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Predicting the habitat expansion of the invasive roach *Rutilus rutilus* (Actinopterygii, Cyprinidae), in Great Britain

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Abstract

The roach is influential ecologically and has a preference for water temperatures >12 ^{o}C. In this study we attempted to predict its habitat expansion in response to global warming, hypothesing its increase in Great Britain. Historical data for air temperature over different time scales (annual, seasonal, monthly and daily) and for the presence of roach in Great Britain were used to create four Ecological Niche Models. Mean seasonal air temperature (EncRoach-S) was the best predictor. Using EncRoach-S two future climate scenarios were tested: a sensitivity test (i.e. incrementally increasing temperature values by 1^{o}C), and using air temperature data from UKCIP 11-member ensemble of climate change projections for 2031-2040, 2061-2070 and 2091-2100. Both approaches predicted an increase in habitat suitability in Great Britain with rising air temperatures but the extent of change differed for England, Wales and Scotland. In England, the rate of expansion was initially slow but rapidly increased mid-century leading to 88% coverage by the century end. In Wales, there was a greater increase by the century end and a similar trend in Scotland. This study supports the conjecture that a rise in air temperature over the next few decades will lead to an increase in potential roach habitat.

Introduction

With the range of environmental changes predicted for this century there has been much interest and speculation about how the habitat range of numerous species will be affected. Beyond the simple gain or loss of individual species in a specific region, there is also the added concern that some species may be affected which are known to have significant impacts on ecosystems i.e. they can be considered invasive (McNeely *et al*., 2001). In British freshwaters, the fish species roach (*Rutilus rutilus* (L. 1758)) fits this criterion and is the subject of this study.

The roach is a eurythermal cyprinid and the fourth most recorded fish species in the UK Database and Atlas of Freshwater Fish (DAFF; Davies *et al*., 2004). Its current distribution is predominately Eurasian, although it is also found in southern Australia (Froese & Pauly, 2014), and it is considered to be expanding its range (e.g. in Ireland (e.g. Ferguson, 2008), Italy (e.g. Giannetto *et al*., 2014)). Their omnivorous feeding habits and ability to reach high population densities means that they have a great potential to establish new populations, influence other freshwater species and even affect ecosystem function (e.g. Brabrand *et al*., 1986; Graham & Harrod, 2009; Winfield *et al*. , 2011; Jeppesen *et al*., 2012; Hayden *et al*., 2014). Such attributes are of concern given the evidence for its continued expansion in both habitat range (e.g. Davies *et al*., 2004) and, where already present, population size (e.g. Winfield *et al*., 2011). The two key drivers behind such changes are believed to be eutrophication and increasing water temperature (Graham & Harrod, 2009; Jeppesen *et al*., 2012), and we have focussed upon the latter in this study as it operates at a national scale whereas eutrophication is site-specific.

The eurythermal characteristics of roach allow it to survive a broad range of water temperatures (4 to >30^{o}C; Cocking, 1959, Graham & Harrod, 2009) but with a distinct preference for warmer temperatures: growth occurs only above 12 ^{o}C (van Dijk *et al*., 2002) and juvenile growth is maximal between 20-27 ^{o}C (Hardewig & van Dijk, 2003). Furthermore, spawning is observed only at temperatures above 12-16 ^{o}C (Graham & Harrod, 2009) illustrating that population recruitment of the species is also tightly linked to higher water temperatures. Given these relationships, it is little wonder that Graham & Harrod (2009) in their review of the implications of climate change for fish populations of the British Isles predicted that the habitat range of the roach will expand. Therefore, this study attempts to test and quantify their prediction by the application of an Ecological Niche Model.

Ecological Niche modelling involves relating environmental variables to the known spatial distribution of a given organism in order to estimate the likelihood of its occurrence in a given area. It should be noted, however, that some confusion has arisen in the literature through the use of numerous other names for essentially the same model methodology (Hirzel & Le Lay, 2008) e.g. Habitat Suitability/Selection Models, Habitat/Species Distribution Models, Resource Selection Functions. Nevertheless, for this study we have constructed and tested a range of Ecological Niche Models for roach in Great Britain in order to predict how its habitat range may change over this century. To do this, we have brought together large spatial and temporal data sets. We have selected air temperature as the key driver of the model because i) air temperature data are available at high spatial and temporal resolution, ii) air temperature is a standard variable found in climate change model scenarios and iii) air temperature is closely related to water temperature, at least within the range of temperatures found in this study (the relationship is linear below air temperatures of 25 ^{o}C: Morrill *et al*., 2005). Thus, following the construction and testing of the models, we examined the sensitivity of the selected model's prediction to increasing temperature and also specific climate change projections developed by UKCIP (United Kingdom Climate Impacts Programme; Murphy *et al*., 2009). Finally, drawing on all of the modelled evidence, we have attempted to assess how roach populations across Great Britain may respond as the climate of this century continues to evolve.

Methods

Observed data

Information on the distribution of the roach in Great Britain was obtained from the National Biodiversity Network (NBN; data.nbn.org.uk (accessed 18 April 2014)) . These data consist of over 40 years of presence recordings attributed to 10 km UK Ordnance Survey National Grid squares. Absence squares were estimated by using all the grids in the NBN where a fish species had been recorded but roach had not. This made the assumption that the roach was a commonly recognisable fish, which we felt was reasonable given it is the fourth most recorded species in the DAFF (Davies *et al*., 2004). These data were split into two equal time periods: 1973-1989 (Period 1) and 1990-2006 (Period 2). This was done so that the Period 1 data could be used to construct the models and Period 2 could be used to evaluate them. Daily observed mean air temperature data (influenced by both the grid's weather and mean altitude) were obtained from the Met Office UKCP09 at 5 km grid resolution. These data were then mapped onto the appropriate 10 km square used by NBN to provide daily mean values at the National Grid scale. Finally, the air temperature data were split into Period 1 and Period 2, as per the roach data, and for each period daily, monthly, seasonal (winter = December to February, spring = March to May, summer = June to August, autumn = September to November) and annual mean values were calculated.

The Ecological Niche Model: EncRoach

Using the Period 1 data, four Ecological Niche Models (called EncRoach (Environmental change & Roach)) were created using a Generalised Linear Model (GLM) with binominal response and a logit link. This method related the mean air temperatures calculated in each grid to the roach presence/absence data in order to create an estimate of the likelihood of roach presence. Each EncRoach model was given an appropriate suffix to indicate which air temperature means had been used i.e. annual (A), seasonal (S), monthly (M) or daily (D).

As each model produces a probability of roach presence, the next step was to define the best threshold on the probability range to switch an “absent” value (0) to a “present” value (1). Thus, we tested each model against the Period 1 roach data using a range of probability thresholds to find which value produced the lowest predictive error rates in the Period 1 observed presence/absence data.

Following this, the four models were tested by using the air temperature data from Period 2 to drive the EncRoach models and their outputs were compared to the Period 2 roach observations. The models were assessed by calculating their respective Receiver Operating Characteristic (ROC) curve, which plots the true positive rate against the false positive rate, calculating the Area Under the Curve (AUC). This provides an evaluation of the percentage of the presence/absence predictions in the modelled output that match the observed. These latter comparisons were made against all grids in Period 2 and also only grids that showed change in roach presence between Periods 1 and 2. Following this, the EncRoach model that was judged to have performed the best was selected for use in the next stage of the study.

Climate change testing of EncRoach

Two approaches were taken to test the effect of changing air temperature on the distribution of roach habitat. Firstly, the EncRoach model selected was re-run using Period 1 data but the air temperature means were forced to be +1, 2, 3 and 4^{o}C warmer and the outputs of these simulations provided a sensitivity test of the models’ predictions. Secondly, air temperature data from UKCIP 11-member ensemble of climate change projections (Prudhomme *et al*., 2012a,b) was used to produce seasonal means for the following periods: 2031-2040, 2061-2070 and 2091-2100. These data were then used to drive the EncRoach model to produce roach habitat predictions for the different future time periods which were then compared using box plots (created using R version 3.0.2; R Developmental Core Team, 2013) and paired t-tests. In order to ensure that there was no bias introduced by using climate scenarios in the prediction against using observed climate data in the model, a bias correction was established between the observed climate and the output from each of the climate scenarios.

Results

Model assessment

The statistics used to assess the four Ecological Niche Models illustrated large differences among them (Table 1). The model using daily mean air temperature values (EncRoach-D) was the poorest at predicting roach presence/absence with a low AUC, percentage match and heavily skewed error values. EncRoach-A (using annual means) was also poor with a percentage match against all grids of only 67%, despite having a high AUC value (0.803), and again the error was skewed towards false positive values. The final two models performed to a similar level, but EncRoach-S (using seasonal means) was slightly better at matching the observed data than EncRoach-M (using monthly means), both overall (82%) and forthe grids that had changed (48%). Furthermore, its error was more balanced and had the lowest false positive error values, meaning it was the model least likely to predict a presence where there was none and was thus the most conservative. On this basis, the EncRoach-S model was selected to explore the potential expansion of roach habitat in Great Britain. The formulation for this model is presented below, where Y_i represents the observant presence or absence at location *i*, η represents the logit link function and SP, SU, A and W represent the mean spring, summer, autumn and winter temperatures respectively:

$$E[Y_i] = p_i \eta(p_i) = -22.81 + 2.10 * SP_i + 0.82 * SU_i + 0.39 * A_i - 2.33 * W_i$$

Predicting the change in roach habitat: sensitivity analysis

EncRoach-S was repeatedly run using Period 1 seasonal air temperature means increased incrementally by 1°C to a maximum rise of 4°C (Fig. 1). The results showed a marked increase in potential habitat available with each 1°C increase in air temperature. The

EncRoach-S probability threshold (0.876) was used to convert the probabilities into presence/absence values. The probability threshold was defined as the value on the ROC curve that minimises the distance to the ideal optimum of 100% True positives and 0% false positives. This illustrated that the rate of habitat increase in Great Britain was not linear (Table 2). Specifically, the number of new grids added per 1 ^{o}C rise increased with the higher temperatures, e.g. across Great Britain there were 163 additional grids for the rise of 0 to 1 ^{o}C, but 301 additional grids for the 3 to 4 ^{o}C increase (Table 2). The main cause of this effect was the rapid increase in new grids in Scotland with increasing temperature, compared to a relatively constant rate of increase in Wales and a declining rate in England (Table 2). In terms of changes in the percentage of potential habitat grids, England and Wales had achieved >90% cover with a 4 ^{o}C increase and Scotland >35% (Table 2).

Predicting the change in roach habitat: climate change projections

The 11-member ensemble of climate projections was used to make a range of predictions for specific periods of the 21st century (Fig. 2). The universal trend was of an increase in potential roach habitat as the century progressed. For the majority of regional areas, the changes between each decade were statistically significant ($P<0.05$) with the exception of England between 2030-2039 and 2060-2069 (Fig. 2b). Furthermore, the 2060-2069 decade generally showed the widest range of predicted values i.e. the greatest uncertainty (Fig. 2).

The trend of increase for England (Fig. 2b) was asymptotic because by the later decades almost all potential grids were indicating roach presence. In Wales and Scotland (Fig. 2c & d), the increase was more linear, although Wales was also approaching total coverage by the end of the century.

Discussion

Understanding how the changes to our climate this century may affect fauna and flora in ecosystems remains a challenging objective. While expert judgement provides one approach, modelling offers a qualitative, and complementary, methodology. For this study Ecological Niche modelling was used, a method that has been widely applied to simulate potential species habitat changes, in order to evaluate how roach habitat suitability in Great Britain may change over this century. However, before discussing the results and their implications, it is valuable to assess critically the model and its assumptions first.

Firstly, the EncRoach-S model only relates the habitat available to air temperature, using it as a proxy for water temperature. The use of air temperature in this way is reasonable (Morrill *et al*., 2005) but it does mean that the model does not consider the nutrient richness of the habitat. The latter could be an issue because roach tend to be associated with eutrophic environments (but certainly not exclusively) but changes in this factor are difficult to predict, especially across the whole of Great Britain. Therefore, we accept that the model is likely to over predict the expansion of roach, especially in areas of the country that are less nutrient rich e.g. uplands. Secondly, dispersal-limitation is another factor that could affect the spread of roach to new habitats and is not considered by the model which deals with potential habitat. It might be imagined that, given the disconnected nature of different river catchments, the natural methods available to the roach for invasion to a new catchment are very limited. Unfortunately, the introduction of roach to catchments is all too common throughout Great Britain because it is a desirable species for use in sport fishing. These movements are supposed to be regulated and controlled (e.g. as use for live bait in Pike fishing) but historically have proven to be very difficult to police (e.g. Winfield & Durie, 2004). Therefore, given its historic level of introduction (Davies *et al*., 2004), it is difficult to conceive that dispersal (i.e. river system connectivity) will be a restraining factor over the rest of this century. Despite these caveats, the EncRoach-S model can be used to predict the suitability of an area in Great Britain as roach habitat based solely upon the species' temperature requirements since it correctly predicted 82% of the observed grids for Period 2 (1990-2006; Table 1) across Britain.

Both the sensitivity simulations and the climate change scenarios showed a universal trend of increasing roach habitat suitability across Great Britain with rising temperatures. This result is in accord with qualitative predictions made by others (Graham & Harrod, 2009) and offers support to them. However, beyond this simple trend of increase, the EncRoach-S model allowed both a regional and temporal nuance to be added to the result. Thus, we can examine the predicted changes in roach habitat over the 21st century for the three countries of Great Britain (England, Wales and Scotland).

England currently has the greatest number of roach occurrences (802 grids between 1973-1989; Davies *et al*., 2004) and EncRoach-S predicted a similar amount (817 grids; Table 2). This equates to about 60% of the potential grid habitats available to freshwater fish in England. Given this large starting value of habitat suitability, it is perhaps unsurprising that the model predicts the almost total expansion of habitat suitability into north and south-west England (Fig. 1 and Fig. 2) with a median percentage cover of 88% predicted for 2090-2099. However, this expansion was initially slow, with only a modest increase occurring in 2030-2039 to raise the percentage cover to 66% (Fig. 2). By 2060-2069, the increase was more substantial (median = 84%) but it should be noted that the uncertainty of this prediction was large. Despite this, we can conclude that in England, if temperature is currently constraining roach, the expansion of roach habitat suitability will be initially slow but could increase rapidly in the middle of the century.

In Wales, the roach is currently less common than in England (16% of grids between 1973-1989; Davies et al., 2004) and this was reflected in the EncRoach-S simulations of the present climate (11% of grids; Table 2). The future simulations suggested an increase in habitat cover in the country throughout the century from 16% (2030-2039) to 55% (2060-69) to 79% (2090-2099). Again, the large mid-century increase seen for England was also simulated in Wales. Given the current level of presence of roach in Wales, these results are dramatic and suggest the potential impact of the species upon freshwater ecosystems in the country is likely to rise.

The final part of Great Britain considered was Scotland. Currently, the roach is relatively restricted in it distribution and mainly concentrated in the central belt (8% of Scottish grids between 1973-1989; Davies *et al.*, 2004). The model predicted zero habitat for the present climate (Table 2) and the median for 2030-2039 was also zero (Fig. 2). This underprediction by the model shows some of its limitations and that the predictions for Scotland are the least certain in the study. Nevertheless, the trend with time was for an increase in habitat suitability leading to a median coverage by 2090-2099 of 39% (Fig. 2). This would suggest that roach expansion is probable in Scotland although it is perhaps likely to be slower than in the rest of Great Britain.

Overall, this study supports the conjecture that the forecast rise in air temperature over the next few decades will lead to an increase in the habitat area suitability of the roach. This, of course, assumes that this habitat area up to now has been restrained at least partly by temperature but, as discussed above, this is not unreasonable given the species' eurythermal range and the good match the model achieved with the observed Period 2 data (Table 1). The confidence of the model's predictions is probably greatest for England and weakest for Scotland, with Wales falling in the middle. Despite this, and the somewhat simplistic nature of this kind of model, we believe this study provides important quantifiable results to support the conjecture that the roach will gain an increase in its potential habitat area in Great Britain as a consequence of climate change induced increases in air temperature.

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Table 1. Assessment statistics for the four Ecological Niche models tested. The suffix to EncRoach indicates the use of annual (A), seasonal (S), monthly (M) or daily (D) mean air temperatures. Note that "Data tested" refers to: "All" = all grids in Period 2 considered, "Changed" = only grids that changed between Periods 1 and 2 considered. Also, "AUC" = Area Under the Curve"; "% Match" = percentage of grids in the modelled output which match the observed in Period 2; "FPE" = False Positive Error and "FNE" = False Negative Error.

Model tested	Data tested	AUC	% Match	FPE	FNE
EncRoach-A	All	0.803	67%	30%	3%
	Changed		46%	44%	9%
EncRoach-S	All	0.867	82%	7%	11%
	Changed		48%	25%	26%
EncRoach-M	All	0.896	78%	18%	4%
	Changed		45%	42%	13%
EncRoach-D	All	0.611	38%	61%	0%
	Changed		50%	50%	0%

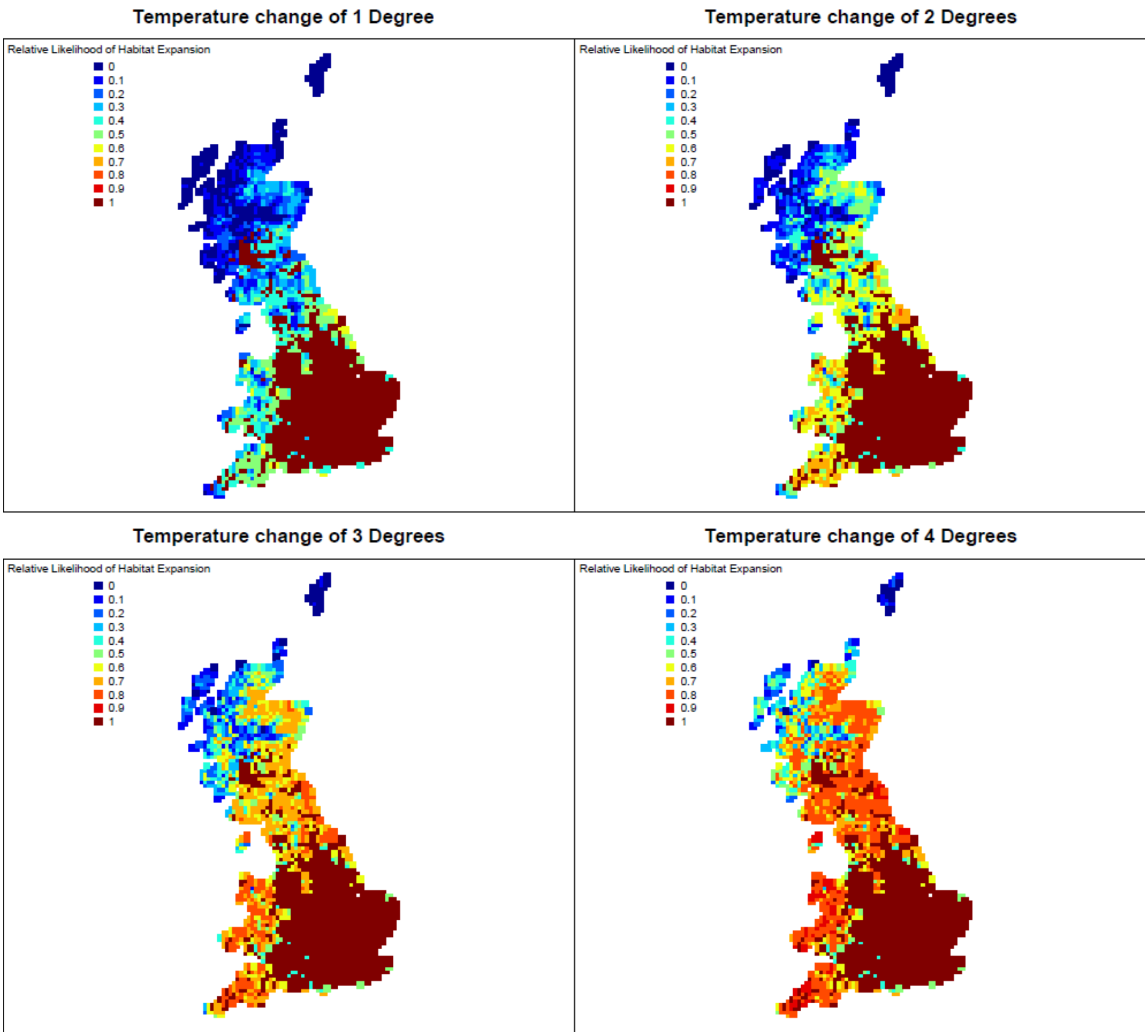
Table 2. The results of the model sensitivity analysis for Great Britain, England, Wales and Scotland showing the total number of grids where roach was predicted to be present (including the percentage of the total grids that represented) as air temperature for Period 1 was increased in 1^{o}C steps.

Area of Great Britain (total no. grids)	**No. of grids**	**Increase in air temperature (°C)**				
		0	**1**	**2**	**3**	**4**
All Great Britain (2470)	Presence	842	1005	1214	1509	1810
	% presence	34.1	40.7	49.1	61.1	73.3
England (1334)	Presence	817	958	1083	1202	1279
	% presemce	61.2	71.8	81.2	90.1	95.9
Wales (233)	Presence	25	47	93	153	211
	% presence	10.7	20.2	39.9	65.7	90.6
Scotland (903)	Presence	0	0	38	154	320
	% presence	0	0	4.2	17.1	35.4

Figure Legends

Fig. 1 The predicted probabilities of roach presence in Great Britain with an increase in Period 1's seasonal mean air temperature of: a) 1, b) 2, c) 3 and d) 4 ^{o}C. Note Dark Red region indicates Period 1 roach presence.

Fig. 2 Box plots of the number of 10 km grids where roach presence is predicted using the 11 UKCIP climate change scenarios for the following decades: 2030-2039, 2060-2069 and 2090-2099. These data are further categorised spatially to cover (a) Great Britain, (b) England, (c) Wales and (d) Scotland. Double headed arrows indicate paired t-tests and level of statistical significance (NS = Not Significant $P>0.05$, * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$).



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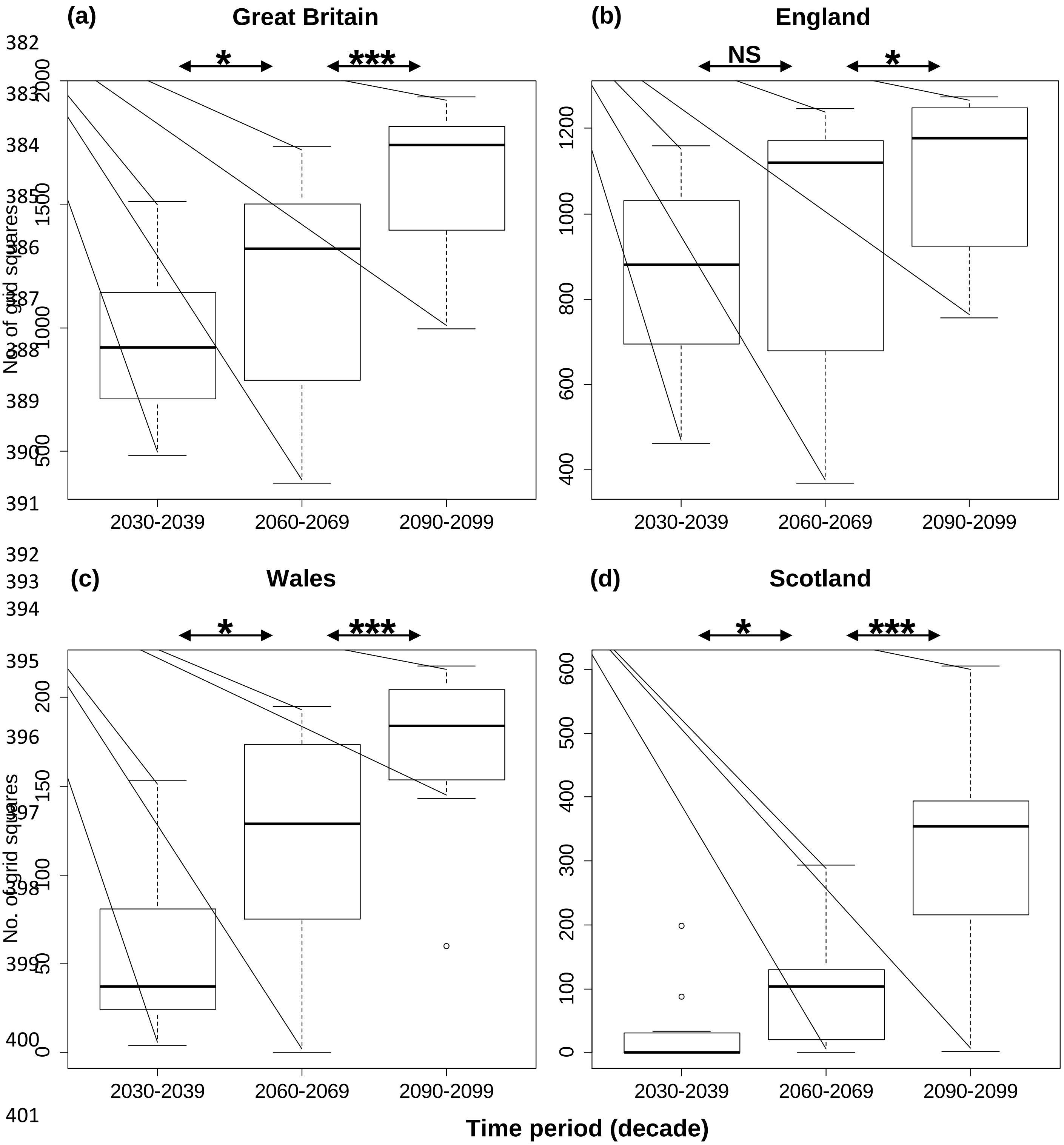
(a)
Great Britain
*
***
No. of grid squares
2000
1500
1000
500
2030-2039
2060-2069
2090-2099
(b)
England
NS
*
1200
1000
800
600
400
2030-2039
2060-2069
2090-2099
(c)
Wales
*
***
No. of grid squares
200
150
100
50
0
2030-2039
2060-2069
2090-2099
(d)
Scotland
*
***
600
500
400
300
200
100
0
2030-2039
2060-2069
2090-2099
Time period (decade)