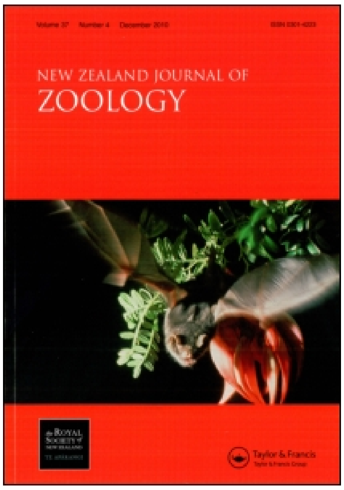

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Assessment of the global potential distribution of the predatory land planarian *Artioposthia triangulata* (Dendy) (Tricladida: Terricola) from ecoclimatic data

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Abstract *Artioposthia triangulata* was originally described from New Zealand in 1895 but was subsequently found to have spread to Northern Ireland in 1963 and Scotland and England in 1965. It is now widespread in both Ireland and Scotland, where it has been shown to reduce earthworm numbers to below detectable levels. Ecoclimatic data were used in the computer program CLIMEX to estimate the potential spread of *A. triangulata* to Europe and the rest of the world. Results indicated it could establish in agricultural land in most of north-western Europe, and persist in domestic gardens throughout much of central Europe, east and west North America, Australia, southern South America, and South Africa. It is difficult to assess either the extent to which earthworm numbers and diversity would be decreased or how far the effect of their loss to soil structure, nutrient cycling, or wildlife would be detrimental in these areas.

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Keywords *Artioposthia triangulata*; CLIMEX; lumbricids; earthworms; distribution; terrestrial predatory planarian

INTRODUCTION

Artioposthia triangulata is a terrestrial planarian that feeds on earthworms. It was first described by Dendy (1895a, b) from specimens collected near Christchurch, New Zealand. Other specimens were subsequently found in other sites in the South Island, but none have been collected in the North Island (Boag et al. 1995).

Artioposthia triangulata was first recorded in Great Britain in 1963 from a domestic garden in Belfast, Northern Ireland (Willis & Edwards 1977). By 1965 it was also discovered in England and in Scotland where it is now widespread (Willis & Edwards 1977; Wakelin & Vickerman 1979; Hancock 1988). A recent survey in Scotland has shown *A. triangulata* to be very common in domestic gardens, garden centres, and botanic gardens but relatively rare in agricultural land in Scotland (Boag et al. 1994a); this distribution is similar to that found in Ireland (Blackshaw & Stewart 1992). In 1982, *A. triangulata* was discovered in the Faroe Islands (Bloch 1992), and it was rediscovered in England in 1992 where it is now considered rare but widely distributed (Boag et al. 1994b). It is probable that the initial introduction and spread was the result of the importation and sale of containerised plants (Blackshaw & Stewart 1992).

At first this species was considered a curiosity, but Blackshaw (1990, 1991) showed it could reduce earthworm populations to below detectable levels. Lumbricid earthworms are a major constituent of the soil fauna throughout most of the British Isles and contribute significantly to nutrient cycling, the physical and chemical properties of the soil, and crop yield (Lee 1985; Logsdon & Linden 1992). Because

A. triangulata was shown to have an adverse effect on earthworm populations, it was added to schedule 9, section 14 of the Wildlife and Countryside Act 1981 (R. B. Ninnes pers. comm.), which has made it an offence to knowingly distribute the flatworm since 1992. In addition this act requires nurseries and garden centres to take all practical measures to control its spread.

Stewart & Blackshaw (1993) suggested the distribution of *A. triangulata* in Europe is the result of human activities, but its establishment probably depends upon three main factors: the presence of earthworms that make up the bulk of its diet (Blackshaw 1991), a soil temperature range that does not exceed 20°C (Blackshaw 1993), and a relatively humid/damp microclimate (Blackshaw & Stewart 1992). Boag et al. (1993) used temperature and rainfall data to produce bioclimatographs that showed close similarity between the climates in which *A. triangulata* lives in both New Zealand and in Scotland.

A computer programme, CLIMEX, devised by Sutherst & Maywald (1985), has been used to apply ecoclimatic data to assess the potential for the establishment of exotic pests in different parts of the world (Worner 1988). In this study, CLIMEX was used to compare climatic data from places with *A. triangulata* in New Zealand and Great Britain, and to list which other parts of the world might be at risk of invasion by this flatworm.

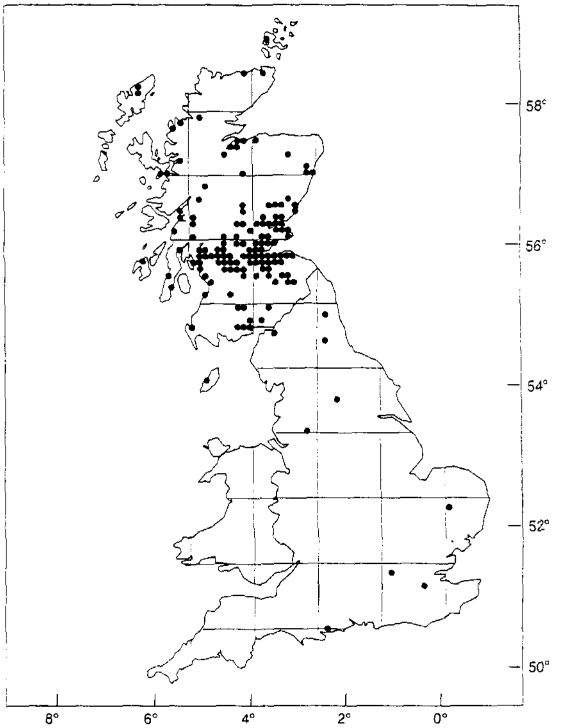

Fig. 1 Distribution of 10 km squares containing records of *Artioposthia triangulata* in Great Britain. Since most of the records were sent in from the general public, it is not possible to map negative 10 km squares.

MATERIALS AND METHODS

Meteorological data for the production of bioclimatographs of sites in New Zealand and the British Isles were obtained from the New Zealand Meteorological Service (Anon. 1983a, b) and Monthly Weather Reports (Anon. 1993).

The CLIMEX computer program, utilises gross features of the response of the organism to its physical environment and provides useful information from sites where meteorological data are available. Although based on temperature and rainfall data, it can incorporate moisture and stress indices. The present investigation started with the 30-year monthly temperature, rainfall, relative humidity, and rainfall patterns for three reference sites where *A. triangulata* has been recorded, and searched for comparable sites throughout Europe and the rest of the world. The "match climates" function of CLIMEX generates a match index on a scale of 0–1 which describes the similarities of these variables between the reference sites and each target location. A match index of 0 is a complete mis-match, and 1 is a perfect match with the target location. Two index values were taken as thresholds in this study: 0.5 as the index representing the lowest practicable match where survival of *A. triangulata* is possible, and 0.7 where survival of *A. triangulata* is favourable. We did not use the CLIMEX facility to estimate stress indices as not enough is known about the biology of *A. triangulata*.

The reference sites represented three different types of flatworm habitat: (1) Rothesay, Scotland, in the river Clyde estuary, which has a climate similar to Dunoon, Scotland, where *A. triangulata* is established in agricultural land; (2) The Royal Botanic Gardens, Edinburgh, where the flatworm was first found in Scotland and is common in domestic gardens and allotments; and (3) Alexandra, New Zealand, which represents the most extreme macroclimatic conditions of both temperature and rainfall in which *A. triangulata* has been recorded.

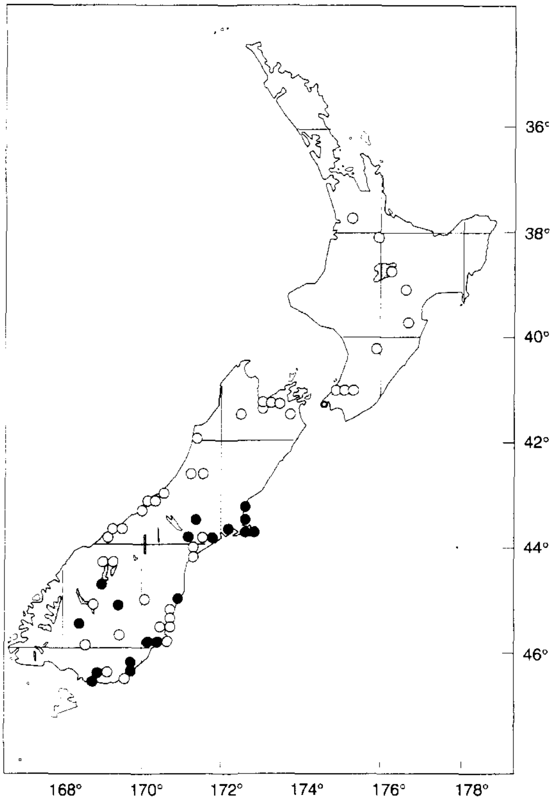

Fig. 2 Distribution of *Artioposthia triangulata* in New Zealand. Mainly based on records and collected during a survey in 1993, plus confirmed historical data. ●, positive; ○, negative.

RESULTS

The known distributions of *A. triangulata* in Great Britain and New Zealand are shown in Fig. 1 & 2. The data show *A. triangulata* to be confined to the centre/south-east of the South Island of New Zealand. An extensive survey by two of the authors (B.B. & P.M.J.) during October/November 1993 found no evidence of *A. triangulata* previously reported from the Nelson area, or elsewhere in the north or west of the South Island (Boag et al. 1995), so the previous Nelson record has been omitted from the maps. *A. triangulata* is far more widespread in Scotland (>500 positive records) than in England or Wales (<20 positive records).

The 30-year monthly mean for daily temperature and rainfall for the three reference sites are shown in Table 1. Rothesay has the wettest climate, whereas Alexandra is the warmest in summer, coldest in winter, and driest all year.

The potential spread of *A. triangulata* in agricultural land in Europe and throughout the world, estimated from climatic matches to Rothesay, can be seen in Fig. 3 and 4, respectively. Using a matching index of ≥0.7, the results indicate that *A. triangulata* could become established in western Norway, southern Sweden, Denmark, Belgium, the Netherlands, northern Germany, and France. A matching index of ≥0.5 extended the area over which the flatworm could become an agricultural problem to include northern Spain, northern Italy, Switzerland, Austria,

Table 1 Comparison of the 30-year mean daily temperature and rainfall monthly average.

Month	Rothesay (Scotland) agricultural land (lat. 55°51′N, long. 5°03′W) Temperature (°C)	Rothesay Rainfall (mm)	Edinburgh (Scotland) horticultural land (lat. 55°57′N, long. 33°13′W) Temperature (°C)	Edinburgh Rainfall (mm)	Alexandra (New Zealand) extreme conditions (lat. 45°16′S, long. 169°23′E) Temperature (°C)	Alexandra Rainfall (mm)
Jan	4.1	127	3.3	46	17.3	38
Feb	4.1	84	3.4	39	17.0	27
Mar	5.5	90	4.2	39	14.9	39
Apr	7.7	76	7.4	39	11.1	31
May	10.5	75	10.2	49	6.6	33
Jun	13.1	80	13.2	45	3.3	22
Jul	14.3	77	14.6	69	2.8	18
Aug	14.3	111	14.4	71	5.3	19
Sep	12.6	138	12.7	57	8.9	21
Oct	10.3	137	9.3	56	11.7	32
Nov	6.6	145	5.8	59	13.9	31
Dec	5.3	148	4.3	57	16.2	35
Mean temperature	9.0	–	8.6	–	10.8	–
Total rainfall	–	1288	–	626	–	346

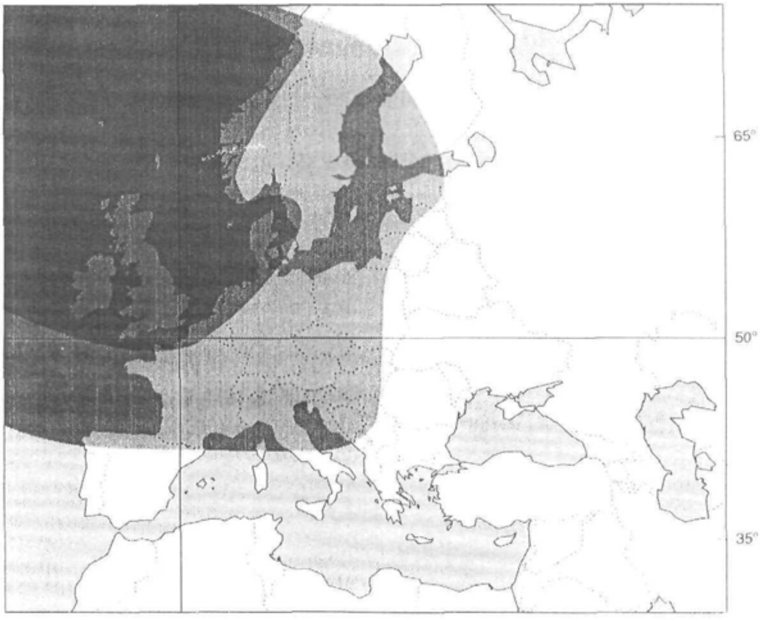

Fig. 3 Potential distribution of *Artioposthia triangulata* in agricultural land in Europe, based on meteorological data from Rothesay, Scotland; darker shading, areas where the flatworm could probably become established (CLIMEX matching ≥0.7); lighter shading, areas where the flatworm might possibly become established (CLIMEX matching ≥0.5).

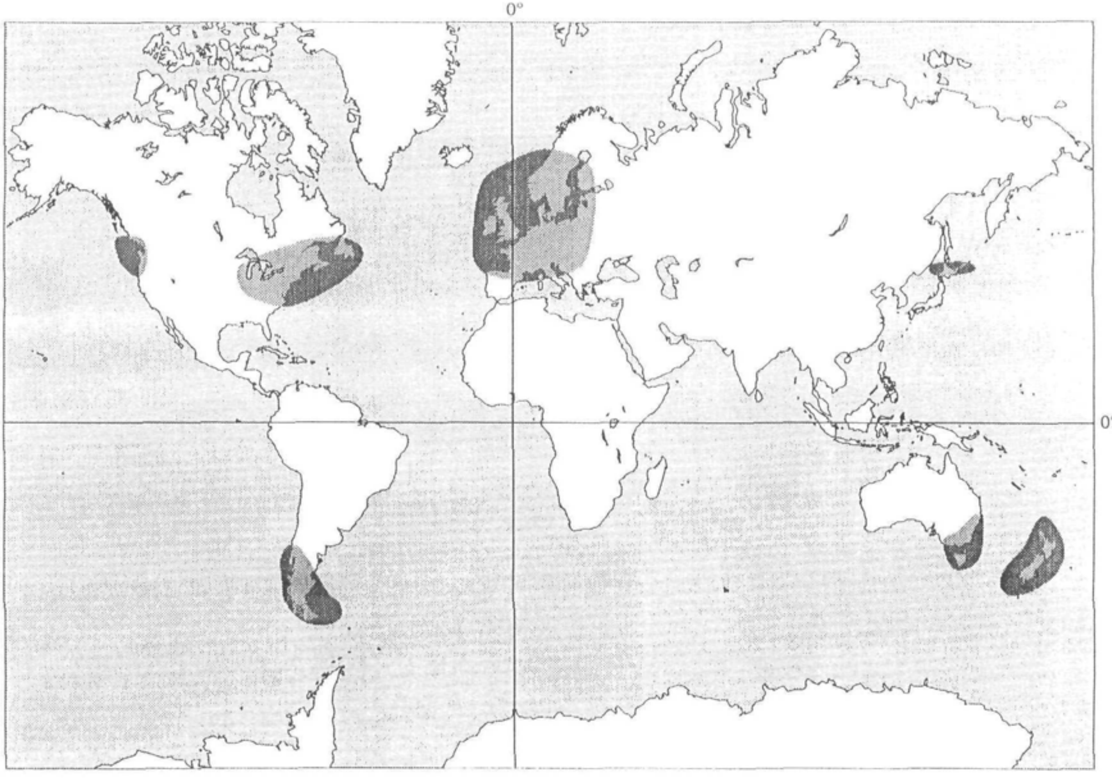

Fig. 4 Potential distribution of *Artioposthia triangulata* in agricultural land throughout the world, based on meterological data from Rothesay, Scotland (CLIMEX matching ≥0.5).

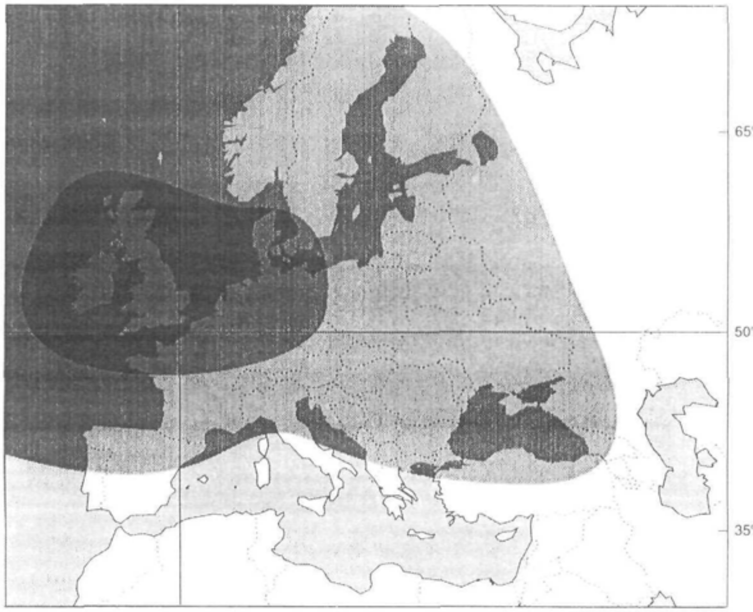

Fig. 5 Potential distribution of *Artioposthia triangulata* in horticultural land in Europe, based on meterological data from Edinburgh, Scotland; darker shading, areas where the flatworm could probably become established (CLIMEX matching ≥0.7); lighter shading, areas where the flatworm might possibly become established (CLIMEX matching ≥0.5).

Slovakia, and the Czech Republic (Fig. 3). Outside Europe, similar climatic data to those from Rothesay were found in eastern and western North America, Hokkaido, Japan, south-eastern Australia, New Zealand, and the southern tip of South America (Fig. 4).

Figures 5 and 6 show the potential distribution of *A. triangulata* in horticultural land using climatic data from Edinburgh, Scotland, where it has been recorded from nearly 200 domestic gardens. Using a matching index of ≥0.5, the possible distribution extends to include part of western Russia and mainland Europe excluding most of the Mediterranean coast. Elsewhere in the world, comparable climates were found in Sakhalin, eastern Russia, South Africa, Chile, New Zealand, southern Australia, and western North America around the Great Lakes.

Climatic conditions comparable with Alexandra, the most extreme climate in which *A. triangulata* is found at present, matched at the ≥0.5 level much of central Europe, central/western north America, New Zealand, south of South America, and South Africa (Fig. 7).

DISCUSSION

We do not know whether the macroclimatic data used in the present investigation relate closely enough to the microclimate in which *A. triangulata* maintains a self-supporting population. In New Zealand *A. triangulata* has been found only in relic forest (where it probably evolved), gardens, and an agroforestry site at Invermay, Mosgiel (Boag et al. 1995). At 11 of the sites in New Zealand where *A. triangulata* was found (Fig. 2), the air temperatures in the shade were within 1°C of the soil temperatures (microclimatic data collected by the senior author during 1993 was similar to the 30-year average meteorological data: i.e. the Alexandra January mean daily monthly average air temperature was 17.3°C (Anon. 1983a) whereas the 20 cm soil temperature was 17.4°C) (Anon. 1983c)). This means the data used in the CLIMEX model probably reflects quite accurately the conditions under which *A. triangulata* lives. At each of the 11 sites, the soil/stone, soil/wood interface where *A. triangulata* was detected was always damp: in Alexandra, where total annual rainfall averaged only 346 mm, the flatworm was found close to the Manuherikia River.

In the British Isles, the rainfall in western Scotland and Ireland is considerably greater than that in most of New Zealand or in eastern Scotland (Boag et al. 1993) and this may explain why *A. triangulata* can apparently survive better in arable farmland in the west, where the soil is unlikely to dry out. The present study suggests that similar conditions are likely in countries bordering the North Sea and English Channel, and are possible at times in farmland

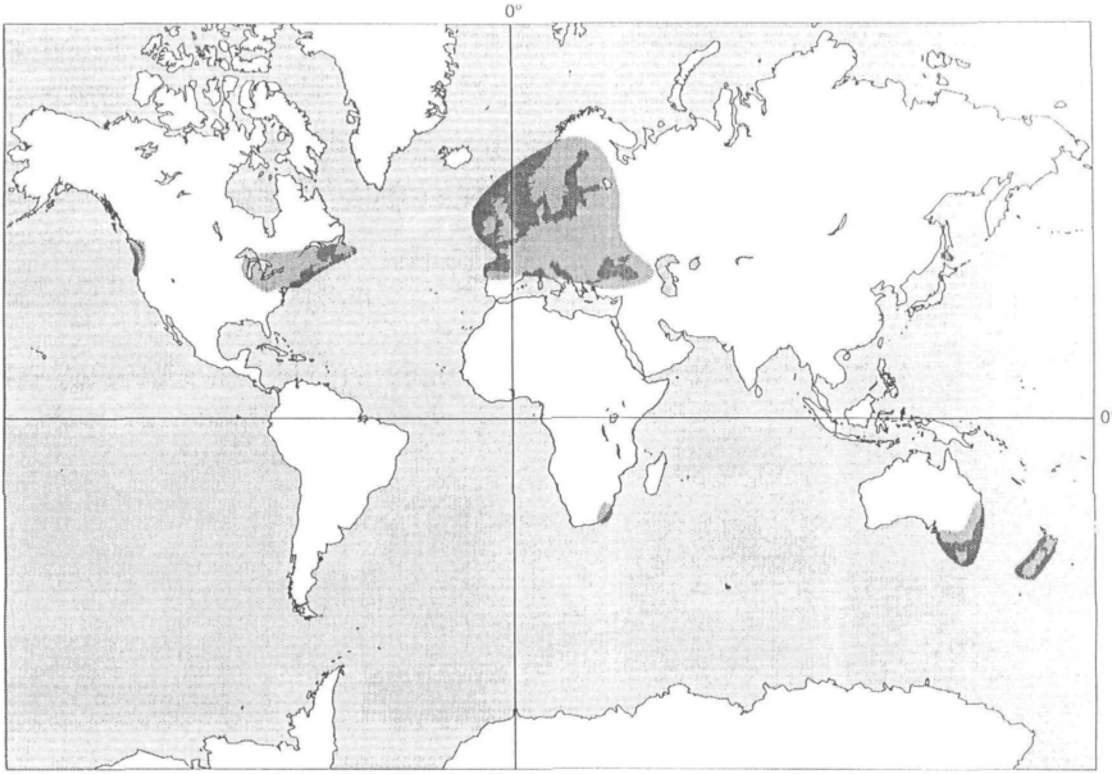

Fig. 6 Potential distribution of *Artioposthia triangulata* in horticultural land throughout the world, based on meterological data from Edinburgh, Scotland (CLIMEX matching ≥0.5).

throughout most of central and northern Europe, especially if irrigated. *Artioposthia triangulata* could become a horticultural problem across central/northern Europe (Fig. 5) and could become established, in only extreme instances, as far south as north Africa (Fig. 7). Moreover, this study indicates that *A. triangulata* could establish in gardens in many temperate parts of the world (Fig. 6) and even survive extreme conditions in central North America if shade and moisture are available, as the Australian – New Zealand planarian *Caenoplana coerulea* (Ogren 1989) already does.

All predictions from these three reference sites indicate that *A. triangulata* should be found in the North Island of New Zealand but it has not been recorded there. The reason for its restricted distribution in New Zealand is not known. However, there are other organisms (e.g., earthworms belonging to the genus *Hoplochoetina*) which also have disjunctive distributions in New Zealand (Lee 1959).

In the British Isles the annual rate of increase in new records of *A. triangulata* suggests that it is only in the initial stages of an invasion, the future progress of which is hard to predict (Boag et al. 1994a). However, on present evidence, the biodiversity of the earthworm community in the west of Scotland and Ireland will be significantly reduced (Blackshaw 1993) and crop yields decreased (Logsdon & Linden 1992). Because earthworms are often the major biomass constituent of the soil fauna, and the main diet of a range of animals and birds (Macdonald 1983; Cook et al. 1992) wildlife may also suffer. Application of the CLIMEX model suggests that *A. triangulata* could become established in other parts of the world, with potentially similar deleterious effects on agriculture and wildlife. Thus, every effort should be made to contain the existing distribution of *A. triangulata* and prevent the introduction of any other exotic terrestrial predatory planarians (Johns 1993).

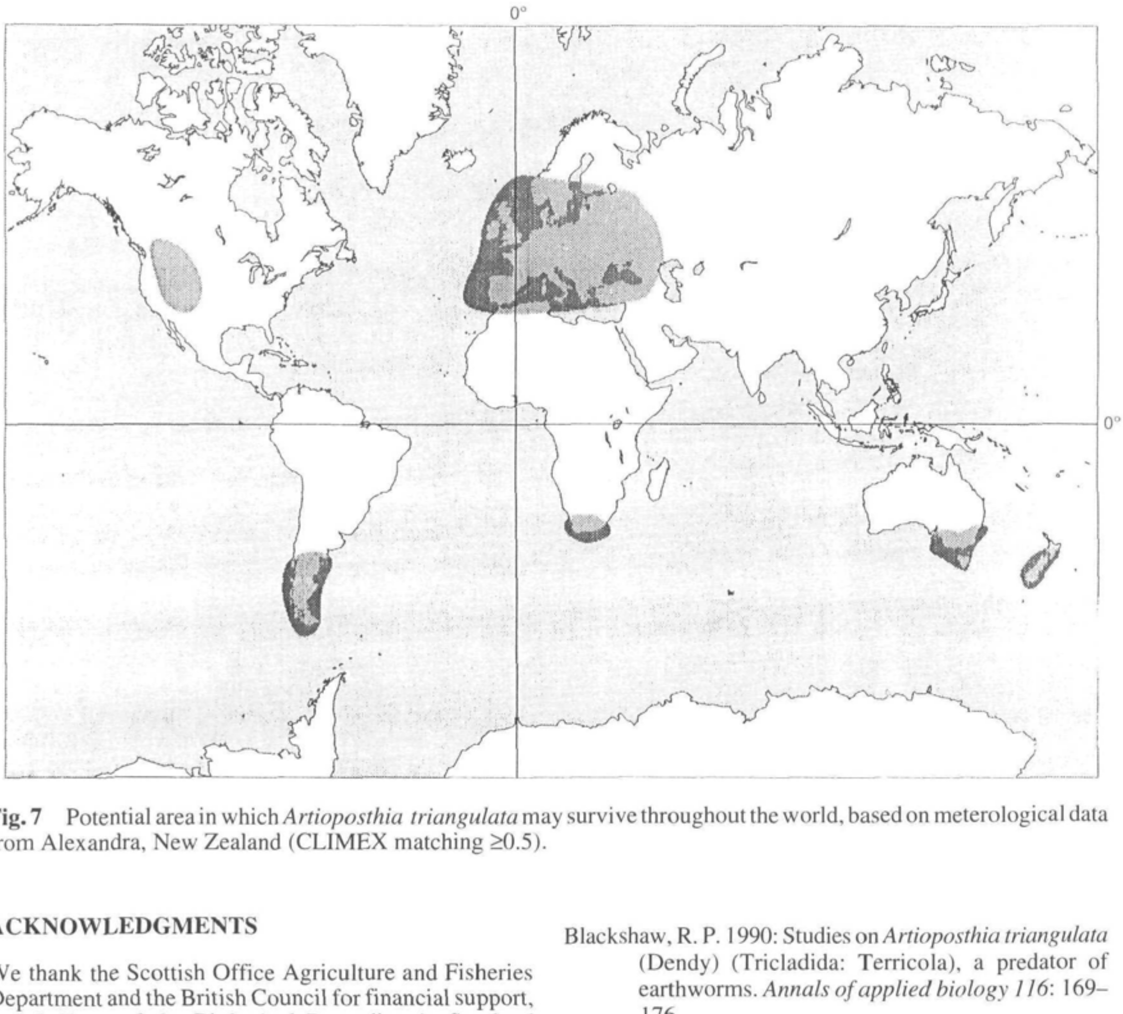

Fig. 7 Potential area in which *Artioposthia triangulata* may survive throughout the world, based on meterological data from Alexandra, New Zealand (CLIMEX matching ≥0.5).

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