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Association of landscape and environmental variables with the recruitment of the freshwater pearl mussel (*Margaritifera margaritifera*) in Norway

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ABSTRACT

Using data from 309 localities with freshwater pearl mussel, *Margaritifera margaritifera*, in Norway, we analyzed the effect of several landscape and environmental variables on this species' recruitment. Median summer air temperature and, to a lesser extent, percentage wetland cover in the catchment were the strongest (negative) influences on recruitment. This is the first study to show an effect of air temperature on recruitment across a wide range of populations. The results are of importance for the conservation of the species, particularly in the context of climate change.

The freshwater pearl mussel (FPM; *Margaritifera margaritifera*) is listed as 'endangered' on the IUCN red list for endangered species (Moorkens, 2011), with populations declining throughout its range due to anthropogenic pressures on river ecosystems (Geist, 2010; Larsen, 2017, 2018; Lopes-Lima et al., 2017). Norway hosts the largest number of FPM in Europe, equivalent to ca. 25% of the remaining populations for the species (Larsen, 2018). Despite this, FPM is classified as 'vulnerable' in the Norwegian red list for endangered species, and was declared a "responsibility species", with its own dedicated conservation and management plan (Larsen, 2018).

Many studies have focused on the effect of environmental parameters on the occurrence and distribution of FPM (summarized in Lopes-Lima et al., 2017; Anon, 2017b). However, understanding the parameters explaining recruitment in FPM populations is paramount to ensure adequate and successful management of this species. Recruitment is the most important criterium in assessing the viability of FPM populations and is used in the Norwegian mussel population classification system (Anon, 2017b; Larsen, 2018). Here we investigated the effect of several environmental parameters on the recruitment of FPM in Norway. We used presence of mussels up to 50 mm in length as an indicator of recruitment (Anon, 2017b; Larsen, 2018). To this end, we performed an analysis using available recruitment information on the river reaches where FPM is found (summarized in Larsen and Magerøy, 2019). Data were obtained from the national database on Norwegian mussel populations ('elvemuslingbasen'; kart.gislink.no). Data on recruitment were available for 309 of 419 currently known FPM river reaches (Fig. 1).

For each river reach, the most downstream point in the known mussel distribution area was used to generate catchment-based information based on the Norwegian Environment and Energy Directorate (NVE)'s NEVINA (catchment and discharge index analysis) system. Ten environmental parameters that may explain recruitment were collected and used in the analysis (Table 1).

The effect of environmental parameters on recent recruitment (presence/absence of mussels <50 mm; Larsen, 2018) was tested with a generalized linear model (GLM) with binomial error link function. We fitted a full model including ten predictor variables (Table 1) and carried out AIC (Akaike Information Criteria)-based backward model selection (Development Core, 2017). Graphical inspection suggested a non-linear relationship between one of the explanatory variables – summer temperature - and recruitment. Therefore, we used a separate GLM to test for a non-linear relationship between summer temperature and recruitment. We also fitted a GLM for the effects of the explanatory variables in the reduced model for populations of mid-Norway (the geographical region with most data available), to test whether effects detected across the country are present on a smaller geographical scale.

The final model indicated that median summer air temperature and wetland area affected recruitment the most in the 309 studied FPM

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populations (Fig. 2, Table S1).

Eighty percent of studied populations occurred at summer temperatures between 8.0 and 11.9 °C and within this range, the predicted likelihood of recruitment decreased from 0.65 to 0.41 (Fig. 2). The likelihood of recruitment was twice as high in the coldest localities (6.3 °C) compared to river reaches with the highest temperature (13.3 °C) (Fig. 2). There was a significant nonlinear effect of summer temperature on recruitment (linear term on logit scale: -2.464 ± 0.984; quadratic term on logit scale: -0.112 ± 0.048; see Table S2). This model predicted that the likelihood of recruitment decreased from 0.91 to 0.45 with an increasing summer temperature up to 11 °C and then increased again to 0.59 at 13.31 °C (Fig. S1).

The percentage of wetland area varied from 0% to 60% in the studied populations, but 80% of the populations were located in areas with between 1.4% and 18.0% wetland cover. Within that range, the predicted probability of recruitment was only moderately reduced from 0.58 to 0.47.

Our analyses were based on localities spread over the whole country with large systematic variation in environmental variables, including median summer temperature and wetland cover (Fig. 3). The positive relationship between summer temperature and recruitment for temperatures above 11 °C was due to a relatively large proportion of recruiting FPM populations being found in south-eastern Norway, where higher temperatures are recorded. However, modelling of the effects of summer temperature and wetland cover on recruitment for populations in the region with most samples (mid-Norway, N = 136) indicated effects of summer temperature (-0.552 ± 0.260) and wetland cover (-0.035 ± 0.022) of similar strength as across the country.

We found a negative relationship between median summer air temperature and FPM recruitment. This is an important finding for the

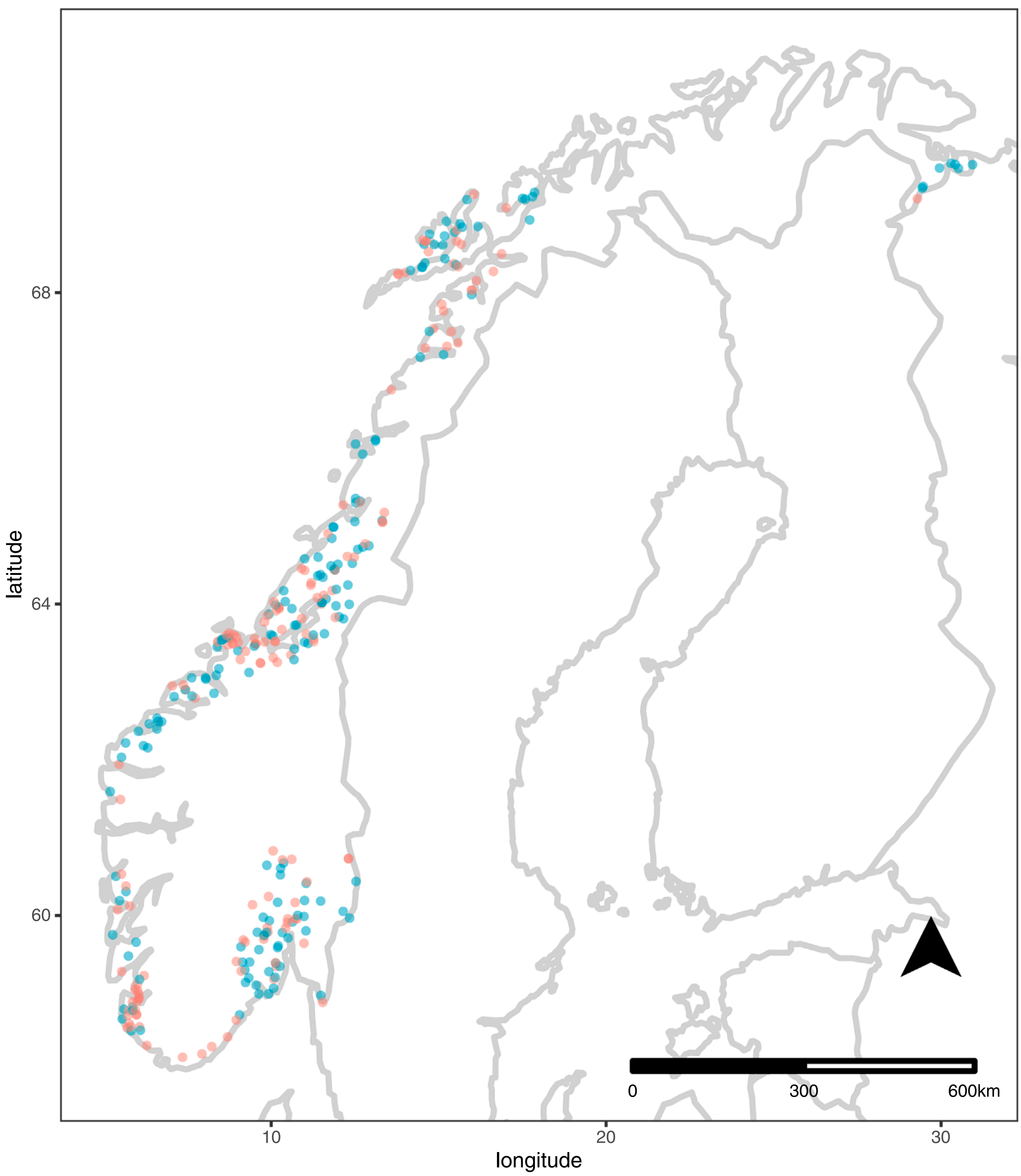

Fig. 1. FPM populations in Norway included in the analysis (N = 309). Recruiting populations are shown in blue, while non-recruiting populations are shown in red (from Larsen and Magerøy, 2019).

Table 1
Predictor and response variables used in the analysis. Due to the high degree of freedom in the analysis, the number of predictor environmental variables were limited to those of the catchment most likely to explain differences in mussel recruitment (based on expert opinion). Environmental variables describe the general conditions in the catchment, based on the NEVINA system (nevina.nve.no).

	Variables	Unit	Notes
Response	Presence /absence of mussel < 50 mm in length		Indicates observed recruitment
Environmental	Catchment area covered by wetland	%	
	Catchment area covered by agricultural land	%	
	Lake area	%	Weighed against how much area of the catchment drains in the lakes
	Median summer air temperature	°c	Median air temperature between May 1 and September 30
	Median summer precipitation	mm	Median precipitation between May 1 and September 30.
	River gradient	m/km	Difference in catchment elevation between the highest and lowest points where mussels were observed, divided by river length along mussel distribution
	Average calcium concentration		Determined from geological composition in the catchment and averaged according to the area covered by different geological types.
	Average catchment altitude	m.a.s.l.	Altitude at which 50% of the catchment lies under.
	Runoff	mm/year	Calculated after the Norwegian Water and Energy Directorate (NVE)'s runoff map for the period 1961–1990
	Catchment size	Km^2 (log transformed)	Catchment area upstream the location of the most downstream mussel observed.

survival and management of FPM in Norway in the context of global warming, even more so given that Norway hosts the largest number of FPMs in Europe. Our results are in line with recent work predicting that suitable FPM habitat in Europe will shrink and be limited to Northern Europe when summer temperature increases with global warming (Bolotov et al., 2018). That the effect of temperature across the country was mirrored in mid-Norway suggests that it was not caused by confounding factors related to north-south gradient. However, we cannot exclude the confounding effects of altitude, a variable that is strongly related to temperature within regions and which we incorporated in the model, and human disturbance (usually less pronounced in higher altitude catchments), (Larsen and Magerøy, 2019).

A positive relationship between high summer air temperature and the distribution of FPM was found in Sweden (Tamario and Degerman, 2017), while the opposite was found in Spain (Lois, 2015; Lois et al., 2015). Several authors have emphasized that FPM is adapted to colder climates and is therefore threatened by global warming (Hastie et al., 2003; Degerman et al., 2013; Tamario and Degerman, 2017; Bolotov et al., 2018). This can be the case in Southern Europe, where the species is already occurring at the high temperature end of its range (Bolotov et al., 2018). In Norway a more negative effect of temperature is expected in the south, where already higher temperatures and lower summer flows are observed, in contrast to the north of the country. Although water temperature, and not air temperature, directly affects mussels, air temperature is the strongest predictor of water temperature (Hastie et al., 2003; Bolotov et al., 2018). Other factors, such as catchment size, number of lakes in the catchment, forest cover in the riparian zone, as well as local geomorphology and flow conditions, will affect the relationship between air temperature and water temperature, and thus the conditions for freshwater pearl mussel (summarized in Larsen, 2012).

The results are based on median temperature data that can overshadow more short-term extreme temperatures. These, when more frequent, can have severe consequences for freshwater mussels, especially juvenile stages. While adult mussels can tolerate water temperature up to 25 °C over long periods of time and up to 28 °C for periods up to 20 min and can survive buried in humid substrate over several weeks depending on the temperature, larvae and juvenile mussels survive best with water temperature around 10 °C (Larsen, 2012).

Our results on wetland cover contrast with those from studies in Sweden (Jensen, 2007; Söderberg et al., 2008), where a positive relationship was found between the percentage of wetland area and mussel recruitment, possibly because these areas are synonym of low human disturbance (Jensen, 2007). Around 50% of wetland areas in Norway are drained or severely impacted, with even greater impacts in the lowlands (Øien et al., 2015). Under heavy precipitation, runoff from drained wetlands will lead to high discharge downstream in the catchment, acidification, and increased transport of fine particles that contribute to clogging of riverbed substrate, a critical habitat for juvenile mussels (Gosselin, 2015; Kadykalo and Findlay, 2016).

Our analysis is novel in that it reveals that air temperature has a strong effect on FPM recruitment and therefore could be used as a predictor both of the suitability of conditions for juvenile mussels in a river and of the probability of survival for a population. Other studies had previously focused on the effect of temperature on FPM distribution and occurrence, and not recruitment (Bolotov et al., 2018). Our results provide a starting point in understanding the catchment-scale parameters that drive FPM recruitment in Norway and highlight the complex and multiscale (both temporal and spatial) nature of parameters affecting the species' occurrence (Gosselin, 2015). Furthermore, they emphasize the need to investigate the linkages between various physical processes, from local to catchment and regional scale, in order to identify FPM recruitment drivers. In addition, mussel recruitment is dependent on a salmonid host fish, which is also affected by a variety of environmental factors, including temperature. An analysis coupling the FPM host fish system with environmental factors over a variety of scales can be a valuable contribution to the understanding of environmental effects on FPM recruitment. The FPM is an umbrella species, which means that its conservation will benefit the whole freshwater ecosystem in which it occurs. Predicting the effect of temperature on mussel recruitment can therefore contribute to implementing suitable conservation actions, particularly in the context of a changing climate.

CRediT authorship contribution statement

Marie-Pierre Gosselin: Writing – original draft, Writing – review & editing. **Sebastian Wacker**: Methodology, Formal analysis, Writing – review & editing, Visualization. **Jon Magerøy:** Investigation, Data curation, Writing – review & editing. **Anders Foldvik:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation. **Bjørn Mejdell Larsen**: Conceptualization, Investigation, Data curation, Writing – review & editing, Project administration, Funding acquisition.

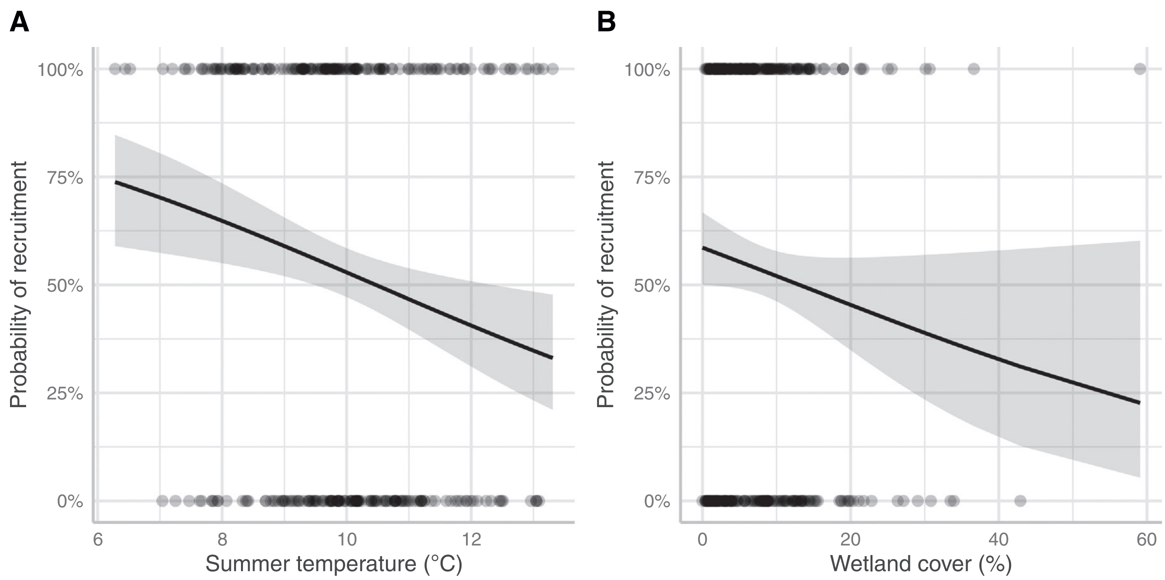

Fig. 2. Effect of median summer temperature (A) and wetland cover (B) on mussel recruitment (occurrence of mussels <50 mm) for 309 FPM populations in Norway. The black lines show effects of summer temperature (slope ± SE: −0.248 ± 0.087 logit proportion recruitment*degree summer temperature^{-1}) and wetland cover (slope ± SE: −0.027 ± 0.016 logit proportion recruitment*percentage wetland cover^{-1}) estimated by a generalized linear model and shaded areas represent 95% confidence intervals. Each circle represents a single FPM population.

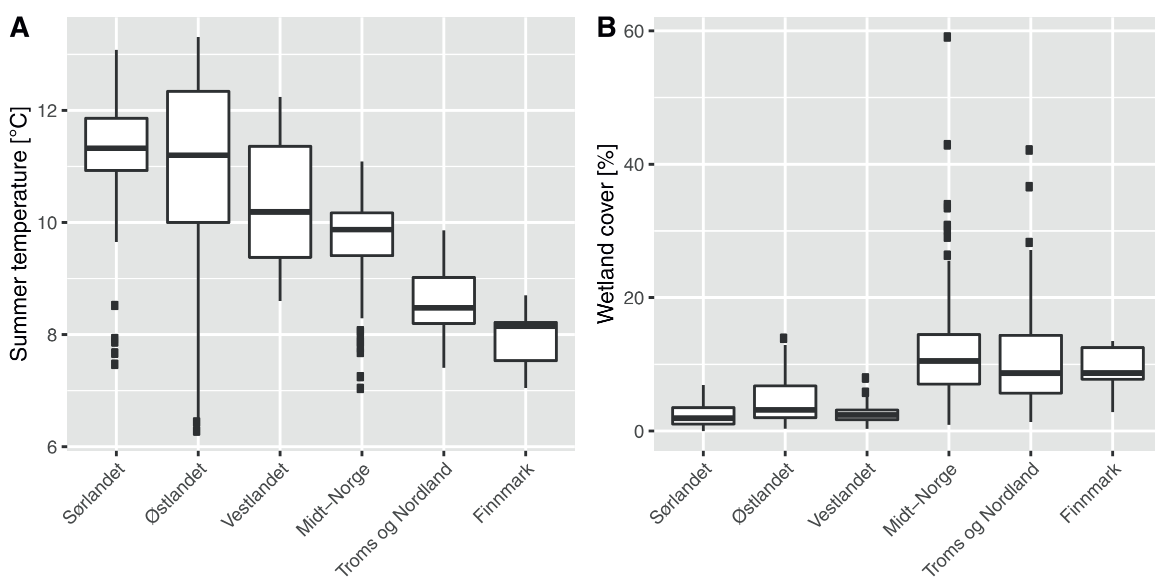

Fig. 3. Variation in median summer temperature (A) and wetland cover (B) in the catchment of 309 FPM populations distributed among six geographical regions of Norway. From South to North: Sørlandet, Østlandet, Vestlandet, Midt-Norge, Northern Norway (Troms og Nordland and Finnmark).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.limno.2022.126031.

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