Predicting the effects of marine climate change on the invertebrate prey of the birds of rocky shores

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By the end of the next century models of climate change predict that the air temperature over most of the British Isles will increase by between 2-3°C and sea level will rise by 40-50 cm. Over that period it will become windier and mean wave height will increase as will the frequency of storms. These changes in climate and weather will impact the intertidal zone of the UK and will cause distribution changes in many of the common invertebrate species that live there. Where these changes are severe they may well impact on patterns of distribution of ducks and wading birds.

In the British Isles a number of organisms live close to their geographical limits of distribution. Some of these species might be expected to extend their range as climatic restraints are relaxed. Species currently limited by cool summers or winter cold will move northwards. In most cases the effects on the distribution of waterbirds will be small. For example the replacement of the northern limpet *Patella vulgata* by the southern *Patella depressa* is unlikely to adversely affect Eurasian Oystercatchers. Of wider concern is the possibility that as climate warms the abundance and productivity of brown algae will decrease. This is likely to have two significant effects for waders. Firstly it would represent a loss of potentially rich feeding grounds for species such as Ruddy Turnstone that feed on small easily desiccated invertebrates living on or below the seaweed. Secondly as algae die or are broken away the resulting debris is exported to sediment habitats where it considerably boosts the *in situ* production of bacteria at the base of the food web.

Increase in sea level will only have a major impact on the extent of rocky shore invertebrate communities where shore topography prevents the upward migration of the biota. Where a seawall limits shores, for example, biological production will be curtailed as the area available for colonisation decreases. Increases in the size of waves and the frequency of storms will mimic increasing exposure and there will be a significant reduction in algal production in areas that are affected.

The majority of scientists agree that the Earth's climate is getting warmer. Analysis of global air temperatures from 1856 to present showed the 1990s to be the warmest decade and 1997 and 1998 as the warmest years (Jones *et al*. 1999). Ocean temperatures have increased in parallel with those of the atmosphere. Long term records from the English Channel (Fig. 1) show that from the early 1980s the sea temperature increased slightly until 1990. During the following decade there was an increase of almost 1ºC. This was far greater than any change in the previous 100 years. In its warm phase annual mean sea surface temperature off Plymouth is between 11.5° and 12.2 °C while during its cold phase the corresponding temperature is 10.0°-11.5 °C. As computer models forecast that by 2080 UK mean air temperatures will rise by between 1.5 and 3.2 °C the trend in inshore sea temperature is likely to continue. As global temperature rises, the volume of water in the oceans will expand and the polar ice caps will reduce in volume. This will cause sea levels to rise by a predicted world average of 13 cm by 2020 rising to 40 cm by 2080. In some parts of the UK sea level rises may be partially offset by coastal sinking (Hulme *et al*. 2002).

Given that there will be substantial changes in climate in the coming decades it is necessary to make predictions concerning the magnitude and nature of the changes to coastal biodiversity that will also occur. For some coastal habitats this might be difficult but predictions for changes in the biota of rocky shores are substantially aided by long running archive data from a number of UK and European sources as well as by a rich literature on the biology of the component species. The Marine Biodiversity and Climate Project (MarClim) takes the long-term records of variations in the abundance of rocky shore species analyses them simultaneously and makes models the future biota of the UK. This project began in mid 2001 and as yet full analyses are unavailable. However, preliminary predictions for shallow water life around the coasts of Scotland have already been made (Hiscock *et al*. 2001). Should a warming of the sea influence the abundance/quality of the prey of waterbirds or change the biota of intertidal habitats in which they forage, then local or even national patterns of bird distribution will be affected. The qualitative nature of such changes is predictable and will exacerbate the changed patterns of distribution that are already recorded as a response to milder winters between the mid 1980s and late 1990s (Rehfisch et al, in press). Changes at over-wintering sites will be over and above any impact to Arctic-nesting species that might result from a compression of breeding habitat (Rehfisch and Crick 2003). In this paper the probable nature of changes to the invertebrate fauna of the rocky seashore is discussed alongside prediction of the response of some waterbirds.

Effects of climate on the distribution of rocky shore species

The geographic distributions of the dominant British and Irish intertidal rock species was mapped in the 1950s (Southward & Crisp 1956, Crisp & Southward 1958). The fauna includes a number of common species that are either at or close to their northern or southern geographic limits of distribution. There has been little subsequent research to contradict Hutchins (1947) or Lewis (1964) conclusion that species with North-South patterns of distribution have their geographic limits set by temperature. Lewis (1976) proposed that species close to their northern distributional limits in UK were limited by the severity of winter conditions while those approaching their southern limit of distribution were limited by summer conditions. Crisp (1964) demonstrated that in the particularly severe winter of 1962-1963 the range of a number of southern species was reduced. Such extreme conditions undoubtedly serve as a check on the expansion of the range of a species but it is highly unlikely that winter conditions alone set distributional limits.

Lewis and his co-workers (Lewis 1986, 1996, 1999, Lewis *et al*. 1982, Kendall & Bedford 1987, Kendall & Lewis 1986) investigated the way in which climate affects a suite of dominant rocky shore species including the southern barnacle *Chthamalus montagui*, and the trochid gastropods *Osilinus* (*Monodonta) lineata* and *Gibbula umbilicalis. S*tudies on the trochids suggested that as species approached their northern limit of distribution they spawned and recruited over a far shorter season than in the centre of their range. Nevertheless, although the range edge breeding season of species appears to be populations close to their northern limits produce gonads and spawn annually (Kendall and Lewis 1986) and animals transplanted beyond their normal range can develop and spawn (Lewis 1986). Northern species at the south of their range are unlikely to be limited by the failure of gonad development although their reproductive season may well switch to an earlier time of the year (Bhaud 1982). In the case of the northern barnacle *Semibalanus balanoides* at its northern limit in the Arctic it spawns in mid summer (Feyling-Hansen 1953), in the centre of its range in April-May (Kendall *et al*. 1985) and close to its southern limit in February/March (Barnes &

Barnes 1976). The distribution of this species on southern shores (Barnes & Barnes 1976), observations of settlement success (Kendall *et al*. 1987, Jenkins *et al*. 2000) and experimental manipulations (Wethey 1984, Jenkins *et al.* 1999) all suggest that desiccation of individuals recently settled from the plankton limits its southerly extension.

Chthamalus montagui, is a southern barnacle species that reaches its northern limit of distribution in NW Scotland. Unlike *S.balanoides, C.montagui* has the potential to spawn successive broods of larvae whenever food and warmth permit. Myares (unpubl. data) recorded that in Spain larval settlement onto the seashore takes place over much of the year. In contrast, Kendall and Bedford (1987) showed that in W Wales there is only a single settlement period. In SW England Burrows *et al*. (1992) recorded as many as four broods of larvae produced annually.

Predicting the future fauna of rocky shores in the British Isles

The MarClim Project will make predictions about the future composition of the biota of rocky shores under a range of climate change scenarios. For many elements of the marine biota this would be a daunting task but the fauna of the rocky shore is comparatively easy to quantify and as a result there is a rich literature. For similar reasons, many schemes for monitoring the impact of man on the environment have included the study of rocky shores and these provided, and in some cases continue to provide, a wealth of data. Both the information in the literature and that in databases accrued by monitoring organisations will be combined by MarClim to provide a powerful basis for the prediction of the future composition of rocky shore communities. The data resources available to the MarClim project are summarised in Table 1. Importantly, many of the data sets that will be considered cover the last decade of rising sea temperatures but unfortunately, many of the other principal data sets were suspended in the late 1980s as a result of changes in national science policy. Although regrettable, if new surveys are undertaken within the next few years using comparable methodology it will still be possible to assess the extent of change during the 1990s. MarClim will re-survey as many as possible of the principal sites used in earlier surveys and will re-map the distribution of the main rocky shore species of the British Isles.

The distribution of the biota of rocky shores in the British Isles is complex and is set by the interplay of broad-scale factors, principally climate and oceanic circulation pattern, and local-scale processes such biological interactions or variables relating to coastal topography (e.g. aspect, rock type exposure) and local hydrography (e.g. current strength, turbidity, tidal range). To predict the effects of climate change on the distribution of individual species it will be necessary to extract broad-scale signals from the noise caused by local-scale factors. Once the relationship between the abundance of a species and climate has been characterised it will be possible to create predictive models that will simulate patterns of distribution under the various climate change scenarios. This stage of the project is in the future but data already analysed indicate clearly the way in which climate change will have an impact on the flora and invertebrate fauna of rocky sea shores.

Many rocky shores in the north of the British Isles are covered by the barnacle S*emibalanus balanoides* a northern species seldom found in any abundance beyond England. As *Semibalanus* declines it is generally replaced by the southern barnacle species *Chthamalus montagui* and *Chthamalus stellatus.* The relative dynamics of these barnacles in South West England have been the subject of long-term study the results of which are summarised in Figure 1b (from Hawkins *et al 2002*) and should be viewed in conjunction with Figure 1a. Figure 1b demonstrates that as *Semibalanus* populations decline the *Chthamalus* species increase and *vice versa*. This relationship is mediated by climate via its effects on inshore sea temperature. Figure 1b is based on a data set that ceased in the late 1980s but monitoring of barnacle populations has continued at a reduced number of sites. The most recent data show that since 1985 the warm-water barnacle species increased in abundance (Southward 1991, S.J. Hawkins & A.J. Southward unpubl. data). It should be noted that although sea temperatures have now reached levels observed in 1949-51, recent observations show the northern barnacle, *S. balanoides* remains fairly common in the Plymouth area, though recruitment may be failing. Such information on the relative population dynamics of intertidal barnacles in relation to inshore sea temperature can be used as the basis for prediction of the effects of the warming of inshore waters.

Other species

Climate-driven species-level change also seems to have taken place in numerous other intertidal organisms during the study period, including the southern limpet species, *Patella depressa* and the warm-water top-shells, *Osilinus (Monodonta) lineatus* (Southward *et al*. 1995) and *Gibbula umbilicalis* (Mieszkowska unpubl. data). Figure 2 shows that *Patella depressa* declined in abundance and range between the warm period of the 1950s and the cooler 1980s. (S.J. Hawkins & A.J. Southward unpubl. data). A number of other common species which are expected to respond to the warming of inshore waters are listed in Table 2. A more complete list is given by Hiscock *et al.* (2001)

Other effects

Fucoid algae are characteristic of all but the most exposed of intertidal of North European rocky seashores; in the infra-littoral they are replaced by larger laminarian species. Brown algae have a substantial effect on the composition of the community in which they live and on that of nearby assemblages. They have a direct role as a food source for grazing species, particularly gastropod snails, and as structural support for such animals as hydroids, ascidians and bryozoans. Fucoids also give shelter from heat and desiccation by keeping the rock beneath them moist and cool during the low water period. This makes it possible for animals and plants that are sensitive to desiccation to survive in an otherwise hostile environment. In this way, small crustaceans, sea anemones, hydroids, bryozoa and polychaete worms may be maintained by the presence of fucoid algae. Dead algae also sustain the biota on nearby sediment beaches where low *in situ* production is substantially boosted by the energy that comes from their decomposition. The strand-line community is also totally dependent on algal production.

Fucoid algae are a feature of northern shores (Ballantine 1961) and will be influenced by climate change. As sea and air temperatures increase it is probable that fucoid cover on moderately exposed shores will decline and as a consequence the biodiversity of rocky shores and the productivity of adjacent sediment assemblages will decline. The loss of fucoid algae, broadly related to temperature increase, may well be exacerbated by the effects of increases storminess that are predicted as a consequence of global warming. Depending on their aspect relative to wind-driven seas, some rocky shores will become more exposed and as a consequence their biological properties will change. In addition to the loss of algae, increased storminess will widen both barnacle and lichen zones in the high shore, increase the shore height reached by red algal assemblages and replace barnacle/limpet associations by those dominated by mussels.

The predicted sea-level rise is unlikely to have a great effect on most macrotidal rocky shores. In the majority of cases the strong slope of the seashore continues well above the level of high water. As sea levels rise so the physical zones occupied by each species will move up-shore but as there is free space available at the top of the shore no species will be displaced. The major exceptions to this prediction will be in places where there is a wave-cut platform beneath cliffs or where natural seashore has either been topped by an artificial sea wall or gives way to sediment. In both cases increasing sea-level will compress existing patterns of zonation.

Effects on invertebrate prey of birds

Although a great variety of birds may feed on rocky seashores very few are specialists relying exclusively on that habitat. At Robin Hoods Bay (N. Yorkshire, UK) only nine bird species regularly fed on the rocky shore. Of these nine species there was a single passerine, the Rock Pipit *Anthus petrosus* the remainder being either gulls or waders (Feare & Summers 1985). The Ruddy Turnstone *Arenaria interpres* and the Purple Sandpiper *Calidris maritima* are species particularly closely associated with intertidal rock where both species feed on small molluscs and crustaceans that live under stones, beneath macro algae or in cracks and crevices. Eurasian Oystercatchers *Haematopus ostralegus* are more specialised, being conspicuous predators of limpets and mussels (Coleman *et al*. 1999). Although Dunlin *Calidris alpina* and Common Redshank *Tringa totanus* are often seen on rocky shores, they are largely transients that specialise in feeding on sand or mud. The Common Eider *Somateria mollissima* is characteristic of rocky habitats in northern Britain where it feeds largely on mussels *Mytilus edulis*. In the light of the observations on the effects of climate on the population dynamics of the more important rocky shore invertebrate species, it is possible to predict the impact such changes might have on waterbirds. The following predictions can be made:

(1) Climate change is unlikely to have a significant effect on the amount of biomass available for bird predation. Where large, more conspicuous species, are concerned the major effect will be to change the balance between competing species. Thus in the south of England *Patella depressa* will become more abundant than *Patella vulgata* and *Chthamalus montagui* and *C.stellatus* will replace *Semibalanus balanoides*. It is likely that in species where reproductive success increases, the mean size of adult animals will decrease. This might have an impact on the efficiency with which prey are handled.

(2) There will be a decline in the abundance of fucoid algae and as a consequence small soft-bodied invertebrates that the algae protect from heat and desiccation will be less common. This might have an impact on species such as the Ruddy Turnstone.

(3) The decline in fucoid algae will have an adverse impact on the productivity of both sediments and strand line. Both habitats have their own avifauna which might suffer as a consequence.

(4) Increased storminess will cause a limited increase in exposure and as a consequence an increased area of seashore will be dominated by mussels

Effects of changes in bird numbers on rocky shore invertebrates

In the previous section of this paper the potential effects of changes in the invertebrate fauna of littoral rock on waterbirds were outlined. However, the interactions between birds and invertebrates are not all necessarily “bottom-up”. Changes in bird populations are likely to affect invertebrates. Should the abundance of Arctic-nesting shore birds be reduced as a result of tundra being replaced by forest (Zöckler & Lysenko undated) then a significant source of predation on small molluscs and crustaceans will be lost and as a result some populations might expand. Under warmer conditions Common Eider might retreat northwards and as a consequence, their predation on mussel beds might be reduced and hence their spatial coverage might extend.

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Table 1. Principal data sets to be used within the MarClim programme.

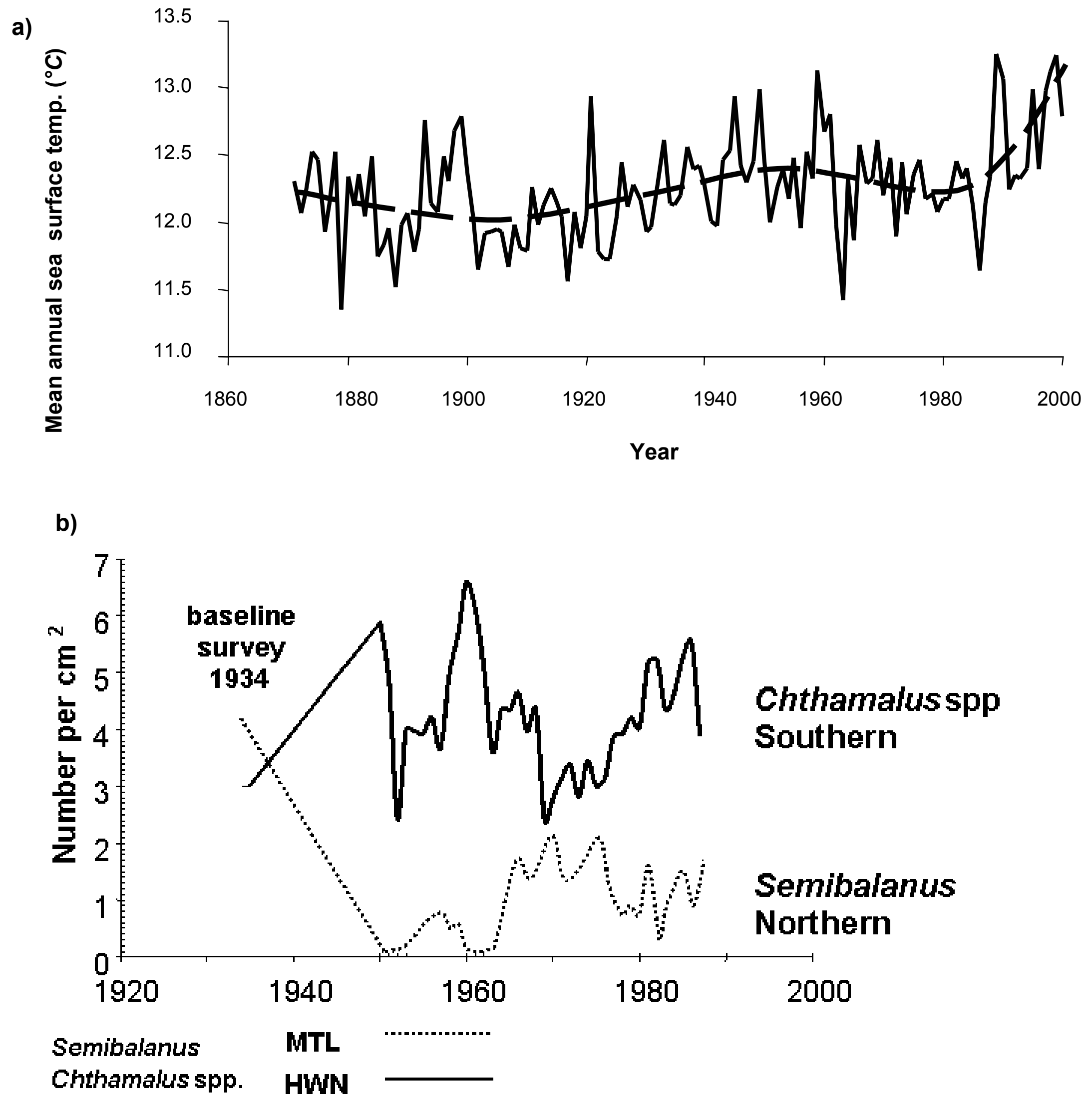
Category	Geographic coverage	Original collector	Years in record
Intertidal organisms	SW England, Isle of Man	A.J. Southward	1950-1987
Intertidal organisms	UK, France and Portugal	S.J. Hawkins	1980-2001
Intertidal organisms	UK, N. France	Rocky Shore Surveillance Group (J.R. Lewis)	1964-1987
Intertidal organisms	Anglesey	Coastal Surveillance Unit (E. Jones)	1974-1984
Intertidal organisms	Southern England	R. Herbert	1982-2001
Intertidal organisms	Shetland	Shetland Oil Terminal Advisory Group	1978-2001
Intertidal organisms	UK / Europe	D.J. Crisp	TBC
Intertidal organisms	UK / Europe	H. Barnes	TBC
Intertidal organisms	Orkney	Orkney Marine Biology Unit	TBC
Inshore fish (power stations)	UK	CEGB	1981-2001
Birds	Europe	BOU	1984-
Hydrography, plankton & fish	Plymouth	MBA	1903-1987
Sea temperature	Plymouth	T. Richards	1967-2001
Hydrography	Port Erin	D.J. Slinn, J.R. Allen, T. Shammon	1904-2000
Sea temperature	Guernsey	R. Sendall	1988-2000
Sea temperature	Worldwide	Hadley Centre	1880-2001

Table 2. Some common rocky shore species that are expected to respond to climate change in UK waters.

Species	**Current distributiom**	**North/ South**
Cnidaria		
Anemonia viridis	Widely recorded on west coast of Britain & Orkney; absent from east coast	S
Bunodactis verrucosa	Southern species recorded at a few locations in SW Scotland & Shetland	S
Actinia fragacea	A southern species, present in the Channel as far east as Brighton	S
Annelida		
Sabellaria alveolata	A southern species; reaches SW Scotland	
Crustacea		
Chthamalus stellatus	A southern species as far as NW Scotland and Shetland	S
Chthamalus montagui	Southern species common on north and west coasts of Scotland, present in Orkney and Shetland; occasionally in N. North Sea	S
Semibalanus balanoides	A northern species reaching it's southern limit in southwest Britain	N
Balanus perforatus	Only recorded in SW Britain as far north as S Wales in British Isles	S
Clibanarius erythropus	Southern species. Northern limit Channel Islands	S
Haliotis tuberculata	Southern species found as far north as Channel Islands	S
Tectura testudinalis	A northern species commonly recorded throughout Scotland but reaching its southern limit in the Irish Sea	N
Patella vulgata	A northern species reaches its southern limit in Portugal	N
Patella depressa	A southern species which reaches its northern limits at Anglesey in the British Isles	S
Patella ulyssiponensis	Commonly recorded on the west coast of Britain and present in Orkney; as far south as Filey in North Sea.	S
Gibbula umbilicalis	A southern species commonly recorded on the west coast of Britain. N limit on north coast of Scotland	S
Gibbula pennanti	Southern species found as far north as Channel Islands	S
Osilinus (Monodonta) lineata	A southern species which reaches its northern limits in Northern Ireland and Anglesey	S
Malaraphe neritoides	A southern species commonly recorded throughout Britain	S
Onchidella celtica	Southern species; reaches Cornwall	S
Paracentrotus lividus	A southern species abundant in parts of SW Ireland but only sporadic recorded occurrences in SW England and at a few locations on the west coast of Scotland	S
Strongylocentrotus droebachiensis	A northern species confined to the east coast of the British Isles; probably occurs on all North Sea coasts of Britain	N

Figure 1. a) Annual variation in means sea surface temperature in the English Channel off Plymouth. The dashed line shows the smoothed trend. From Meteorological Office Hadley Centre grid square 50-51°N, 4-5°W. b) Long term variability in the abundance of warm water barnacles of the genus *Chthamalus* and the cold water barnacle *Semibalanus balanoides*.

Figure 2. The distribution and abundance of *Patella depressa* around SW England and Wales during the 1950s (open circles) and early 1980s (filled circles). The diameter of the symbols is proportional to the abundance.



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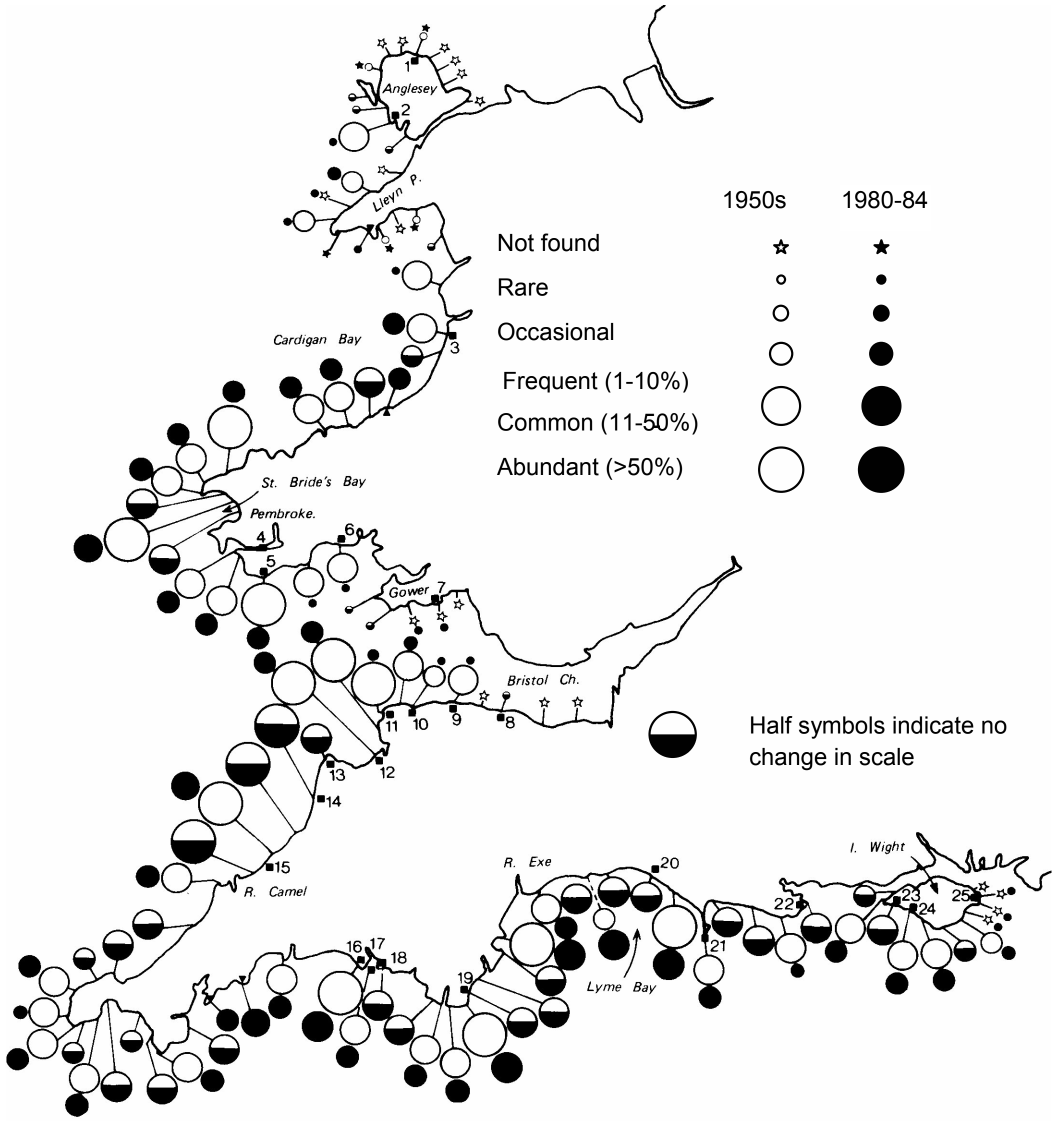

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