Ecological Applications, 11(5), 2001, pp. 1276–1286

THE POTENTIAL IMPACT OF THE NEW ZEALAND FLATWORM, A PREDATOR OF EARTHWORMS, IN WESTERN EUROPE

BRIAN BOAG[1,3] AND GREGOR W. YEATES[2]

[1]*Scottish Crop Research Institute, Invergowrie, Dundee, DD2 5DA, Scotland*
[2]*Landcase Research, Private Bag 11052, Palmerston North, New Zealand*

Abstract. The New Zealand flatworm *Arthurdendyus triangulatus* (=*Artioposthia triangulata*) is an example of an invasive organism that, by reducing lumbricid earthworm populations, could have a major impact on soil ecosystems in Britain and the Faroe Islands. How it was introduced into the British Isles is not known, but like many invasive species, it is suspected that it was introduced by humans and was associated with the trade between New Zealand and Britain. Once established in Britain it found in the large, readily available earthworm population a niche that it could exploit. The microclimate of the forests in the center and south of the South Island of New Zealand from whence the flatworm came is similar to that in parts of the British Isles and consequently conducive to its survival. Although when compared with many other invertebrate introductions (e.g., insects) the flatworm's rate of increase has been slow, a retrospective study strongly suggested that, in Scotland, they spread from botanic gardens to horticultural wholesalers, then to domestic gardens, and only latterly did they invade agricultural land. As with other invasive species, the application of the CLIMEX computer model and geographic-information-system techniques have been used to try to ascertain its potential distribution within both the British Isles and Europe. The data suggest that *A. triangulatus* could become established in northwest continental Europe, and Denmark, Iceland, and Sweden have added it to their quarantine pest lists. The fact that *A. triangulatus* is the only one of 12 alien terrestrial planarians in Britain to be considered a pest suggests that this group of invertebrates is behaving in a fashion similar to other invasive organisms and obeys the "tens rule" suggested by M. Williamson. Since within the period 1995–1997 another three species of predatory terrestrial planarians have been recorded in Scotland it is evident that the existing phytosanitary regulations must be more strongly enforced or new ones introduced if the spread of terrestrial planarians is to be halted.

Key words: Arthurdendyus triangulatus; *CLIMEX model; earthworms; flatworms; invertebrate invasions; invasive species, impacts and controls; New Zealand flatworm, potential invasive impacts; plant quarantine regulations and exotics; rule of "tens"; soil ecosystems, vulnerability; terrestrial planarians.*

INTRODUCTION

The impacts of the introduction of alien species into new countries have been reviewed (e.g., Williamson 1996, Shigesada and Kawasaki 1997), and the attributes of invading plants and vertebrates have been discussed (Noble 1989, Mack et al. 2000). However, although Williamson and Brown (1986) discussed 11 insect species introduced to Britain and the reasons for their success they did not cover the attributes of terrestrial invertebrates, especially soil invertebrates that have successfully colonized new lands. This is probably because soil invertebrates, which have much more limited dispersal abilities than aboveground-dwelling organisms, have other poorly known characteristics that allow them to invade and become established at new sites. The extent to which soil faunal invasions have taken place throughout the world is unknown. Those invasions that are known about generally concern agricultural pests, and consequently what knowledge we do have is rather fragmented. The spread of the potato-cyst nematodes (*Globodera* spp.) (Tylenchida: Heteroderidae) from South America into Europe and subsequently to at least 65 countries throughout the world has been associated with the spread of the domestic potato (*Solanum tuberosum*) (Turner and Evans 1998). The reason for the success of potato-cyst nematodes as invasive species has been attributed to the propagation of the potato by tubers with adhering contaminated soil (rather than by seed), the potential for rapid multiplication (200 cysts/yr), and their ability to live and remain viable for a long time (in excess of 20 yr) (Koenning and Sipes 1998). Boag and Hunt

Manuscript received 1 September 1999; accepted 26 August 2000; final version received 23 October 2000. For reprints of this Invited Feature, see footnote 1, p. 1259.
[1] E-mail: bboag@scri.sari.ac.uk

TABLE 1. Species of terrestrial planarians recorded from the British Isles (modified from Jones [1998]).

Species†	Predator?‡	Origin§
Native		
Microplana terrestris (Müller, 1774)	···	···
M. scharffi (von Graff, 1899)	···	···
M. humicola Verjdovsky, 1890	···	···
Introduced		
Arthurdenyus albidus Jones and Gerard, 1999	Y	New Zealand
A. australis (Dendy, 1892)	Y	New Zealand
A. triangulatus (Dendy, 1985)	Y	New Zealand
Australopacifica coxii (Fletcher and Hamilton, 1888)	···	Australia
Australoplana sanguinea alba (Dendy, 1891) (sensu Jones, 1981)	Y	Australia or New Zealand
Bipalium kewense Moseley, 1878	Y	South East Asia
Caenoplana coerulea Moseley, 1877	Y	Australia
Dolichoplana striata (Moseley, 1877)	···	Sri Lanka or Indonesia
Kontikia andersoni Jones, 1981	···	unknown
K. ventrolineata (Dendy, 1892)	···	Australia
Rhynchodemus hallezi von Graff, 1899	···	Philippines
R. sylvaticus (Leidy, 1851)	···	unknown

† For each species the name of the person who described it is given; if the mean is in parentheses, the generic name has changed.
‡ Y = yes; species is known to prey on earthworms.
§ Probable country of origin.

(2001) list a further 21 new soil-dwelling plant/insect parasitic nematodes introduced into Britain since 1973.

How and why earthworms and flatworms are introduced and become established in new countries is unknown. Some species have been deliberately introduced; e.g., in New Zealand none of the 174 native Megascolicid earthworms could tolerate intensive agricultural cultivation and up to 18 species of earthworms, mainly of European origin, were introduced (Lee 1959). In Britain the native earthworm fauna is restricted to <30 species and none of the few introduced species have become widely established (Sims and Gerard 1985). However, only an estimated 6 flatworm species have been introduced into New Zealand, which has a native fauna of over 100 species (Johns 1998), while in Britain, which has a native fauna of 3 species, 12 exotic species have become established (Jones 1998). Modern statutory regulations have not halted the spread of either earthworms or flatworms since *Dendrobebaena octoedra* (Lumbricidae) has recently been recorded from *Pinus contorta* plantations in Canada (McLean and Parkinson 1997) and three new species of earthworm-eating flatworms have been recorded from Scotland in the last five years (Boag and Neilson 1999). The extent to which flatworms have been spread around the world is not generally recognized—one species, *Bipalium kewense*, having been recorded from >50 countries (Winsor 1983).

The progress of an invading species once locally established in a region is governed by a number of factors but can probably be described using diffusion models. However, Shigesada and Kawasaki (1997), have pointed out that such approaches require detailed knowledge of both the autecology and the synecology of the organism.

In developing a conceptual framework for the study of invasive species, Williamson and Brown (1986) and Williamson (1996) developed the "tens rule," namely that 10% of invaders become established and 10% of those established become pests. There are many exceptions and to see if a particular class of invader is successful or not Williamson (1996) introduced a standard roughness factor that extends the rule to 5–20%; these cover the uncertainty about the status of an invader and sampling error.

This paper describes the biology of the invasive flatworm *Arthurdendyus triangulatus;* discusses its ability to invade with respect to factors associated with the invasion of plants, insects, and vertebrates; and examines whether the invasion of flatworms follows the same pattern as seen for other organisims, i.e., the "tens rule."

HISTORICAL BACKGROUND

Only 3 indigenous species of terrestrial planarians are found in the British Isles while at least 12 alien species have been introduced (Jones 1988, Boag and Neilson 1999, Jones and Gerard 1999) (Table 1). Of the introduced species, *Arthurdendyus triangulatus*—"the New Zealand flatworm"—has caused concern to both agriculturists and naturalists since it is an indiscriminate obligate predator of earthworms (Lilico et al. 1996). *Arthurdendyus triangulatus,* which was first described from near Christchurch, New Zealand, and subsequently recorded from the British Isles in the 1960s, was originally considered a curiosity until its presence was associated with reductions in earthworm populations to below detectable levels over a two-year period (Blackshaw 1990). Blackshaw and Stewart (1992) comprehensively reviewed the information on *A. triangulatus* up to 1991. It had also been recorded from the Faroe Islands (Bloch 1992, Mather and Christensen

1992). Jones and Gerard (1999) transferred the species from *Artioposthia* to the new genus *Arthurdendyus.*

There are a number of reasons why *A. triangulatus* is, so far, the only species to be considered a problem in the British Isles. The three native flatworms are very small, rare, and their diet has not been fully investigated but they may not be obligate predators of earthworms. Some of the other species, e.g., *Bipalium kewense,* which does eat earthworms, requires high temperatures to survive and are only found in greenhouses. Others, which are also known to be obligate predators of earthworms, e.g., *A. albidus,* have only been recorded for a few years and in the fullness of time will probably spread within the country and will have an impact on earthworm populations. The reason for the larger number of exotic flatworms in Britain compared with New Zealand may reflect the type and amount of imports of goods that could be contaminated entering these countries or the statutory regulations and the thoroughness with which the regulations are implemented.

Ecology and Biological Impact

Reproduction

To understand why *Arthurdendyus triangulatus* has been such a successful invasive species it is necessary to understand its biology. Apart from *A. triangulatus* being a dark-brown color, which means it is well camouflaged against soil, it produces an egg capsule that can be relatively large compared with the size of the adult flatworm, (Yeates et al. 1997). They are usually laid through the dorsal surface of the flatworm and are initially white/yellow or cherry red before turning to become shiny and black after a few hours. Yeates et al. (1997) reported that the egg capsule mass of a New Zealand population of *A. triangulatus* could range from 8.4% to 16.6% of the post-deposition adult mass while comparable data from the Faroe Islands indicated a range of 5.1–21.9% (Christensen and Mather 1997). It is still not known how many egg capsules are produced per adult per season but observations by Christensen and Mather (1997) and the B. Boag have noted several being produced over a period of months from starved specimens while Blackshaw (1997*b*) suggested one egg capsule per 15–27 d. One important factor that could help account for *A. triangulatus* being such a successful invasive species is that each egg capsule contains between 1 and 14 young (Christensen and Mather 1997, Mather and Christensen 1998) and hence only a single egg capsule is needed to start a new colony.

Feeding, growth, and "degrowth"

Arthurdendyus triangulatus is, as far as known, an obligate predator of earthworms and its mode of feeding by external digestion of its prey was described by Blackshaw and Stewart (1992). Stable-isotope analysis of soil fauna at flatworm sites confirmed that *A. triangulatus* was a predator at the top of the soil food chain, above earthworms (Boag et al. 1994*b*). While it could be argued that feeding on only one type of prey might, in theory, be a hindrance to it becoming a successful invasive species, the fact that it feeds on all earthworm species found throughout the British Isles means that there is a widespread abundant food supply for it to exploit (Williamson 1996).

Blackshaw and Stewart (1992) stated that there was no evidence that *A. triangulatus* actively tracked earthworms, but subsequently Lillico et al. (1996) suggested that *A. triangulatus* did actively hunt. Blackshaw (1997*a*) did a prey-preference trial and found no difference in numbers of various species of earthworms killed, while Lillico et al. (1996) found that some species were more vulnerable to predation than others. This they attributed to a function of burrow width while Blackshaw (1995) also suggested earthworm vulnerability might explain why only *Octolasium cyaneum* (a species of earthworm usually found relatively deep in the soil) survived at one *A. triangulatus* site. The growth of flatworms has been studied at a number of sites. The food-conversion ratio of earthworms into flatworm mass gain varies considerably, with estimates of 9.7% (Lillico et al. 1996), 36% (Blackshaw 1991), and 53% (Yeates et al. 1997). The reason for this variability may be due to the size of container used and energy required to hunt for the prey (Lillico et al. 1996).

An unusual phenomenon, which helps *A. triangulatus* to be a successful alien, is its ability to survive by "degrowing" (contracting in size due to starvation) rather than starving to death. Blackshaw (1992) found that a negative exponential model could describe the pattern of degrowth of *A. triangulatus* at temperatures between 5° and 15°C. Christensen and Mather (1995) reported starved *A. triangulatus* could survive for 15 mo at 12°C in soil while B. Boag (*personal observation*) found starved flatworms survived 9 mo at that temperature. The longevity of *A. triangulatus* under field conditions is unknown. However, Gibson et al. (1997) demonstrated that in Scotland both carabid and staphylinid beetles could feed on *A. triangulatus* and this might be responsible for the reduction in mean survival times of flatworms under field conditions.

Movement

Another factor that could explain why *A. triangulatus* has been successful is the rate at which it can move. Gibson and Cosens (1998) studied movement of *A. triangulatus* under laboratory condition and found it would either glide over damp surfaces or use retrograde peristaltic waves to travel over dry surfaces. They found it could travel up to 12 m/h, while Mather and Christensen (1995) reported 17 m/h for specimens studied in the Faroe Islands. Factors affecting rate of movement include the size of the flatworm (Gibson and

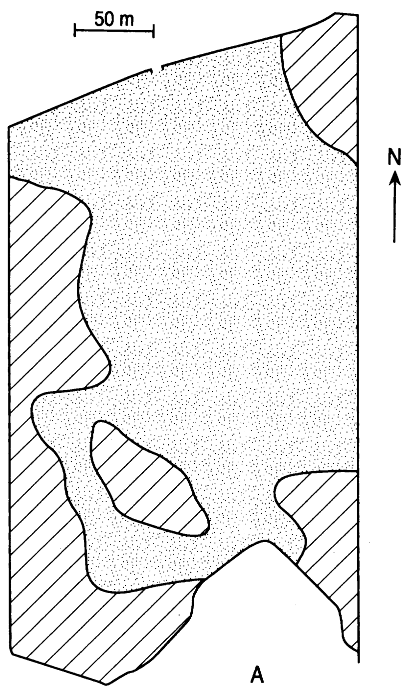

FIG. 1. Population distributions in a 4.65-ha silage field in Scotland. (A) Diagonal hatching identifies the area infested with *Arthurdendyus triangulatus*. (B) Unshaded (clear) areas identify the distribution of earthworm populations of ≤5 individuals counted on the soil surface below silage bales (Boag et al. 1999).

Cosens 1998, Mather and Christensen 1998), temperature (Yeates et al. 1998) surface moisture (Gibson and Cosens 1998), and period of starvation (Yeates et al. 1998). Under horticultural conditions, Lillico et al. (1996) found color-marked *A. triangulatus* could travel up to 17 m in 30 d. The adhesive nature of the mucous associated with *A. triangulatus* may also play an important part in how it becomes attached to its prey when feeding and during dispersion since it has been found attached to the fur of cats that have been hunting at night in domestic gardens and to the plastic wrappings around silage bales.

Colonization and distribution

The pattern of colonization of horticultural sites has been investigated by Lillico et al. (1996) and by Christensen and Mather (1995, 1998). Lillico et al. (1996) was able to demonstrate a negative correlation between earthworm and flatworm populations. Christensen and Mather (1995) investigated the spatial distribution of both flatworms and earthworms and found progressive colonization in three different plots. Christensen and Mather (1992, 1998) also studied the spatial distribution of both *A. triangulatus* and earthworms in a field. Under these conditions, where New Zealand flatworm populations could reach 40 adults and 60 egg capsules per square meter, earthworm populations of over 200 individuals/m^2 were decreased to below detectable levels within one growing season. A study by Boag et al. (1999) of the distribution pattern of *A. triangulatus* in a grass field demonstrated, for the first time, the adverse impact that the flatworm could have on earthworms in agricultural land in Scotland. In this field *A. triangulatus* was found around much of the perimeter of the 4.65 ha silage field but not in the center (Fig. 1A and B). The reason for the distribution pattern observed in this field is unknown as it could represent either the initial spread of the flatworms into the field or the existence of unfavorable conditions for the flatworm in the center of the field (e.g., water logging).

Biological impact

The potential deleterious effect of *A. triangulata* on the British fauna would probably not just be confined to where it invaded agricultural land but also where it became established in domestic gardens, e.g., Edinburgh on the east coast of Scotland. The animals and birds most likely to be adversely effected were comprehensively reviewed by Alford et al. (1995) and included mammals such as the badger (*Meles meles*), fox (*Vulpes vulpes*), shrew (*Sorex* sp.) and mole (*Talpa europea*) and birds—e.g., blackbird (*Turdus merula*) and song thrush (*Turdus philomelos*). Boag (2000) subsequently found a statistically significant negative relationship between the presence of flatworms and moles in fields near Dunoon in the west of Scotland.

FACTORS CONTROLLING DISTRIBUTION ABUNDANCE AND INVASIBILITY

Existing distribution

A review of the literature by Boag et al. (1998*b*) concluded that within a given temperature range the distribution of terrestrial planarians was dictated by two major factors, (1) the presence of sufficient moisture, and (2) an adequate supply of food. Since the detrimental effects of *Arthurdendyus triangulatus* on lumbricid earthworms in Northern Ireland and Scotland became apparent, there has been much interest in knowing its existing geographical distribution, both in the British Isles and New Zealand.

In New Zealand, it has been suggested that *A. triangulatus* evolved in native *Nothofagus* forests feeding on native Megascolecid earthworms (Johns et al. 1998). It is now found in forest remnants, in garden centers, and in nurseries in the South Island (Johns et al. 1998, Mather and Christensen 1998). Although many of these sites are in the cooler, damper areas of the South Island, it has been recorded from Alexandra where the total annual rainfall is only 346 mm and the mean monthly 10-cm soil temperature exceeds 17°C in some months (Boag et al. 1995*b*). The indigenous flatworms, including *A. triangulatus,* are not generally a problem in New Zealand since New Zealand has a dryer, warmer climate than that existing in Northern Ireland and Western Scotland. However, Yeates et al. (1999) have shown that under minimum cultivation practices, where crop residues provide refuges, flatworms in New Zealand have the potential to reduce lumbricid populations.

The known European distribution of *A. triangulatus* in the mid-1960s was restricted to a total of three site one each in England, Northern Ireland, and Scotland. The 1991–1993 Scottish Office of Agriculture and Fisheries Department survey enabled a retrospective picture of the spread of *A. triangulatus* to be constructed (Boag et al. 1994*a*). Initially it was confined to central Scotland but thereafter it spread north and west, and to a lesser extent to the south, until by 1990 it was recorded from the extremities of mainland Scotland (Fig. 2). The publicity associated with the Scottish survey and a television survey (Jones and Boag 1996) elicited more records and a polygon constructed from them covered 91% of the Scottish land mass (Boag et al. 1997*a*).

The Scottish survey produced evidence of a probable mechanism of *A. triangulatus* spread. Initially it was only recorded from botanic gardens, garden centers, and nurseries. Then, during 1971–1975, the first reports from domestic gardens were received (Boag et al. 1994*b*). The first records from farmland were not until the 1980s. From these data it could be surmised that infected containerized plants were moved from grower to wholesaler who then propagated the plants and sold the infested containerized plants to the general public.

In Northern Ireland an estimated 40 000 ha of arable land was infected by 1992 (Anonymous 1992) but this estimate had increased considerably by 1998 (Murchie et al. 2001). Once an agricultural field was infested further spread could be by either migration on a local scale or by agricultural practices. Between Sandbank, Dunoon, and Loch Eck, a distance of over 6 km, all the fields are infested with *A. triangulatus*. Some of this spread between farms and fields could have been due to the sale and movement of infested silage or hay bales since both have been shown to act as refugia for the New Zealand flatworm (Boag et al. 1999). So far all established infestations of agricultural land in Scotland have been in the west of Scotland. This may be due to the fact that the west has a far damper climate and less extreme temperatures than the East of Scotland (Boag et al. 1993). Also, the farms in the west of Scotland are less intensively cultivated and hence are likely to have more earthworms than farms in the east of Scotland (Boag et al. 1997*b*).

When Blackshaw and Stewart (1992) did their review there was still only one record of *A. triangulatus* from a garden in England and that dated back to 1965. In 1992 a second site was discovered in a garden center (Boag et al. 1994*a*); in 1993 three more sites were found in garden centres, and by 1995 there were more than 40 sites most of which were domestic gardens (Jones and Boag 1996, Boag et al. 1997*a*).

Potential distribution

The projection of possible future geographical distribution of *A. triangulatus* has important economic and environmental implications since it could indicate where earthworm populations could be at risk. Since there are only three major factors controlling flatworm distribution (moisture, temperature, and presence of prey; Boag et al. 1998*b*) modeling the potential distribution of *A. triangulatus* has been a relatively simple exercise. Initially Boag et al. (1993) used bioclimatographs to estimate the potential distribution of *A. triangulatus* in Europe but then, to more accurately define the area of Europe and the world that could become infested, Boag et al. (1995*a, b*) applied the CLIMEX computer model (Sutherst and Maywald 1985). This computer program allows for the simultaneous matching of monthly temperature, rainfall, and day length of many geographical locations based on 30-yr monthly mean data. If an organism is known to exist at a certain place and the climate of that place is known, then the CLIMEX program will predict, by finding other sites with a similar climate, where that organism could possibly become established. This computer program has been successfully applied to a range of other invasive organisms, e.g., to describe the limitations to the geographical distribution and abundance of the Queensland fruit fly (Sutherst and Maywald 1991). The results of the application of both bioclimatographs and the CLIMEX model indicated that parts of Norway, Sweden, Poland, Germany, Denmark, Belgium, The Netherlands, and France could be potentially infested with *A. triangulatus* (Fig. 3). Boag et al. (1995*a*) also mapped out the potential distribution of *Australoplana sanguinea,* another alien predatory

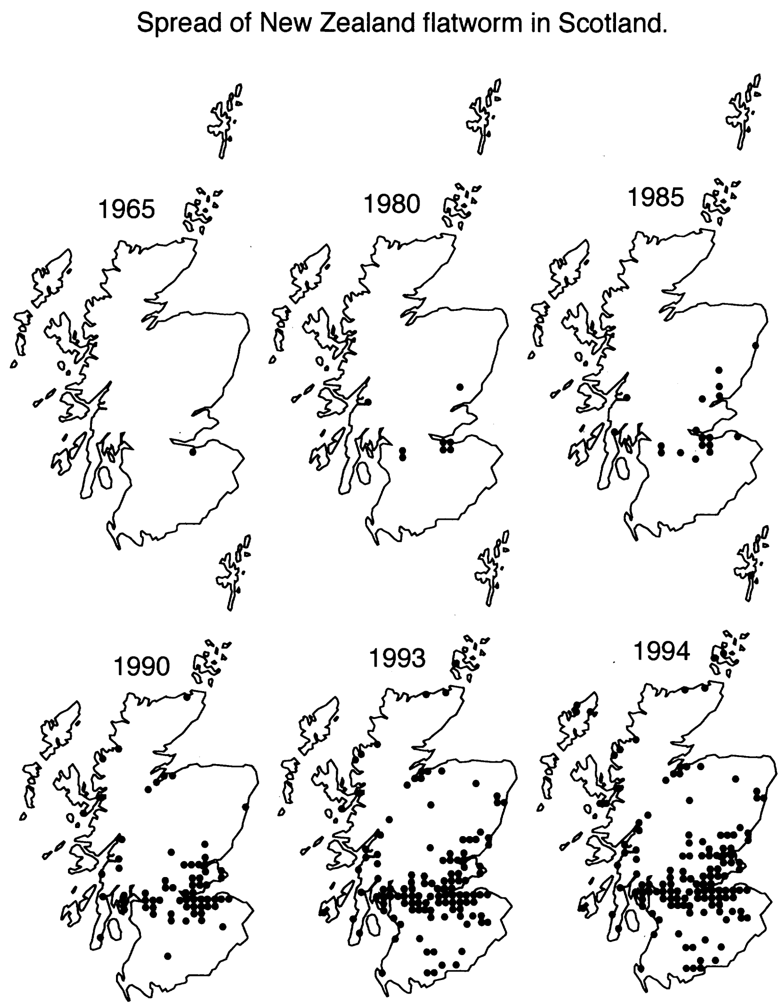

FIG. 2. Distribution of 10-km squares in Scotland containing records of *Arthurdendyus triangulatus* in the years indicated (after Boag et al. 1997*b*).

terrestrial planarian, and found that this species, which is more prevalent in the south and west of England (Jones and Boag 1996), could possibly become established as far south as the north of Spain. While the CLIMEX model suggested that *Arthurdenclyus triangulatus* could become established in western Europe, a more detailed knowledge about its ecological requirements will be required before more definitive statements can be made as to where it may become a serious problem (i.e., where it is likely to significantly reduce earthworm populations).

To better define areas where *A. triangulatus* significantly decreases earthworm populations in Scotland, Boag et al. (1998*a*) applied geographic information systems (GIS) techniques and included additional factors not used in the CLIMEX model—e.g., soil pH since it can effect earthworms distribution (Lofs-Holmin 1986) and land use. The results suggested that the harmful effects of *A. triangulatus* on earthworm populations in arable land were likely to be concentrated in a relatively small area in the southwest of Scotland.

ECONOMIC IMPACT

Impact within the British Isles

The possible long-term impact of *Arthurdendyus triangulatus* on earthworm populations—and hence agriculture and wildlife—is unknown, but since earthworms are known to have a beneficial effect on agricultural productivity and the well-being of the soil (Stockdill 1982) it is assumed that the New Zealand flatworm will have a deleterious affect on both agriculture and wildlife wherever it becomes established (Alford 1998). If the flatworm only becomes established in agricultural land in Northern Ireland and western Scotland, then the impact on overall agriculture productivity in the British Isles (e.g., through impeded drainage; Haria et al. 1998) would probably be minimal

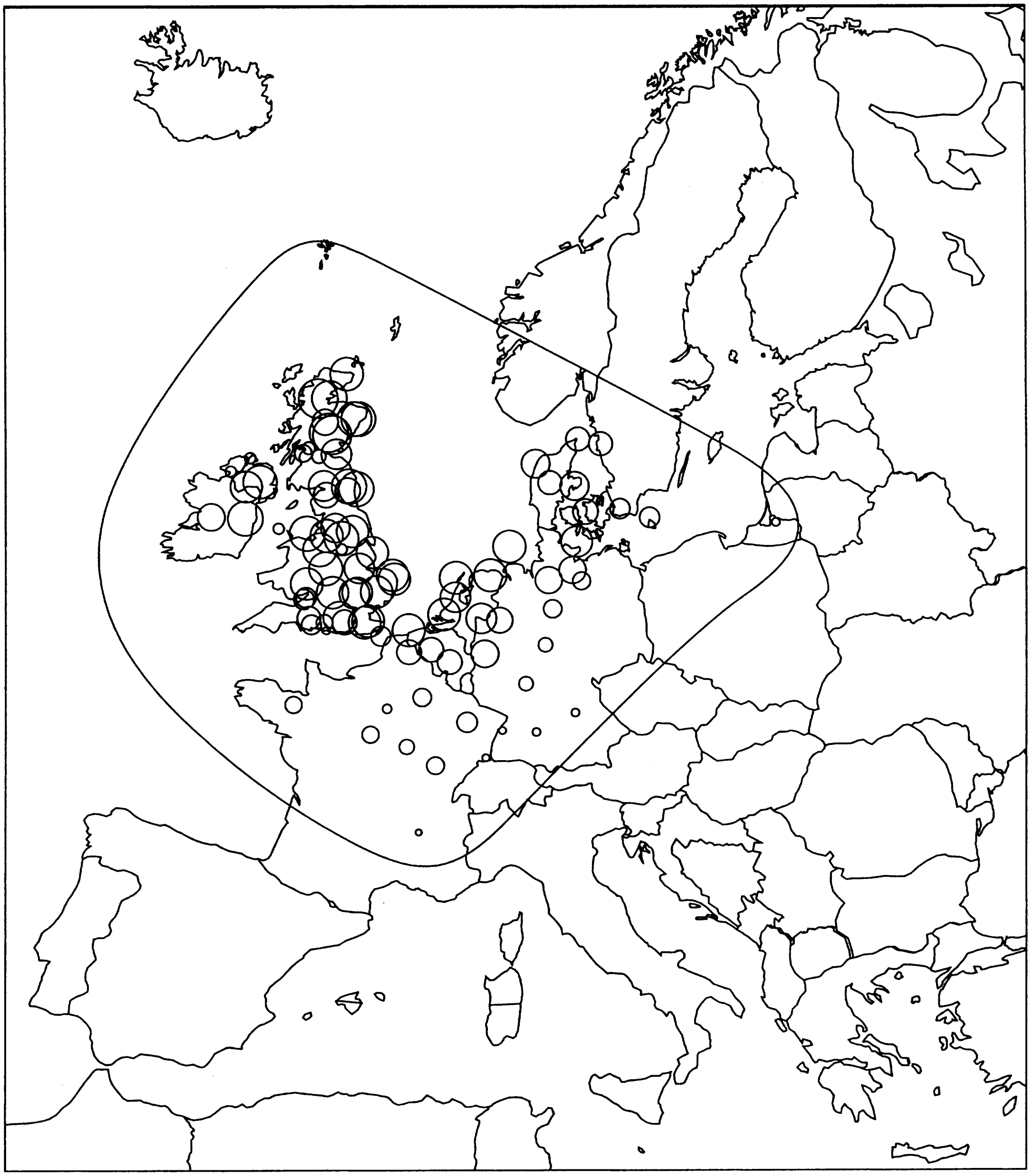

FIG. 3. Potential distribution of *Arthurdendyus triangulatus* in Europe using the CLIMEX model matching index of 0.7 based on 30-yr mean meteorological data from Edinburgh, Scotland (Anonymous 1993, Boag et al. 1995*a*). The larger the circle size, the closer the climate is to that in Edinburgh; the outer line encompasses the area where it is considered *A. triangulatus* could become established.

(Boag et al. 1998*a*), although infested farms may suffer significant financial losses (Boag 2000).

The diligence of horticultural retailers and the introduction of good hygiene procedures has led to a decrease in infested nurseries and garden centers in Scotland, since in 1991–1992 26% were infested (Boag et al. 1994*b*) but by 1998 this had been reduced to 8% (Cannon et al. 1999). To stop the transfer of *A. triangulatus* between sites Murchie and Moore (1998) were able to demonstrate the feasibility of a hot-water treatment. Exposure to 30°C for 20 min killed all the flatworms within 24 h of treatment. However, the best form of control is probably the implementation of good hygiene regimes at all stages of handling containerized plants.

Spread of A. triangulatus to continental Europe

One of the characteristics that *A. triangulatus* shares with some other terrestrial planarians (e.g., *Bipalium kewense*) and that makes it a good invasive species is its ability to avoid detection at international boundaries. *Bipalium kewense* is now known from over 50 countries including Belgium, Finland, Germany, and the United Kingdom (Winsor 1983, Alford et al. 1998). Although this species is only a minor pest in warmer climates (Winsor 1998*a*), it is another example of an alien terrestrial planarian that feeds on earthworms being introduced into Europe. Indications are that, like all other terrestrial planarians, the major factors limiting the distribution of *A. triangulatus* are temperature, moisture, and availability of an appropriate food supply (Boag et al. 1998*b*). Evidence described above suggests that the climatic conditions conducive to the establishment of *A. triangulatus* exists in continental Europe albeit mainly confined to the north and west. Since the earthworm faunae of northwest Europe is similar to that found in the British Isles (Fraser and Boag 1998), the establishment and impact of *A. triangulatus* in that area could be similar to that in the British Isles.

The establishment of *A. triangulatus* in continental Europe depends to some extent on the amount of trade in appropriate goods (i.e., plants which have soil adhering to them) between infested countries and continental Europe. At present the amount of trade is small and already subject to phytosanitary regulations (Unger 1998). Iceland, Denmark, and Sweden have included *A. triangulatus* in their plant quarantine pest lists. Another possible route by which *A. triangulatus* could become established in continental Europe is the movement of containerized plants by residents of the British Isles and Faroes visiting relatives or friends on the continent and taking them plants as presents. This threat will steadily increasing as the number of people travelling between countries increases and the visitors from the British Isles and Faroes are increasingly more likely to have access to contaminated material, since *A. triangulatus* continues to spread within the British Isles and Faroes. The CLIMEX model also suggests *A. triangulatus* could also become established in parts of Japan, Argentina, Australia, the United States, and Canada, so these countries could also be at risk (Boag et al. 1995*b*).

Potential spread and impact of other planarian species from Australasia

No matter what the route, evidence would suggest that new introductions of terrestrial planarians into the British Isles and continental Europe are likely from other countries throughout the world. *Australoplana sanguinea* was first reported from Scotland in 1995. In 1996 an undescribed terrestrial planarian, which may have been associated with the importation of *Camellia* propagated in New Zealand, was discovered in Edinburgh and named *Arthurdendyus albidus* (Jones and Gerard 1999). In 1997 a second Scottish site for this species and another species, *Arthurdendyus australis,* previously only known from near Dunedin, New Zealand (Johns et al. 1998), were found. These three new records in Scotland of terrestrial planarians known to prey upon earthworms in three years suggest that the situation regarding the movement of terrestrial planarians is dynamic and new introductions are probable. Although all three species new to Scotland are known to feed upon earthworms, little is known about their ecological requirements. The distribution of *Australoplana sanguinea* in the British Isles (Jones and Boag 1996) and New Zealand (Johns et al. 1998) would suggest that it could tolerate warmer, drier conditions than *Arthurdendyus triangulatus.* The same cannot be said about *Arthurdendyus albida* or *A. australis* since their ecological niches are unknown.

New Zealand and Australia each have over 100 species of terrestrial planarians, many of which are undescribed (Johns 1998, Winsor 1998*b*), and many have been shown to be predators of lumbricid earthworms (e.g., *Arthurdendyus testaceus;* Yeates et al. 1997). This species would seem to be a prime candidate for human-mediated dispersal as it is found in garden centers throughout much of New Zealand. If introduced into the British Isles it could be a more serious problem than *A. triangulatus* since it can tolerate higher temperatures than *A. triangulatus* and as its natural geographical distribution is the north of the South Island and south of the North Island (Johns et al. 1998). Other terrestrial planarians have been shown to be a threat to native earthworms. Ducey and Noce (1998) reported *Bipalium adventitium,* which was first discovered in the United States over 90 yr ago, now rapidly spreading in New York state; by preying on local earthworm species it may represent a significant threat to soil ecosystems in northeastern North America. Winsor (1998*a*) also reported an Australian native *Dolichoplana* sp. to be a problem in earthworm farms in New South Wales and Queensland, Australia.

The New Zealand flatworm as an example of a potentially harmful invasive soil organism and the challenges it imposes

The New Zealand flatworm represents a group of organisms that are likely to become more of a problem in the future, and unlike some invasive vertebrate species could have an insidious impact on the total ecosystem, but from belowground.

In Britain the 3 native terrestrial planarians have been augmented by 12 introduced species (Table 1). Only one of these so far has been shown to be a problem in Ireland, Scotland, and the Faroe Islands, although it is likely that at least two of the most recent introductions, *A. albidus* and *A. australis,* also have the capability to become serious pest species. While the diet of some of the introduced and native species of flatworms is unknown, due to a dearth of information on the biology of terrestrial planarians (Riser and Morse 1974), it has been demonstrated that at least six of the introduced species feed on earthworms (Table 1). The direct and indirect impact that the presence of flatworms might have on the soil food web and the biodiversity of soil organisms has not been investigated. Brown (1995) reviewed the affect that earthworms have on soil biota and their interactions and found most microflora and fauna were enhanced while the impact on larger microarthropods, enchytraeids, and Isopods could, in some cases, be decreased due to competition. In food-web studies earthworms are often considered a major component representing a member of one of the higher trophic groups (Beare et al. 1995) and consequently the presence of a top predator of earthworms is of concern and warrants further research.

The ecological niche filled by native earthworm predators in Britain means that equilibrium has been struck at ~200 earthworms/m^2 (P. M. Fraser and B. Boag, *unpublished data*). These relatively high populations of earthworms would seem to represent an underutilized niche (Mack et al. 2000) to *Arthurdendyus triangulatus* and probably is the reason why it has been so successful. Similar situations have arisen for a range of other successful invasive species (Williamson 1996). Williamson (1996), while trying to devise a general concept of invasive species, proposed that 10% of invasive species would become established and of those only 10% would become a problem. While there is no way of knowing how many terrestrial planarians have been introduced into the British Isles, the fact that *A. triangulatus* makes up 8% of the known established alien flatworm fauna would seem to support Williamson's hypothesis. Thus the data so far would suggest that the New Zealand flatworm and the group of terrestrial planarians it represents is behaving in a manner typical of other invasive species. As more species become established then the likelihood of another flatworm species being a pest is increased.

The Organisation for Economic Co-operation and Development (OECD) workshop held in Christchurch, New Zealand, in 1988 (Alford et al. 1998) concluded that the degree to which alien terrestrial flatworms will, through their effect on earthworm populations, adversely affect agriculture, wildlife, and sustainable land use is still unknown. However, since in the Faroe Islands, Northern Ireland, and western Scotland, *A. triangulatus* has been shown to significantly reduce earthworm populations, it was considered prudent to apply the precautionary principle, which assumes that unless proved to the contrary, the New Zealand flatworm should be considered a serious pest. This is because earthworms are known to enhance the availability of soil nutrients, increase soil drainage, redistribute soil organic matter, assist in residue decomposition, and improve soil structure and root penetration. Earthworms are also the major constituent of the diet of many mammals and birds, and significantly lower earthworm populations could lead to a reduction in the faunal biodiversity in some areas, e.g., the localized extinction of moles. However, an economic threat that could occur is the imposition of more stringent phytosanitary regulation against the export of certain commodities from the infested countries. Such regulations may be imposed by a country not because of the potential threat to its indigenous earthworm populations but because of the size of the international trade that country has in containerized plants to the rest of the world.

As a result of the potentially serious impact that *A. triangulatus* and other terrestrial planarians might have on agriculture, wildlife, and international trade the OECD workshop produced a series of recommendations (Alford et al. 1998). Of these the most important were that, since human-mediated dispersal was responsible for the present distribution of many terrestrial flatworm species, it was imperative that the present border control measures, which were not working, be either more rigorously enforced or new regulations be imposed. They also recommended that more needed to be done to raise the public awareness of the implications of spreading terrestrial flatworms and that research had to be undertaken into the biology, ecology, and control of *A. triangulatus* to complement any phytosanitary regulations that are instituted.

The wider implications of the findings associated with the New Zealand flatworm are that it advances our understanding of how a soil organism that was initially considered a curiosity can spread and have the potential to become a serious pest once it has been introduced into an ecological niche where no comparable organism already exists.

Acknowledgments

Much of this work was undertaken by the authors who received financial assistance via Higher Education LINK fellowships from the British Council and OECD Co-operative Research Programme grants. The Scottish Crop Research Institute is grant aided by the Scottish Executive Rural Affairs Department.

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