term, and support the view of Cosgrove et al. (2000a), that historical pearl fishing pressure was a major cause of extinction in a number of Scottish *M. margaritifera* populations. However, to provide meaningful up to date information on pearl fishing incidents and potential impacts, pearl fishing is listed as a direct current threat/pressure only on those rivers where there has been direct evidence of recent pearl fishing activity (post 1999).

Despite being fully protected since 1998, large numbers of freshwater pearl mussels have been illegally killed each year since then (Cosgrove et al. 2012b). The most recent statistics in the Scottish wildlife crime annual report (Table 6; Scottish Government 2015) show that between two and 12 confirmed incidents of wildlife crime affecting pearl mussels were recorded annually between 2009 and 2014. These incidents have been reported across the Scottish mainland and from several of the Hebridean Islands. The consequence of this pressure on the conservation of the species is such that freshwater pearl mussels remain a UK wildlife crime priority.

Pearl-fishing offences are hard to detect for a number of practical and logistical reasons. Given the remote distribution of the majority of remaining pearl mussel populations, offences tend to occur in places seldom visited by many people. If evidence is left behind, it can often be years before it is found and reported, severely reducing the likelihood of perpetrators being apprehended (Cosgrove et al. 2012b). Furthermore, few people know what pearl-fishing signs to look for and where to find them. Finally, we have seen evidence of pearl-fishers changing their behaviour and deliberately hiding evidence of offences (discarded shells), so that populations of pearl mussels just 'disappear' from an area for no apparent reason (*pers. obs.*).

The complete disappearance of mussels in this manner means that assessment of pearl fishing impact can become more speculative, because direct evidential basis of decline or loss in such cases is lacking. There is no evidence to suggest that natural predation of pearl mussels causes significant mortality. Indeed, such events are rather rare and opportunistic in nature, resulting in the death of very small numbers of mussels in an identifiable manner (Cosgrove et al. 2007).

Given the difficulties in identifying and recording pearl fishing incidents, it is likely that the number of rivers where evidence of illegal pearl fishing activity has been recorded is an underestimate of the number of actual incidents since the first national survey. Nevertheless, based on the data collected from the four sources outlined above, there is direct evidence of pearl fishing since the 1998 ban (e.g. Fig. 7) in a minimum of 34.9 % of 126 Scottish rivers that were included in the analysis (Table 5). No particularly striking regional trends emerge, the proportion of affected rivers being largely independent of geography at the scale used for analysis. The individual river accounts do not throw much

Table 6 Suspected criminal incidents on freshwater pearl mussels in Scotland 2009–2014 (Scottish Government 2015)

Financial year	Number of incidents
2009–2010	10
2010–2011	12
2011–2012	4
2012–2013	2
2013–2014	8

Fig. 7 Despite full legal protection, illegal pearl fishing kills are reported annually. This pile of shells was part of an estimated pearl fishing kill of >1000 mussels, West Highlands, 2014

additional light on which rivers are most likely to be threatened; accessible sites and remote sites both showing evidence of impact. However, a high proportion of designated sites, which have been surveyed much more than undesignated sites, have reported pearl fishing kills since 1998. Whether this is simply a reflection of survey and reporting effort being greater on designated sites or reflects a real focus by illegal pearl fishers on some of largest extant (and publicised) watercourses is unknown. It is clear that effort to reduce this threat via current media campaigns, increased intelligence gathering and improved policing remain necessary and a conservation priority.

Pollution/water quality

Pollution and poor water quality are known to kill and adversely affect pearl mussels (e.g. Bauer 1988; Moorkens 2000; Young et al. 2001; Degerman et al. 2009). Given that this survey did not measure water quality, the issue is only identified for pearl mussel rivers where there was direct evidence or evidence of impact (e.g. dead in situ mussels, plumes of silt or pollution from point sources, excessive algal growth, sewage fungus etc.). Former pearl mussel rivers where pollution would have wiped out entire populations were surveyed in the first national survey and were not revisited again in the current survey. Thus, only on-going or recent incidents involving pollution and/or poor water quality are reported. Based on the data collected by surveyors during the current survey, there is evidence that 24.6 % of 126 pearl mussel river populations having been affected by pollution or poor water quality between 1999 and 2015 (Table 5).

Care needs to be taken interpreting these data and further analyses may be warranted. In a number of rivers where pollution was recorded it was highly localised (e.g. a single septic tank outfall impacting on one mussel bed). Such localised impact may not affect the overall status of a large, dispersed mussel population, but may threaten a very small, restricted one. Water quality effects that are more diffuse or whose impact is more widespread are of greater concern. Perhaps surprisingly, 23 % of West Highlands watercourses were judged

to be threatened to some degree by water quality concerns despite the region's relative remoteness. In addition to the toxic impact already mentioned above, the three main factors resulting in water quality concerns in West Highlands were forestry, agriculture (mainly trampling by cattle leading to runoff and associated siltation) and the presence of dense algal growth. Surveyors also recorded greatly increased algal growth in two watercourses after one large intentional fire (known in the UK as 'muirburn') and one large potentially unintentional fire. Recent research has documented chemical changes, increased suspended solids and detrimental impacts on stream biota in catchments subject to regular muirburn (Ramchunder et al. 2013).

Agricultural effects on water quality were identified as a concern in some rivers in Grampian, NE Highlands and SW Scotland, a factor that has already led to the extinction of many pearl mussel populations in these regions (Cosgrove et al. 2000a). Deliberate or accidental poisoning of streams, such as occurred in two watercourses, are also a cause for real concern, adversely impacting both on pearl mussels and their host salmonids.

Hydrological management/river engineering

Hydrological management, including river engineering, dams, water abstractions, and channel modifications has historically been responsible for the decline and extinction of a number of Scottish pearl mussel populations and potentially remains a significant threat (Cosgrove and Hastie 2001). Based on the data collected during the current survey, there is evidence of a minimum of 18.3 % of pearl mussel river populations having been adversely affected by hydrological management or river engineering between 1999 and 2015 (Table 5). This includes eight sites where historic changes to hydrology, mainly by construction of major dams and barriers for hydroelectric generation, are likely to have an ongoing impact on flow regimes and sediment budgets.

There is a degree of interplay between river engineering and water quality, especially during the construction phase of engineering projects when siltation or other forms of pollution may occur. Siltation associated with the construction of hydro-electric schemes has been identified on two extant pearl mussel rivers, one leading to the first successful prosecution for damaging pearl mussels in Scotland (Scottish Government 2013). Rigorous monitoring of water quality for construction projects in pearl mussel streams requires '*eyes on the river*' and the employment of suitably accredited, trained and independent Ecological or Environmental Clerks of Work is recommended wherever such projects take place to ensure compliance with planning conditions and pollution prevention measures.

Host fish

Low numbers of host salmonid stocks have been identified as a potential threat to pearl mussels in Scotland (Hastie and Cosgrove 2001). The issue can be both generic (as with the threat of pearl fishing across all populations) and specific with locally low densities of host salmonids (e.g. Sinclair 2011). This is further complicated by the apparent issue of host specificity, where some pearl mussel populations appear to utilise only one species of fish; Atlantic salmon or trout, and not both (Hastie and Young 2001). Potential low host fish density has been listed as a threat where evidence of an apparent lack of host fish (e.g. few/none seen) was observed or where specific electric fishing data have been identified showing low fish abundance. However, it is important to recognise that a more general pressure may be occurring in some areas, such as the widespread sea trout stock decline in West Highlands (e.g. Walker 1994; Butler and Watt 2003; Butler and Walker 2006).

Actual or potential low host fish densities are identified as a concern on 34 watercourses (27 %) included in the survey (Table 5). There is a very clear and striking regional pattern, with the greatest threat in West Highlands and Western Isles. Twenty-eight rivers in West Highlands (45.9 % of the total) were classified as being threatened by low host fish numbers. In 18 of these watercourses, the classification is backed up by electric fishing data on juvenile salmonid densities (e.g. Sinclair 2011; Argyll Fisheries Trust 2007; Wester Ross Fisheries Trust 2012; West Sutherland Fisheries Trust 2015). In 15 West Highland rivers sea trout and/or salmon stock collapses have been reported and documented by local fisheries organisation or in published literature (e.g. Argyll Fisheries Trust 2009; Waterside Ecology 2010).[1] In our view, these numbers are likely to be conservative as few data are available for many smaller watercourses without commercially valuable fisheries. Data from the Western Isles are scarce as fewer electric fishing or catch data for individual watercourses are publicly accessible. Nevertheless five (26.3 %) rivers in the Western Isles were considered at threat based on electric fishing data (Argyll Fisheries Trust 2004; Sinclair 2011; Waterside Ecology 2010; Watt 2006). It is likely that low fish numbers may be a significant concern and linked to the lack of recruitment in several other pearl mussel populations in the West Highland and Western Isles regions for which no fish population data have been identified. Sea trout stock collapses have occurred in a number of rivers in SW Scotland (Ayrshire River Trust 2009) and, dependent on host species, may represent a further significant threat to mussels in this region.

Ongoing research suggests that a number of (but not all) pearl mussel populations in NW Scotland may be trout adapted (e.g. Baum 2015; Hastie et al. 2011), suggesting that low juvenile trout numbers may be a major concern in the core part of the extant Scottish pearl mussel range. Host fish concerns feature less heavily in eastern catchments, where salmonid densities are typically higher (Godfrey 2006). This is consistent with contrasting historic data trends in sea trout numbers on the two sides of the country (see e.g. Anon 1995; Scottish Government 2009). More recent analyses conducted by Scottish Government (2015) also indicate ongoing concern over salmon stocks in the West Highlands and Western Isles, where most require management action due to their predicted failure to meet conservation targets.

Climate change and habitat loss

The threat posed to pearl mussels by climate change has been recognised for many years (e.g. Hastie et al. 2003). During recent work to identify potential reintroduction sites for pearl mussels in Scotland, it became apparent that several rivers appeared to have changed in character (Cosgrove et al. 2012a). In particular the riverbed habitat in some former pearl mussel rivers had become predominantly unstable and this habitat loss has been attributed to increased spate events consistent with the changing climate in Scotland. Such change was particularly pronounced in rivers without headwater lochs to ameliorate very rapid changes in water discharge during spates (Cosgrove et al. 2012a). In the present survey climate change was identified as a potential threat where there was reason to believe that the habitat has changed and become unstable recently. It is recognised that this is a very difficult and subjective assessment because no empirical, systematic substrate stability data has been collected on pearl mussel rivers. Climate effects were only included when loss of previously suitable habitat had clearly occurred (i.e. no suitable habitat at former transect

[1] Many stock collapses have been reported on a named river by river basis so cannot be referenced herein as this would identify vulnerable pearl mussel watercourses.

locations and adjacent areas) or where professional judgement indicated a high probability of ongoing loss of habitat (extreme scouring, bank collapse, etc.).

Climate change and increasing substrate mobility was identified as a probable threat in 26 (20.6 %) watercourses surveyed (Table 5). Climate induced change may be one of the most difficult threats to ameliorate through medium-term management actions and it may only be possible to make generic recommendations in this regard. For example, expanding native riparian woodland cover in catchments denuded of tree cover and blocking moorland/farmland/forestry drainage ditches are warranted, as well as actions to restore natural geomorphological processes, which can help sustain sediment transport and maintain pearl mussel and host fish habitat.

Other factors

Approximately 10 % of surveyed streams were judged to be threatened from sources not covered by the broad categories set out above (Table 5). These 'other' factors range from non-native introductions e.g. *Ranunculus* spp. (Laughton et al. 2008) to over-shading by conifers, caused by former poor forestry management. Whilst other non-native species introductions (such as signal crayfish *Pacifastacus leniusculus* and zebra mussel *Dreissena polymorpha*) potentially threaten many rivers, none of these yet directly threaten extant Scottish pearl mussel populations and so have been excluded from the threat analysis. Nevertheless, signal crayfish are now present in catchments adjacent to globally important pearl mussel rivers (Spey Fishery Board 2014), and have recently been recorded within catchments supporting pearl mussels (but not yet in the watercourses hosting pearl mussels themselves).

Conclusion

Whilst it is encouraging that just over half of Scotland's extant freshwater pearl mussel populations show some signs of recruitment, the overall trend since the first national survey is one of continuing decline. This has come about due to the apparent extinction of some populations and recruitment failure in others. Furthermore, the trends identified above may mask weak or failing recruitment in many rivers, since the coarse analyses conducted are based only on the presence or absence of juvenile pearl mussels. Such analyses do not distinguish between the presence of one large juvenile, which would suggest very weak recruitment, and many juveniles of varied sizes, which would suggest strong and regular recruitment. In fact it is clear from the data from individual rivers that weak recruitment is an ongoing threat to many existing Scottish *M. margaritifera* populations. For a number of reasons pearl mussel sample sizes varied considerably between rivers and this may have affected the results, particularly in small or sparse populations where few mussels were found or measured. Nonetheless, this was also true of the first national survey and the overall trends are almost certainly genuine.

In the medium term, mitigation effort to enhance pearl mussel recruitment levels should be targeted in those catchments where recruitment is absent or weak, through actions such as host infection initiatives or host fish conservation measures. Protecting mussel populations from direct threats such as pearl fishing must also continue and the implementation of site specific actions should be encouraged and supported where possible. These should focus on implementing measures to protect and restore suitable habitat for juvenile pearl

mussels in particular. Cosgrove et al. (2000a) highlighted that a distinctive and worrying feature of remaining *M. margaritifera* populations across its range was a general lack of juveniles (e.g. Bauer 1986; Zuiganov et al. 1994; Chesney and Oliver 1998; Cosgrove et al. 2000a; Hastie et al. 2000b; Osterling et al. 2010). Hence any locations or areas of rivers with signs of recent juvenile recruitment are of particular importance in terms of the long-term viability of a pearl mussel population. The results of the present study support and reinforce this emphasis and practitioners should make conservation efforts in such areas a priority in Scotland and elsewhere. Even in the absence of specific autoecological information, clear 'no regrets' conservation measures such as riparian woodland restoration, blocking of forestry, moorland or agricultural drainage ditches and reductions in diffuse pollution should continue. In the longer term, identifying and ameliorating the particular causal factors underlying weak or failed recruitment remains the most pressing conservation priority for this species in Scotland.

Scotland's extant freshwater pearl mussel populations continue to be of international importance but their continued decline since the first national survey is of great concern. The decline is particularly pronounced in West Highlands and Western Isles strongholds, compared to eastern rivers in Grampian and NE Highlands. Over the last 100 years the species has been lost from much of its former range and new and continued action from a range of stakeholders is required to secure the future of *M. margaritifera* in Scotland.

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Compliance with ethical standards

Conflicts of interest P. Cosgrove, J. Watt, L. Hastie, D. Shields, C. Cosgrove, L. Brown, I. Isherwood and M. Bao received conservation research funding from SNH to undertake the Scottish national freshwater pearl mussel survey reported here. I. Sime was the SNH Project Manager for the Scottish national freshwater pearl mussel survey and undertook the desk study element of this work.

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