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First records of the exotic garlic snail *Oxychilus alliarius* on Takapourewa and a reassessment of its distribution in New Zealand

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ABSTRACT: We present the first report of an exotic snail from Takapourewa (also known as Stephens Island), New Zealand: *Oxychilus alliarius* (J.S. Miller, 1822), the garlic snail (Stylommatophora: Oxychilidae). This species has been introduced worldwide; it is widespread in New Zealand, where it is potentially problematic to the native fauna. We also revise the species' distribution in New Zealand based on historical material deposited in the collection of the Museum of New Zealand Te Papa Tongarewa.

KEYWORDS: DNA barcode, introduced species, snails, Oxychilidae, Takapourewa, Stephens Island, Stylommatophora.

Introduction

Takapourewa (also known as Stephens Island) is the northernmost land in the Marlborough Sounds in New Zealand's South Island, and lies 3 km from the nearest island. It is *c.* 120 ha in area, rises 283 m above sea level and is almost entirely bounded by steep cliffs (Campbell *et al.* 1984). Takapourewa is infamous in New Zealand conservation research, because it was home to the last relict population of the now extinct Lyall's wren (*Traversia lyalli* Rothschild, 1894). Folklore has it that the extinction of this flightless passerine on Takapourewa was caused by a single lighthouse keeper's cat, but this is an oversimplification of the swift but devastating effect that feral cats had on the island's avian fauna (Galbreath & Brown 2004; Medway 2004).

About 90% of Takapourewa's original vegetation cover was lost to farming and grazing, but the island is undergoing ecological restoration (East *et al.* 1995) and was declared a wildlife sanctuary in 1966 and a nature reserve in 1997 (Medway 2004). Takapourewa has an overlay classification as a result of the 2012 Treaty of Waitangi settlement that acknowledges the traditional, cultural, spiritual and historical associations of Ngāti Koata. It also requires joint management between Ngāti Koata and New Zealand's Department of Conservation (DOC), this being redress for the appropriation of the island by the government for the construction of a lighthouse in the 1890s.

Today, the island has a lighthouse and other associated facilities that are staffed by DOC personnel but no permanent human inhabitants. It is home to the largest population of tuatara (*Sphenodon punctatus* (Gray, 1842)), while its sizeable colony of fairy prions (*Pachyptila turtur* (Kuhl, 1820)) is thought to support the island's mix of invertebrates and reptiles through the enrichment that their droppings provide to the soil (East *et al.* 1995).

Even with all the anthropic interference on the island, no exotic species of snail has been reported from there in the scientific literature (e.g. Barker 1999). In fact, even in the entire Marlborough Sounds region, the only (and scarce) records of exotic terrestrial gastropods are of the garden slug (*Arion hortensis* (A. Férussac, 1819)) and garden snail (*Cornu aspersum* (O.F. Müller, 1774)) (Barker

1999). In this article, the authors present the first report of an exotic snail from Takapourewa, namely *Oxychilus alliarius* (J.S. Miller, 1822), vernacularly known as the garlic snail or garlic glass-snail (family Oxychilidae). This species has been widely introduced worldwide (Cádiz *et al*. 2013) and is widespread in New Zealand's North Island, being potentially problematic to the native fauna (Barker 1999). We confirm the identification of New Zealand's *O. alliarius* (questioned by Giusti & Manganelli 2002), using anatomical and molecular data. We also take the opportunity to revise the species' distribution in New Zealand based on new material available in the collection of the Museum of New Zealand Te Papa Tongarewa (NMNZ; Wellington, New Zealand).

Material and methods

After the first garlic snails were spotted on Takapourewa by the children of DOC rangers C. Birmingham and L. Kilduff, the couple conducted a full visual search of likely habitats in April and May 2019, focusing on plants, leaf litter and human-made structures. Table 1 shows the list of the 20 search sites on Takapourewa. The collected specimens were anaesthetised by partial immersion in beer (Gilbertson & Wyatt 2016); this was followed by full immersion in euthanising and fixative 70% ethanol. The specimens were deposited in the collection of the NMNZ, preserved in 98% ethanol (whole specimens) or dry (empty shells) (Table 1).

Table 1 List of the 20 sites studied on Takapourewa (Stephens Island), with date of search, coordinates and resulting museum specimens (NMNZ register numbers). Sites with no specimens listed indicate that no garlic snails were found. Abbreviations: sh, empty shells (dry); spm, whole specimens (98% ethanol).

Site ID	Location name	Coordinates	Date(s)	Specimens
S1	Weather Station Track	40°39’55” S, 174°00’00” E	25/05/19	NMNZ M.329041 (2 spm)
S2	Garden, top	40°39’56” S, 173°59’58” E	19 & 27/05/2019	NMNZ M.329045 (5 sh)
S3	House 1, Summit Track end	40°39’57” S, 173°59’59” E	27/05/19	NMNZ M.329045 (1 sh)
S4	House 2, Summit Track junction	40°39’59” S, 173°59’58” E	16 & 27/05/2019	—
S5	Summit	40°40’00” S, 173°59’58” E	22 & 27/05/2019	—
S6	Summit Track, below Claires junction	40°40’03” S, 173°59’57” E	22 & 27/05/2019	NMNZ M.329043 (2 spm)
S7	Summit Track, tunnel below Claires junction	40°40’04” S, 173°59’56” E	22 & 27/05/2019	NMNZ M.329042 (2 spm)
S8	Claires Track, midway down	40°40’06” S, 173°59’57” E	22/05/19	NMNZ M.329040 (2 spm)
S9	House 3, gully	40°40’08” S, 174°00’00” E	27/05/19	—
S10	Tower	40°39’56” S, 174°00’01” E	16/05/19	NMNZ M.329045 (2 sh)
S11	Quarantine Store, outside	40°39’55” S, 174°00’00” E	1/04/19	NMNZ M.329044 (c. 20 spm)
S12	Nursery	40°39’57” S, 174°00’01” E	23/05/19	—
S13	Nursery steps	40°39’55” S, 174°00’00” E	23/05/19	—
S14	Palace	40°40’11” S, 174°00’02” E	23/05/19	—
S15	Museum	40°40’12” S, 174°00’02” E	23/05/19	—
S16	Cleavers Site 5	40°40’16” S, 174°00’07” E	21/05/19	—
S17	Lister	40°40’25” S, 174°00’08” E	21/05/19	—
S18	Lister, Charing Cross Track	40°40’23” S, 174°00’06” E	21/05/19	—
S19	Biosecurity Route, Ruston end	40°40’25” S, 173°59’53” E	20/05/19	—
S20	Ruston	40°40’15” S, 173°59’59” E	20/05/19	—

One randomly selected adult specimen (from lot NMNZ M.329044) was dissected to confirm the species' identity, specifically through investigation of the reproductive trait (see below). Dissection was conducted under a stereomicroscope (Leica M60), aided by a digital camera (Leica MC170 HD) and its accompanying software (Leica Application Suite v.4.12.0), using standard techniques (Simone 2011). In addition, a small section of the foot of one randomly selected adult specimen (from lot NMNZ M.329044) was clipped for DNA extraction (QIAGEN DNeasy® Blood & Tissue Kit, standard protocol). We targeted the barcoding fragment (*c.* 650 bp) of the mitochondrial COI gene (primers LCO and HCO of Folmer *et al.* 1994) and a fragment of the nuclear rRNA cluster encompassing the 3' end of the 5.8S gene, the complete ITS-2 region and the 5' end of the large subunit 28S gene (*c.* 1,400 bp total; primers LSU-1 and LSU-3, and LSU-2 and LSU-5 of Wade & Mordan 2000; Wade *et al.* 2006).

The PCR protocols are as follows. COI fragment: initial denaturation at 96 °C (2 min); 35 cycles of denaturation at 94 °C (30 s) and 48 °C (1 min), extension at 72 °C (2 min); final extension at 72 °C (5 min). Nuclear rRNA cluster fragment: initial denaturation at 95 °C (3 min); 40 cycles of denaturation at 95 °C (30 s), annealing at either 50 °C (ITS2 section) or 45 °C (28S section) (1 min), extension at 72 °C (5 min); final extension at 72 °C (4 min). PCR products were quantified via agarose gel electrophoresis, followed by cleaning (ExoSAP-IT™, Affymetrix Inc.), and Sanger sequencing at Massey Genome Service (Massey University, Palmerston North). The sequences were assembled and quality-checked in Geneious Prime (version 2019.0.3, Biomatters Ltd), before being uploaded to NCBI GenBank under register number MN267019 (COI barcode) and MN267018 (nuclear rRNA cluster). Our sequence was compared to the only ones available (nuclear rRNA cluster): (1) Saadi & Wade (2019), GenBank register number MN022673, specimen from the UK; (2) Wade *et al.* (2007), AY014114, from the UK; (3) Cádiz *et al.* (2013), JF837183, from Chile.

Finally, we considered the distribution of *Oxychilus alliarius* in New Zealand, revising and expanding on the work of Gary Barker (1999). A good portion of that author's material is deposited in the NMNZ; furthermore, the collection also includes a wealth of additional specimens that can give a better picture of the species' range in the country. The specimens are all empty dry shells and were identified based on comparative material from the UK in the NMNZ collection and on specialised literature (e.g. Pilsbry 1946; Kerney *et al.* 1979; Welter-Schultes 2012). A full list of specimens is provided in the Appendix. The map was composed using the QGIS software (v.3.8.1; QGIS Development Team 2019). Unfortunately, the information accompanying most specimens did not include reliable coordinates, so we had to derive these using Google Earth Pro (v.7.3; Google LLC).

Results and discussion

Identification

Garlic snails originate from west and central Europe but have been introduced to several other regions worldwide, including North America, Colombia, Chile, Hawaii, Australia and southern Africa, among others (Cowie 1997; Barker 1999; Hausdorf 2002; Griffiths & Florens 2006; Herbert 2010; Cádiz *et al.* 2013). Despite its now wide distribution, the species is considered vulnerable in parts of its original range (Welter-Schultes 2012). In New Zealand, this species was already reported from the North Island by the 1890s (Barker 1999). It was well established there in the 1900s in urban and agricultural areas, although only scarce urban-restricted records have been reported from the South Island (Barker 1999, 2002).

However, the identity of New Zealand *Oxychilus alliarius* was disputed by Folco Giusti and Giuseppe Manganelli (2002), who revised specimens from the species' type locality. These authors argued that the identification of New Zealand specimens by Barker (1999) was dubious because of the latter's report of a papillate inner structure of the penis. Giusti and Manganelli understood the internal surface of the penis to be covered in papillae, which is not the case; Barker (p. 109) reported 'papillate longitudinal folds'. These folds, observed in the specimen dissected for the present study, are reminiscent of pleats, each with tiny sequential papillae-like bulges on its 'summit'. These 'papillate longitudinal folds' are exactly what Giusti and Manganelli observed, even though their illustration (fig. 6) is less detailed than that of Barker (fig. 92).

The comparison of our sequence data provided further evidence of the species' identity as *Oxychilus alliarius*, with 100% identity to sequences AY014114 and JF837183, and *c.* 99% to MN022673. Furthermore, morphological characters are also extremely helpful for identification, and are in line with what is known of this species (Taylor 1914; Pilsbry 1946; Kerney *et al.* 1979; Barker 1999; Giusti & Manganelli 2002; Welter-Schultes 2012): the small shell size (*c.* 6.3 mm width, *c.* four whorls); and conchological features such as the comparatively small protoconch, the faintly raised spire and the more narrowly coiled body whorl (Fig. 1). The morphology of the soft parts is additionally helpful in identification, especially the dark, almost black pigmentation of the body and features of the skin (Lloyd 1970a), although the latter are more difficult to observe in preserved specimens. Furthermore, when the snails were collected live in the field, the typical predator-deterrent garlic-like odour produced by *O. alliarius* (Lloyd 1970b; Welter-Schultes 2012) was perceived by the collectors (even to the point that they could rely on it to locate specimens).

As such, in this article we confirm the identity of the snails on Takapourewa, and New Zealand in general, as *Oxychilus alliarius* (*contra* Giusti & Manganelli 2002), based on conchological, anatomical, behavioural and molecular data.

Takapourewa

It is not known how or when garlic snails were introduced to Takapourewa. The typical mode of introduction is unintentional human transportation, usually with plants and soil (Cádiz *et al.* 2013), which was likely the case here. In the present survey, *Oxychilus alliarius*, both juveniles and adults, were found in eight out of 20 sites studied (Table 1). These typically represent more disturbed or modified areas, such as concrete walls and stairs (where these snails can be very abundant), and dry microhabitats exposed to the sun (Birmingham & Kilduff, pers. obs.), and grass and leaf litter along forest edges. However, on one site (Table 1: S3) a snail was found inside established forest, even though this record consists of only a single empty shell.

Although *Oxychilus alliarius* feeds primarily on plant material (live or decaying), it can consume snail or slug eggs and very small snails (less than 3 mm in shell length; Meyer & Cowie 2010). Unfortunately, the majority of native New Zealand snails (belonging to the families Punctidae and Charopidae) fall into this category (Powell

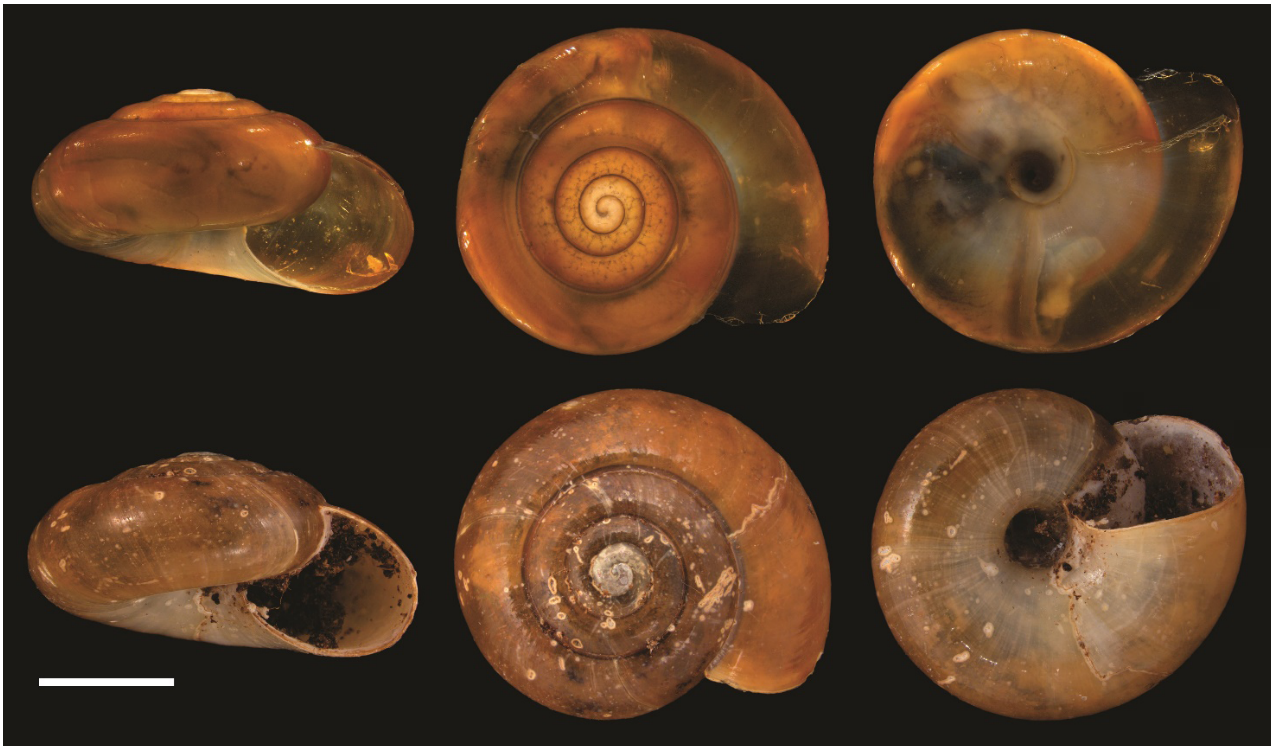

Fig. 1 *Oxychilus alliarius* from Takapourewa (Stephens Island). Fresh specimen (top row), NMNZ M.329044; dry shell (bottom row), NMNZ M.329045. Scale bar = 2 mm.

1979; Spencer *et al.* 2009). Even so, most accounts of predation by garlic snails remain anecdotal (e.g. Curry & Yeung 2013) and the magnitude of its effect on native gastropods, in New Zealand or otherwise, remains largely unstudied (although see Curry *et al.* 2016). Regardless, this species can prove problematic for the native gastropods if it starts to expand away from its typical habitats (anthropically modified areas) and into native forest, something that has already happened in a few areas in northern New Zealand (e.g. Brook & Goulstone 1999). The abundant tuatara and reptiles of Takapourewa are known molluscivores (Laporta-Ferreira & Salomão 2004) and might be able to keep the expansion of garlic snails to native forest in check, provided they are not affected by the predator-deterrent garlic odour. This odour is known to ward off some mammalian predators (Lloyd 1970b; Allen 2004), but there is no information on its effects on other vertebrates. Anecdotally, no avoidance behaviour by birds and reptiles has been observed so far (Birmingham & Kilduff, pers. obs.).

However, given that the effects of garlic snails on the native fauna remain anecdotal, we cannot exclude the possibility that a causation has been inferred based on superficial correlation. That is, *Oxychilus alliarius* does quite well in degraded habitats, where the native snails are largely absent. Superficially, it might appear that the garlic snails are the cause of the decline in native biodiversity, whereas the habitat's degradation as a result of human action is actually responsible. Further studies should focus on disentangling the chain of events to better assess the impacts (if any) of garlic snails on the native fauna, be it in New Zealand or in other places where the species has been introduced.

New Zealand

We used specimens from the collection of NMNZ to reassess the geographic distribution of *Oxychilus alliarius* within New Zealand (Fig. 2). In NMNZ, there were voucher specimens from all localities cited by Barker (1999), totalling 34 lots. For three pairs of locality and date, we could not find vouchers, but there were specimens from the exact same localities, collected by Barker himself, but from different dates; it is likely that these are the vouchers and that the dates were noted down incorrectly in either Barker's publication or the NMNZ database. In addition, specimens from two localities were misidentified by Barker and belong to *O. cellarius* (O.F. Müller, 1774). However, there are other specimens of *O. alliarius* from nearby areas, thus the overall pattern of the distribution map (Fig. 2) is not affected.

In total, we found an extra 66 lots of *Oxychilus alliarius* specimens in NMNZ (i.e. discounting the new specimens from Takapourewa and the vouchers of Barker (1999)). This tripled the number of occurrences listed by Barker, thus allowing the preparation of a much more comprehensive distribution map (Fig. 2). In comparison to Barker's map (map 25), the new data reveal that garlic snails are also present throughout Northland, around Gisborne and in Hawke's Bay in the eastern North Island, and along the Whanganui coast south to Wellington in the west. In the South Island, besides the new record from Takapourewa (and Marlborough Sounds), garlic snails can additionally be found in Tasman and Westland.

Overall, garlic snails are widespread in the North Island (Fig. 2), where they are found in virtually all urban centres and have also spread to rural and more 'natural' settings, including some reserves and conservation areas (see Appendix). In the South Island, though, information is scarce. Here, garlic snails are present in the main urban centres, but also in more remote locations such as Tasman Head and Punakaiki. However, it is difficult to confirm whether the species is indeed present in low numbers in the South Island or if this is a case of collection bias.

This raises an important point: there is a poor representation of introduced and invasive species in natural history collections. These animals are typically deemed 'unworthy' of being kept in collections by collection managers and curators, the rationale being that they take up time and space that would be better devoted to native species. While native species are undoubtedly a priority, introduced species are important in a range of different studies, including those investigating geographical expansion, long-term micro-evolutionary trends and global change biology. These are all extremely interesting and important topics, both from a purely scientific perspective and from a more applied standpoint, not only for conservation but also for studies into agriculture and public health. Thus we echo the argument of Ruedas *et al.* (2000) and Salvador and Cunha (2020) that even well-known common species, including exotics, should have vouchers deposited in natural history collections.

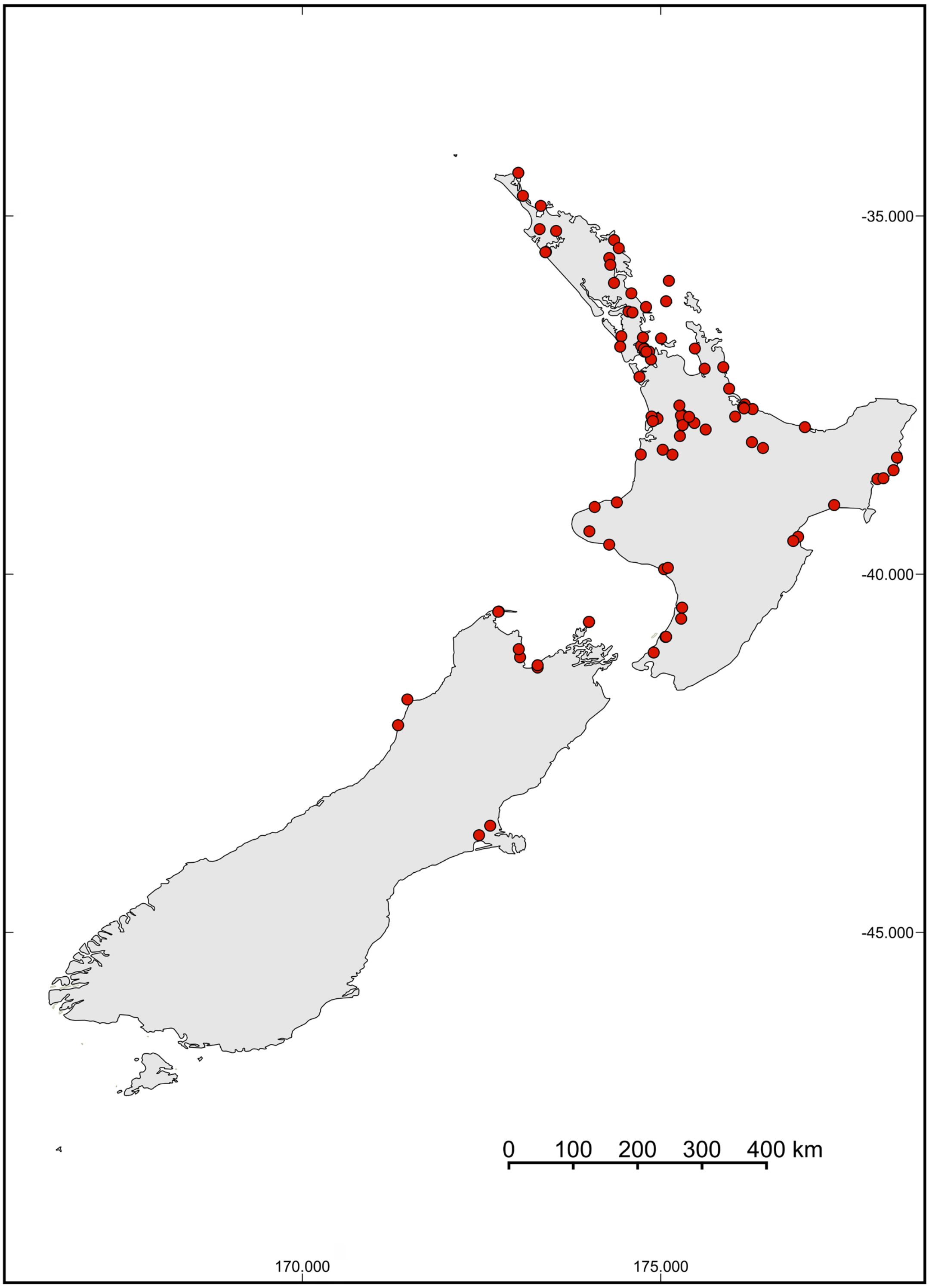

Fig. 2 Map of New Zealand showing the distribution of *Oxychilus alliarius*. The location of Takapourewa (Stephens Island) is indicated by a 'T'.

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Appendix

Below is listed all the material belonging to *Oxychilus alliarius* housed in the collection of the Museum of New Zealand Te Papa Tongarewa and used for Fig. 2. We provide the register number (in numerical order), collection date (when available) and collection locality. We excluded the NMNZ prefix for brevity and clarity. All specimens are dry shells, with the exception of those from Takapourewa listed in Table 1.

Material analysed: M.022072 (Dec 1935, Napier, Bluff Hill, The Mount Garden); M.032115 (Waikanae); M.073591 (28 Apr 1979, Hauraki Gulf, Maria Island); M.086022 (1984, Tauranga, Mt Maunganui); M.087830 (Nov 1986, North Cape, Akura Stream); M.101101 (4 Sep 1988, Thames, Kauaeranga Valley); M.104416 (26 Dec 1978, Whangarei, Waro Reserve); M.104473 (28 Dec 1978, Karikari Peninsula, Puheke Beach); M.107751 (Waikanae, 13 Kotare Street); M.120293 (2 Jan 1980, Westport, Cape Foulwind); M.121985 (12 Jul 1986, Collingwood, Puponga Farm Park); M.123207 (21 Apr 1992, Motueka, Kina Peninsula); M.125565 (Jun 1995, Whanganui); M.129105 (7 Sep 1988, Auckland); M.156988 (4 Dec 2003, Whakatane, Kohi Point); M.162711 (Oct 1979, Nelson, Hackett Track); M.163511 (Oct 1978, Kaitaia, Mangamuka Bridge); M.163628 (Nov 1984, Motukaraka Scenic Reserve); M.164223 (Jan 1990, Opononi, Waima Forest, Hauturu Highpoint Track); M.170322 (Nelson); M.170323 (Taranaki); M.170324 (New Plymouth, Pakekura Park); M.179930 (2 Nov 2000, Auckland, Epsom); M.179931 (8 Jul 1993, Great Exhibition Bay, Rarawa Beach); M.179932 (13 Apr 2003, Kaitaia, Diggers Valley Road); M.179934 (20 Oct 1978, Helensville, Otakanini Research Farm); M.179935 (25 Jun 1977, Tauranga, Lower Kaimai); M.179936 (29 May 1996, Whangamata, Opoutere); M.179937 (11 Sep 1976, Te Kuiti, Haggas' Farm); M.179938 (19 Sep 1978, Te Kuiti); M.179939 (16 Jul 1977, Raglan, Te Uku); M.179940 (23 Apr 1978, Whangamata, Waihi Beach); M.179941 (6 Jun 1977, Hamilton); M.179942 (8 Jan 1977, Hamilton, Rukuhia, Lake Cameron); M.179943 (1 Sep 1989, Tauranga, Papamoa Beach); M.179944 (20 Apr 1987, Wellsford, Hoteo, Hoteo River Bridge); M.179945 (6 Jun 1977, Hamilton, Peachgrove Road); M.179946 (13 Feb 1989, Auckland, Ellerslie, Michaels Avenue); M.179947 (26 Dec 1988, Tauranga, Otumoetai); M.179948 (8 Oct 1988, Auckland, Ellerslie); M.179949 (12 May 1980, Hamilton, Ohaupo); M.179950 (6 Oct 1994, Motueka, Dummy Bay); M.179951 (20 Jun 1987, Auckland, Mt Wellington, Lunn Avenue); M.179952 (22 Jun 1977, Hamilton); M.179953 (1 Jul 1991, Hamilton, Ohaupo); M.179954 (5 Dec 1979, Leigh, Goat Island Bay); M.179955 (2 Aug 1987, Hamilton, Ohaupo); M.179956 (17 Feb 1989, Whangarei, Bland Bay); M.179958 (22 Sep 1991, Wairoa); M.179959 (3 Oct 1991, Christchurch, Merivale); M.179961 (18 Aug 1977, Te Kuiti); M.179962 (Apr 1980, Te Kuiti, Kiritehere); M.179963 (21 Jan 1996, Rotorua, Mamaku Forest Park); M.179965 (18 Apr 1979, Hamilton, Matangi); M.179966 (21 Sep 1978, Te Kuiti); M.179967 (16 Jul 1977, Raglan); M.179968 (25 Mar 1976, Whangarei, near Waipu Caves); M.179969 (5 Aug 1977, Whangarei, Kamo); M.179970 (27 Apr 1974, Gisborne, Tolaga Bay); M.179971 (15 Jan 1977, Te Awamutu, Kakepuku Mountain); M.179972 (19 Jan 1987, Auckland, Wiri); M.179973 (1 Jan 1988, Auckland, Birkenhead, Le Roys Bush); M.179974 (18 Jul 1977, Hamilton, Komakorau); M.179975 (10 Oct 1991, Tauranga); M.179976 (12 Mar 1979, Wairoa); M.179977 (29 Jun 1999, Christchurch, Lincoln, Lincoln College); M.179978 (4 Aug 1983, Te Hauturu-o-Toi/ Little Barrier Island, Awaroa Stream); M.179979 (2 Jul 1977, Cambridge, Hora Hora); M.179980 (7 Dec 1993, Whangarei, Mimiwhangata); M.179981 (20 Apr 1987, Warkworth, Dome Valley, Hotea River); M.179982 (31 Dec 1978, Auckland, Grafton Gully); M.179983 (1 Aug 1988, Tauranga); M.179984 (23 May 1979, Hawera); M.179985 (1 May 1990, Cambridge); M.179986 (16 Jul 1977, Raglan, Te Mata); M.179988 (24 Feb 1980, Levin); M.179989 (18 Apr 1979, Hamilton, Matangi); M.179990 (6 Dec 1980, Foxton); M.179991 (12 Aug 1983, Coromandel, Manaia); M.179992 (1 Aug 1993, Mangawhai, Warkworth); M.179993 (18 Aug 2004, Auckland, Torbay); M.180057 (28 Aug 1998, Opononi); M.181800 (23 Nov 2000, Auckland, Greenlane, 3 Wairakei Street); M.199012 (14 Nov 1971, Taradale, Napier); M.199186 (19 Oct 1975, Whanganui, Gordon Reserve); M.199348 (21 May 1965, Abel Head, Puponga); M.199835 (21 May 1965, Abel Head, Puponga); M.281756 (25 Jan 1969, Waiuku, Taurangaruru, Adred Road); M.296052 (4 Jun 1998, Gisborne, Kaiaua Beach, Waiokahu Stream mouth); M.296120 (7 Nov 2009, Gisborne, Kaiaua Beach, Waiokahu Stream mouth); M.296466 (7 Nov 2009, Gisborne, Waihau Bay, Wairua Stream mouth); M.296572 (6 Jun 1998, Gisborne, Pakarae River mouth); M.296577 (8 Nov 2009, Gisborne, Pakarae River mouth); M.296606 (8 Apr 1998, Gisborne, Whangara); M.297992 (29 Mar 2009, Auckland, Muriwai Beach, Motutara Road); M.305199 (Dec 2011, Punakaiki); M.305209 (Dec 2011, Punakaiki); M.305283 (Dec 2011, Punakaiki); M.310546 (27 Jan 1999, New Plymouth, Urenui); M.329040 (22 May 2019, Stephens Island, Claires Track); M.329041 (25 May 2019, Stephens Island, Weather Station Track); M.329042 (22–27 May 2019, Stephens Island, Summit Track); M.329043 (22–27 May 2019, Stephens Island, Summit Track); M.329044 (1 Apr 2019, Stephens Island, outside Quarantine Store); M.329045 (16–27 May 2019, Stephens Island); M.329065 (11 Nov 1993, Mokohinau Islands).