Research Article

Risk screening and management of alien terrestrial planarians in The Netherlands

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Abstract

Worldwide over 910 terrestrial planarian species have been described. They mainly occur in tropical and subtropical regions. In Europe, 22 alien terrestrial planarian species have been recorded over the last decades. In The Netherlands, 9 alien species have been found so far, mostly in greenhouses. Three of these species have established populations in gardens (i.e., *Marionfyfea adventor*, *Caenoplana variegata* and *Parakontikia ventrolineata*). Alien terrestrial planarians that consume earthworms and are established outdoors can have a negative impact on biodiversity and soil quality by reducing earthworm populations. Their impact on earthworm populations can be high, but is difficult to assess due to limited knowledge of the feeding patterns and ferocity of most terrestrial planarian species. Risk assessments for The Netherlands carried out with the Harmonia$^+$ scheme shows that only the New Zeeland land planarian *Arthurdendyus triangulatus* scores high for potentially risks due to its ability to significantly reduce earthworm densities. This species has not yet been found in The Netherlands, but already occurs in the United Kingdom, Ireland, and Iceland. *Obama nungara* obtained a medium risk score and all other species a low risk score. Due to the limited information about terrestrial planarians and their potential impact, the certainty of most risk scores is low to moderate. Therefore, it is recommended to update their risk assessments periodically based on new information about their invasion biology. Phytosanitary measures can limit the unintentional import of alien planarian species.

Key words: hitchhikers, introduction pathways, invasive species, non-native species, risk scanning, risk management, land flatworms

Introduction

Most planarians (Platyhelminthes, Tricladida) are aquatic animals with a flattened body hence the name planarian. Terrestrial planarians, land flatworms or land planarians are usually not so flattened and have a rounder body (Ball and Reynoldson 1981). Nowadays worldwide over 910 terrestrial planarian species have been described in scientific literature (Sluys 2016). These species were mainly found in tropical and subtropical regions, such as Southeast Asia, New Zealand, Australia, South America and parts of Africa (De Waart 2016).

Most terrestrial planarians do not tolerate drought and therefore live in a humid environment, preferably in humus rich or clayey soil with a rich soil life, such as snails, slugs and earthworms that can serve as prey. Moreover, shaded places under dense vegetation, stones or planks where a high humidity is maintained are preferred (Den Hartog 1962a). They do not tolerate inundation by seawater (Den Hartog 1962b). Terrestrial planarians are top predators as they are hardly consumed by other animals (Sluys 1999). However, research by Boll et al. (2015) showed that some terrestrial planarians eat other terrestrial planarians. They are also known to be preyed by some snail species (Lemos et al. 2012). Terrestrial planarians reproduce sexually by producing egg cocoons after mating from which young individuals hatch, and asexually by fission in which case clones are produced (Ball and Reynoldson 1981).

In Europe, the number of alien terrestrial planarian species increases. Currently, 22 alien species have been recorded (Ogren and Kawakatsu 1991; Boag and Yeates 2001; Jones 2005; Sluys 2016; Jones 2019; De Waart et al. 2021). Some species were introduced for biological control (Mather and Christensen 1992; 1996; Hodkinson and Thompson 1997). Otherwise, important introduction pathways are hitchhiking with (potted) plants and soil. Therefore, the first records of most of the alien planarian species were from greenhouses and garden centres from where they can escape to establish themselves in the wild. Several alien terrestrial planarian species have already established populations in the wild in France (Justine et al. 2018), United Kingdom (Jones 2005), Belgium (Soors et al. 2019; Van den Neucker et al. 2020) and The Netherlands (De Waart 2016; Thunnissen et al. 2020).

Alien terrestrial planarian species that have established in the wild can influence soil life, with undesirable consequences for the functioning of natural ecosystems and agricultural areas (Murchie and Weidema 2013). Predatory planarians can consume large quantities of native earthworms, planarians, isopods, snails, and slugs (Terrace and Baker 1994; Jones 2005; Boag et al. 2010; Jones 2019; Jones et al. 2020). However, most of the possible consequences of this reduction of soil life are until now largely unknown. Nevertheless, extensive measures have already been taken to prevent the introduction and spread of the worms and to control some introduced alien terrestrial planarians. For example, the European Commission included the New Zealand planarian *Arthurdendyus triangulatus* on the list of invasive alien species of EU concern in 2019 (European Commission 2019). In the top 100 of the most invasive species according to the IUCN, the terrestrial New Guinea planarian *Platydemus manokwari* is listed

(Lowe et al. 2000; Global Invasive Species Database 2020). In the past, *P. manokwari* was introduced to control the giant African snail (*Achatina fulica* (Férussac, 1821)) in the Philippines, Japan and the Maldives (Justine et al. 2014). However, *P. manokwari* is now considered to be the cause of the extinction of endemic land snails on various islands in the Pacific region (Sugiura and Yamaura 2009).

Only two native terrestrial planarian species occur in The Netherlands (Nederlands Soortenregister 2020a): *Microplana terrestris* (O.F. Müller, 1773) and *Rhynchodemus sylvaticus* (Leidy, 1851) (Den Hartog and Van der Velde 1973; Van der Velde and De Vries 1985). Since the fifties of the last century, several alien terrestrial planarians have been observed in The Netherlands (De Waart 2016; Sluys 2016). Potentially, the European climate could become more suitable for alien warm temperate or subtropical terrestrial planarians to establish themselves outdoors, due to climate change. This could affect the success rate of introduction and establishment of alien terrestrial planarian species in the future.

Therefore, the aim of this study was to screen risks of alien terrestrial planarian species in The Netherlands, and to evaluate their potential effects on biodiversity, ecosystem functioning, ecosystem services, human health and agriculture. Furthermore, this study aimed to provide an updated overview of alien terrestrial planarian and their distribution in The Netherlands. This risk screening includes a literature study of the risks of introduction, establishment, distribution and impacts of alien terrestrial planarian species. Furthermore, feasible management strategies for control were identified. In this study we aimed at answering the following questions:

- Which alien terrestrial planarians have been introduced and established in The Netherlands?
- Which alien terrestrial planarian species can be expected to be introduced in the near future?
- What are the risks of their (potential) impact?
- Which management strategies for alien terrestrial planarians can be identified?

For this purpose, we performed extensive literature reviews and interviews with experts, and used data of recent surveys of alien terrestrial planarians in several gardens and greenhouses in zoos and botanical gardens in The Netherlands. The outcomes of this study may be relevant not just for in The Netherlands but also for surrounding countries and other areas in Europe or other continents with similar habitat and climatic conditions.

Materials and methods

The risk screening focuses on The Netherlands. Species found only indoors in The Netherlands and both outdoors and indoors in surrounding North-

West European countries will be assessed on their expected capability to survive outdoors with winter temperatures below zero.

Data collection

A literature search was conducted with Google Scholar and Web of Science using the scientific species names of all assessed terrestrial planarian species, in combination with the following set of search terms: "*species name*", "*species name* invasive" and "*species name* risk". For each species, the first 100 hits were judged on relevance for our study according to the approach used by Matthews et al. (2017). Additionally, relevant information was obtained by interviews with three terrestrial planarian experts (see Supplementary material Table S25 for used questionnaires). The available information was used for identifying introduction pathways, assessing the risks of alien terrestrial planarian species and developing feasible management strategies. The present paper follows the most recent taxonomic classification and nomenclature of terrestrial planarian species (Nederlands Soortenregister 2020a).

Species list

Selection criteria for species assessed in this study were (1) species that have already been found in The Netherlands, and (2) species that are expected to be found in The Netherlands due to their presence in neighbouring countries in North-western Europe (i.e. Belgium, Germany, France, the United Kingdom and Ireland) (De Waart 2016; Nederlands Soortenregister 2020a; H. Jones *pers. comm.*).

Risk assessment of species

Risks of alien terrestrial planarian species for The Netherlands were assessed using the internet-based Harmonia$^+$ risk assessment protocol (D'hondt et al. 2015). This protocol takes into account environmental risks, impact on human infrastructure, impact on ecosystem services and effects of climate change on risks (D'hondt et al. 2015; Vanderhoeven et al. 2015). The protocol consists of 41 questions grouped in the following six categories: 1) context, 2) introduction, 3) establishment, 4) spread, 5) impact categories (environment, plant cultivation, animal production, human health, infrastructural and ecosystem services), and 6) future effect of climate change. Risk scores for planarian species and confidence levels were assigned to all questions. Risk scores (RS) were categorized as high ($RS > 0.66$), medium ($0.33 \leq RS \geq 0.66$) and low ($RS < 0.33$). The Harmonia$^+$ risk classification yielded an invasion score, impact score and overall risk score for each species by calculating the arithmetic mean and maximum score for each risk category. The assessment was carried out and discussed by the authors until consensus was reached. In case of data deficiency, risks were assigned based on best professional knowledge of the authors.

Climate match of species

The occurrence of alien species in surrounding countries with similar climatic conditions is generally the best predictor for the invasiveness of species that have not yet been introduced to a particular area or country (Williamson and Fitter 1996). Therefore, all species were assessed that are already present in surrounding North-western European countries with a similar climate based on the Köppen-Geiger climate classification (Kottek et al. 2006; Peel et al. 2007; Beck et al. 2018). The Netherlands has the climate classification Cfb. The C means that the air temperature of the hottest month is on average higher than or equal to 10 °C and the temperature of the coldest month is on average lower than 18 °C but higher than −3 °C. Codes f and b indicate that precipitation is evenly distributed throughout the year and the average temperature of each of the four hottest months is 10 °C or higher, but the hottest month on average less than 22 °C. The Cfb region also includes Belgium, Germany, France, the United Kingdom, Ireland, and Northern Spain. If the precise areas of origin of the alien terrestrial planarians were known, this information was also used to assess the climatic match of species.

Results

Alien species introduction and establishment in The Netherlands and surrounding countries

Based on the literature review, interviews and data of recent surveys, in total, 22 alien terrestrial planarian species were recorded in North-western Europe, of which 9 were found in The Netherlands (Figure 1). Of these 22 species, 11 species were found outdoors (e.g., in garden plots) (Table 1; Figure 2). Already in 1912, the first alien terrestrial planarian was found in a greenhouse in The Netherlands (Naturalis 2020; Nederlands Soortenregister 2020a, 2020b; Figure 2). The first observation of an alien terrestrial planarian outdoors in The Netherlands concerned a single record of *Marionfyfea adventor* in a garden in the municipality of Goes in 2012 (Jones and Sluys 2016; Figure 2). The number of first new records of alien terrestrial planarians has increased over the years throughout North-western Europe, in particular in the United Kingdom, France and The Netherlands (Figure 2). Most introductions occurred in the United Kingdom (Table 1; Figure 2). Of the 9 alien terrestrial planarian species reported for The Netherlands, three (*M. adventor*, *Caenoplana variegata* and *P. ventrolineata*) have been found outdoors (Figure 3).

The hammerhead land flatworm (*Bipalium kewense*) has been occasionally reported from greenhouses in botanical gardens and zoos since 1912 (Naturalis 2020). The blue garden planarian *Caenoplana coerulea* was found in a heated greenhouse in 2018 (De Waart 2019). The large Australian yellow-stripe *C. variegata* was first observed in a garden in 2014, and later

Figure 1. Photographs of the alien terrestrial planarian species found indoors and outdoors in The Netherlands: *Anisorhynchodemus* sp., found in greenhouses in Rotterdam, Amsterdam and Arnhem (A, Photo by Roy Kleukers); *Bipalium kewense* found in greenhouses Amsterdam, Utrecht and Leiden (B, Photo by Pierre Gros); *Parakontikia ventrolineata* found in a garden in Amsterdam Noord (C, Photo by Roy Kleukers); *Caenoplana coerulea* found in a greenhouse in Nijmegen (D, Photo by Roy Kleukers); *Caenoplana variegata* found in gardens in Castricum, Bleiswijk, Hillegersberg, Zwijndrecht, Zaandam and Heemstede (E, Photo by Roy Kleukers); *Caenoplana* cf. *micholitzi* found in a greenhouse in Arnhem (F, Photo by Roy Kleukers); *Dolichoplana* sp. found in greenhouses in Amsterdam and Arnhem, (G, Photo by Roy Kleukers); *Marionfyfea adventor* found in gardens in Goes, Schiedam and Beek-Ubbergen (H, Photo by Jochem Kuhnen) and *Obama* cf. *nungara* found in a garden center in Gilzen (I, Photo by Pierre Gros).

in five other gardens (De Waart 2016; De Waart et al. 2021). In 2019, *C. variegata* appeared to be established in a garden, and is thus able to survive the Dutch winters (De Waart et al. 2021). The blue spotted land planarian *Marionfyfea adventor* was recorded in gardens in 2012 and 2020 (Jones and Sluys 2016). One individual of *Obama nungara* was observed in a garden centre in 2020 (De Waart et al. 2021). *Parakontikia ventrolineata* was observed in a garden in Amsterdam Noord in 2020 (De Waart et al. 2021). The species *Anisorhynchodemus* sp., *Caenoplana micholitzi* and *Dolichoplana* sp. have only been observed in heated greenhouses in 2020 (De Waart et al. 2021).

Pathways for introduction and dispersal

Based on literature review and interviews, the most important pathway for introduction of alien terrestrial planarian species is as contaminant with potted plants and soil (Mather and Christensen 1992, 1996; Hodkinson and Thompson 1997). All alien terrestrial planarian species with established populations in The Netherlands, indoors as well as outdoors, can also spread through natural dispersal and human interference (*viz.* through the

Table 1. Overview of the first observations of alien terrestrial planarians in The Netherlands and surrounding countries with information on their origin, climate in their native range and indoor and outdoor occurrence in Europe.

Scientific name	Native range	Climate code native range according to Köppen-Geiger (Beck et al. 2018)	Distribution in Europe	First record in The Netherlands	First record in surrounding countries	Species found outdoors in Europe
Anisorhynchodemus sp. Kawakatsu, Froehlich, Jones, Ogren and Sasaki 2003 [a]	Worldwide [1]	Unknown	England, Switzerland, The Netherlands [1,2]	2020 [2]	Year unknown[1]	No
Arthurdendyus albidus Jones and Gerard, 1999	New Zealand [3]	Bsk, Cfb,Cfc	Scotland [3]	None	1996, Scotland[3, 4]	Yes
Arthurdendyus australis (Dendy, 1894)	New Zealand [5]	Bsk, Cfb,Cfc	Scotland [5]	None	1997, Scotland[5]	Unknown
Arthurdendyus triangulatus (Dendy, 1895)	New Zealand [6]	Bsk, Cfb,Cfc	Faroe Islands, Iceland, Ireland, United Kingdom [6,7]	None	1963, Northern Ireland [6]	Yes
Artioposthia exulans (Dendy, 1901)	New Zealand [8]	Bsk, Cfb,Cfc	England [8]	None	2013, England [8]	Yes
Australoplana sanguinea (Mosely, 1877)	New Zealand [9]	Af, Aw, Bwh, Bsh, Bsk, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	United Kingdom [10]	None	1974, Northern Ireland [9]	Yes
Bipalium kewense Moseley, 1878	Southeast Asia[11]	Af, Am, Aw, Cfa, Cfb, Cwa, Cwb	Austria, Belgium, Czech Republic, Finland, France, Germany, Ireland, Norway, Poland, Portugal, Spain, The Netherlands, United Kingdom [12, 13, 14, 15]	1912 [12]	1877, England[11]	Not in surrounding countries, it does occur in Portugal and Spain
Caenoplana coerulea Moseley, 1877	Australia [14]	Af, Aw, Bwh, Bsh, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	England, France, Spain, The Netherlands [14, 16]	2018 [16]	1986, England[4, 17]	Yes, Spain and France; in other countries only in greenhouses
Caenoplana decolorata Mateos, Jones, Riutort, and Álvarez-Presas, 2020	Australia [18]	Af, Aw, Bwh, Bsh, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	France, Spain [18, 19]	None	2012 Spain [18]	No
Caenoplana micholitzi (von Graff, 1899) [a]	Tanimbar Island Group [20]	Aw	The Netherlands [2]	2020 [2]	None	No
Caenoplana purpurea (Dendy, 1894)	New Zealand [21]	Bsk, Cfb,Cfc	England [21]	None	Year unknown, Engeland [21]	No (hothouse UK)
Caenoplana variegata (Fletcher and Hamilton, 1888)	Australia [22]	Af, Aw, Bwh, Bsh, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	England, France, Greece, Spain, The Netherlands [22, 23]	2014 [22]	2008, England [22]	Yes
Diversibipalium multilineatum (Makino and Shirasawa, 1983)	Japan [24]	Cfa	France, Italy [24, 25]	None	2013, France [24]	Gardens in France and Italy
Dolichoplana sp. Moseley, 1877 [a]	Probably Indonesia and/or Malaysia [26]	Af, Am, Aw, Cfb	Belgium, The Netherlands [2, 15]	2020[2]	2020 Belgium [15]	No
Dolichoplana striata Moseley 1877	Phillipines [27]	Af, Am, Aw, As, Bwk, Bsh, Cfa, Cfb, Cwa, Cwb, Dsb,	Belgium, Ireland, Jersey, Germany, United Kingdom, Spain [15, 26]	None	1936, Ireland [28]	No
Kontikia andersoni Jones, 1981	Australia or New Zealand [17]	Bsk, Cfb, Cfc	United Kingdom and Ireland [21, 29]	None	1976, Northern Ireland [29]	Yes
Marionfyfea adventor Jones and Sluys, 2016	New Zealand [30]	Bsk, Cfb, Cfc	France, Belgium Denmark, Germany, Ireland, United Kingdom and The Netherlands [4, 30, 31]	2012[30]	1997, Ireland [4]	Yes
Obama nungara Carbayo, Álvarez-Presas, Jones and Riutort, 2016	Brazil and Argentina [31]	Af, Am, As, Aw, Bsh, Cfa, Cfb	Belgium, England, France, Guernsey, Italy, Portugal, Spain, Switzerland, The Netherlands [2, 32, 33]	2020 [2]	2008, Guernsey [31]	Yes
Parakontikia atrata (Steel, 1897)	Australia [34]	Af, Aw, Bwh, Bsh, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	England [34]	None	2015, England [34]	Unknown
Parakontikia coxii (Fletcher and Hamilton, 1888)	Australia [17]	Af, Aw, Bwh, Bsh, Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	England [17]	None	1975, England [4, 17]	No
Parakontikia ventrolineata (Dendy, 1892)	Australia [14, 35]	Af, Aw, Bwh, Bsh,Csa, Csb, Csc, Cfa, Cfb, Cfc, Cwa	Belgium, England, France, Ireland, Spain, The Netherlands [2, 13, 14, 15]	2020 [2]	1994, England [35]	Yes
Platydemus manokwari de Beauchamp, 1963	Papua-New Guinea [36]	Af, Am	France [37]	None	2013, France [37]	No, however Justine et al. (2014) expect they can survive outdoors.

a: To be confirmed by DNA analyses;
1: Kawakatsu et al. (2003), 2: De Waart et al. 2021, 3: Jones and Gerard (1999), 4: Jones (2021), 5: Boag and Yeates (2001), 6: Boag et al. (1995), 7. Murchie and Gordon (2013), 8: Jones and Fenwick (2018), 9: Jones et al. (2001), 10: Mather and Christensen (1996), 11: Winsor (1983), 12: Naturalis (2020), 13: Álvarez Presas et al. (2014), 14: Sluys (2016), 15: Van den Neucker et al. (2020), 16: De Waart (2019), 17: Jones (2005), 18: Mateos et al. (2020), 19: Justine et al. (2020), 20: von Graff (1899), 21: Ogren and Kawakatsu (1991), 22: Jones et al. (2020), 23: De Waart (2016), 24: Justine et al. (2018), 25: Dorigo et al. (2020), 26: Winsor et al. (2004), 27: Moseley (1877), 28: Ball and Reynoldson (1981), 29: Wilkinson (2016), 30: Jones and Sluys (2016), 31: Carbayo et al. (2016), 32: Soors et al. (2019), 33: Justine (2021), 34: Jones (2019), 35: Jones et al. (2009), 36: Jones (1998), 37: Justine et al. (2014).

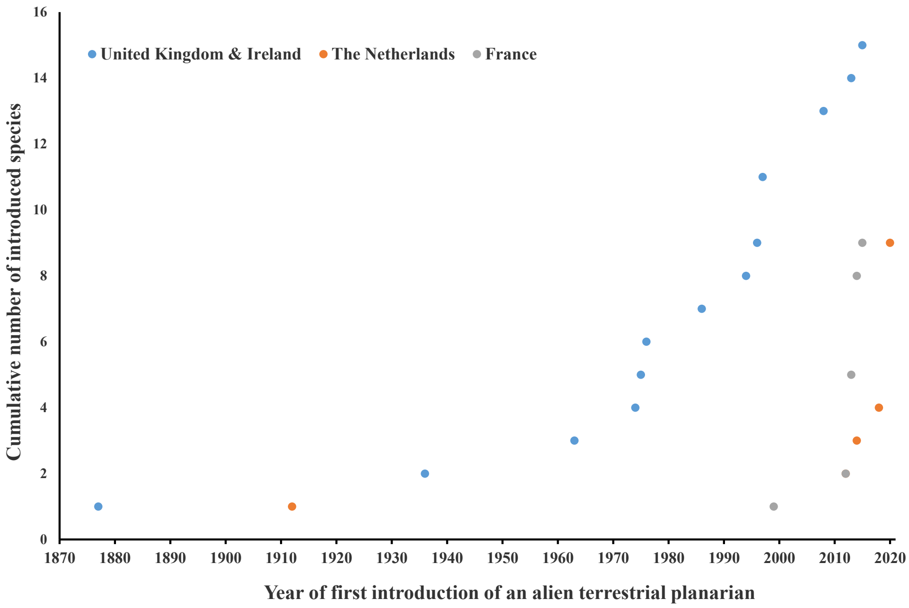

Figure 2. Cumulative number of introduced species based on the years of first records of alien terrestrial planarians in the United Kingdom, France, and The Netherlands.

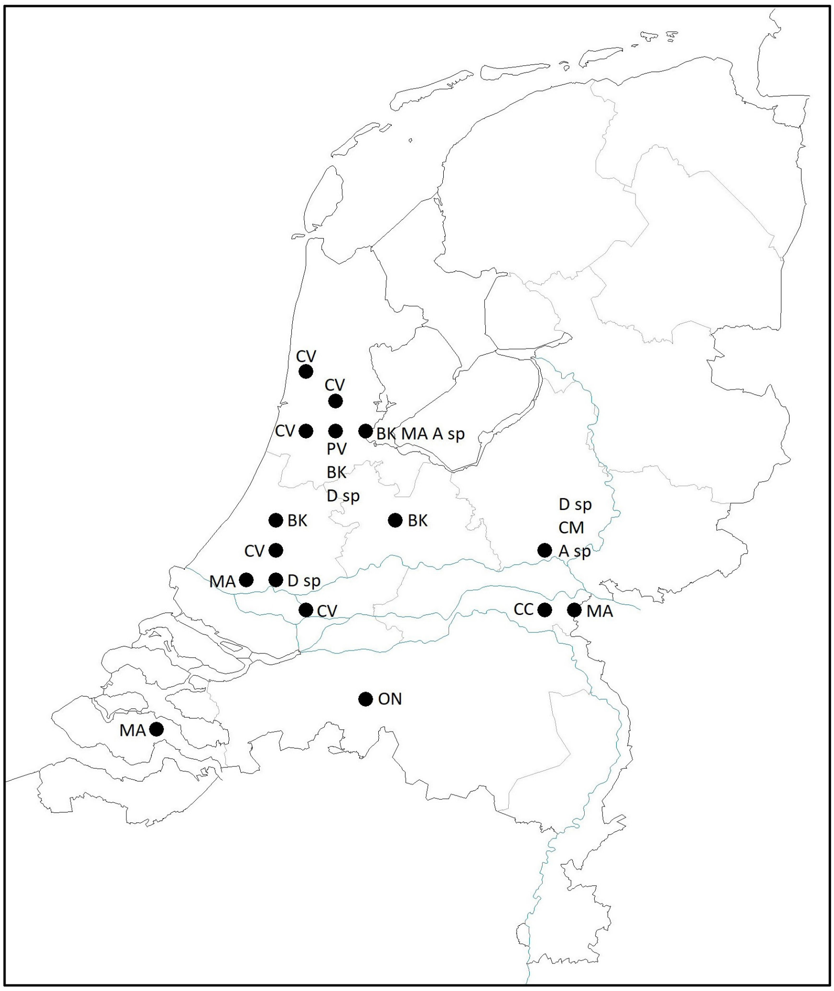

Figure 3. Distribution of alien terrestrial planarian species in The Netherlands (A sp = *Anisorynchodemus* sp; BK = *Bipalium kewense*; CC = *Caenoplana coerulea*; CM = *Caenoplana* cf. *micholitzi*; CV = *Caenoplana variegata*; D sp = *Dolichoplana* sp. MA = *Marionfyfea adventor*; ON = *Obama* cf. *nungara*; PV = *Parakontikia ventrolineata*). For details see Supplementary material Table S24.

abovementioned introduction route). However, escape from gardens and greenhouses is also possible, as well as via disposal of garden waste and plants, and unintentionally release of individual planarians in nature (Winsor 1983; Jones and Sluys 2016). Subsequently, species can spread themselves through natural distribution mechanisms and through large-scale soil movement and landscaping by human activities (Mather and Christensen 1996; Boag and Neilson 2014).

Impact risk inventory of alien terrestrial planarian species

Based on literature review, we concluded that terrestrial planarians can negatively affect biodiversity and agriculture by predating on earthworms and other invertebrates (Alford et al. 1995; Boag 2000). A decrease in density of earthworms affects fertility and infiltration capacity of the soil, which in turn affects biodiversity and crop productivity. Quantitative data, however, on such effects are scarce or non-existent for several species. Murchie and Gordon (2013) showed that *A. triangulatus* could reduce earthworm biomass by 20% in a grassland in Ireland. As *A. triangulatus* prefers small earthworms, it bypasses the normal predator-prey dynamics, which mainly involve predation on large individuals (Murchie and Gordon 2013). This could potentially lead to severe local reductions in earthworm populations that may not fully recover if *A. triangulatus* stays present. Other earthworm-dependent animals can also be adversely affected by earthworm-consuming alien terrestrial planarians. Earthworms are an important food resource for many animals, including insects, birds, reptiles and medium-sized mammals (Alford et al. 1995; Boag 2000; Andriuzzi 2015).

Pendulous earthworm species such as *Lumbricus terrestris* Linnaeus, 1758 play a role in soil permeability (Faber and Van der Hout 2009; Van Eekeren et al. 2014). These earthworms dig vertical tunnels in the soil, which ensures water regulation by the infiltration of rainwater in the soil. These tunnels provide access to deeper soil layers for roots as well. Due to this access, available water and nutrients can be better utilized by crops. In view of climate change, which is expected to cause heavier periods of rainfall and longer periods of drought, these types of ecosystem services are of great value to agriculture (Faber and Van der Hout 2009; Van Eekeren et al. 2014). A reduction in earthworm densities can affect grassland productivity (Murchie and Gordon 2013; Van Groenigen et al. 2014), with an expected 6.8% decrease in grass yield with high economic costs (Murchie 2017). Therefore, *A. triangulatus* has been considered an indirect plant pest by the European and Mediterranean Plant Protection Organization (EPPO) (IPPC-Secretariat 2005).

Furthermore, alien terrestrial planarian species that prey on other invertebrates besides earthworms can also negatively affect biodiversity and ecosystem functioning (Murchie and Weidema 2013). *Platydemus manokwari*, for example, was deliberately introduced as biological control of the snail *Achatina fulica* (Férussac, 1821) (Sugiura et al. 2006). However, *P. manokwari* is now considered to be the cause of the extinction of endemic land snails on various islands in the Pacific (Sugiura and Yamaura 2009). In an experimental setting, over 50 % and 90% of the living snails were dead during a period of 3 to 11 days, respectively, and this was mainly caused by predation due to *P. manokwari* (Sugiura et al. 2006). In this experimental setting on Chichijima, Ogasawara (Bonin) Islands, snails were placed in areas where snails were absent and *P. manokwari* was present. The high predation pressure on terrestrial snails can prevent the recovery of snail populations (Justine et al. 2014).

In theory, alien terrestrial planarians may cause similar damage in greenhouses as outside of greenhouses. However, most greenhouses are well maintained by, for example, removing leaf litter and population control of (unwanted) hitchhikers, which probably limits the effects of terrestrial planarians (Choate and Dunn 2012; H. Jones *pers. comm.*). Williams et al. (2010) indicated that good hygiene measures are already applied in most nurseries and therefore there are no additional costs for removing established terrestrial planarian populations.

Little is known about the human health consequences caused by alien terrestrial planarians. The mucus of *A. triangulatus* can cause skin irritation by touching the worms (EPPO 2001). This skin irritation is caused by the breakdown products of enzymes and neuropeptides that this planarian species secretes. In most cases, this resulted in mild symptoms, like skin irritation (Blackshaw and Stewart 1992). Another health risk is posed by *P. manokwari*. This species may be involved in the life cycle of the lungworm *Angiostrongylus cantonensis* (Chen, 1935), the cause of angiostrongyliasis in humans (Chaisiri et al. 2019).

Risk assessment of alien terrestrial planarian species

Taking into account the above-mentioned potential effects, impacts of alien terrestrial planarian species were assessed using the Harmonia$^+$ protocol. The risk assessment outcomes indicated that *Arthurdendyus albidus*, *Arthurdendyus australis, A. triangulatus*, *Australoplana sanguinea, B. kewense*, *Dolichoplana striata*, *O. nungara, P. ventrolineata* and *P. manokwari* can have negative impacts on biodiversity and soil quality by reducing earthworm populations (Tables S1–S23). Only *A. triangulatus* showed a high overall risk score (Table 2), due to its ability to reduce earthworm populations and to potentially survive outdoors in The Netherlands. *Obama nungara* has a medium overall risk score. All other species have a low overall risk score. Due to the limited availability of quantitative information about terrestrial planarians and their impact, the certainty of most risk scores is low to moderate (Tables S1–S23).

Table 2. Risk assessment of alien terrestrial planarians performed with the Harmonia⁺ protocol. Both the maximum value and the average value per effect category were used to calculate a risk score. Colour scheme: Red, orange and yellow colour indicate that Harmonia⁺ risk scores (RS) were > 0.66, ≤ 0.66 RS ≥ 0.33 and < 0.33, respectively.

Species	Introduced in The Netherlands	Overall risk score according to Harmonia⁺ protocol		Potential survival under current climate conditions in The Netherlands	Food source (Thunnissen et al. 2020)
		Maximum	Average		
Anisorhynchodemus sp.[1]	Yes	0.00	0.00	0	Unknown
Arthurdendyus albidus	No	0.16	0.03	++	Earthworms
Arthurdendyus australis	No	0.16	0.03	0	Earthworms
Arthurdendyus triangulatus	No	0.79	0.14	++	Only earthworms
Artioposthia exulans	No	0.00	0.00	++	Unknown
Australoplana sanguinea	No	0.32	0.04	++	Earthworms
Bipalium kewense	Yes	0.13	0.02	--	Earthworms and other invertebrates
Caenoplana coerulea	Yes	0.16	0.03	-	Invertebrates
Caenoplana decolorata	No	0.00	0.00	-	Unknown
Caenoplana micholitzi[1]	Yes	0.00	0.00	0	Slugs
Caenoplana purpurea	No	0.00	0.00	0	Unknown
Caenoplana variegata	Yes	0.16	0.03	++	Invertebrates
Diversibipalium multilineatum	No	0.25	0.03	+	Earthworms
Dolichoplana sp.[1]	Yes	0.00	0.00	0	Unknown
Dolichoplana striata	No	0.00	0.00	0	Earthworms
Kontikia andersoni	No	0.00	0.00	0	Unknown
Marionfyfea adventor	Yes	0.00	0.00	++	Unknown
Obama nungara	Yes	0.50	0.06	++	Earthworms
Parakontikia atrata	No	0.00	0.00	0	Scavenger
Parakontikia coxii	No	0.00	0.00	0	Unknown
Parakontikia ventrolineata	Yes	0.16	0.01	++	Earthworms and other invertebrates
Platydemus manokwari	No	0.25	0.06	+	Earthworms

[1]To be confirmed by DNA analyses; ++: can certainly survive, +: is likely to survive, 0: unknown, -: is unlikely to survive, --: cannot survive.

Climate match

Based on the Köppen-Geiger classification system, alien terrestrial planarians are expected to be able to survive outdoors in The Netherlands when they already occurred outdoors in other countries with the same Cfb climate. For eleven species it was unknown whether they can maintain and establish populations under the current Dutch climatic conditions, since so far, they have only been found in greenhouses (Table 2). Three species are known to survive in the Dutch climate. Eight more species were already observed outdoors in Europe and will most likely survive Dutch winters. For these predictions, it is assumed that there will be sufficient humid localities for establishment of populations. Drought may prevent establishment and even strongly reduce the populations and impact of terrestrial planarians.

Available management measures and control strategies

The introduction and spread of potentially invasive terrestrial planarians can be reduced by checking the imported (soil of) pot plants for possible hitchhikers (Álvarez-Presas et al. 2014; NVWA 2019). Research shows that phytosanitary measures, such as soil decontamination and heat treatment of contaminated soil, are useful to limit the unintentional import of invasive alien species (Sugiura 2008; NVWA 2019). Raising awareness of the potential effects of alien terrestrial planarians among citizens through the communication of reliable information may also reduce the spread of these species (Pieters et al. 2018). Through monitoring and further research on the probable effects and distribution of alien terrestrial planarians, more knowledge can be gained for an improved risk assessment and management of these species, as this knowledge could help to prioritize measures by stakeholders to prevent the introduction and spread of unwanted species.

Discussion

Current and expected distribution

Based on the available information, *C. variegata, M. adventor* and *P. ventrolineata* are the only species that have established outdoor populations in The Netherlands. In Europe, most alien terrestrial planarian species have been found in greenhouses. However, the distribution of alien terrestrial planarians in Great Britain indicates that a number of species could establish in the wild. Especially *A. triangulatus* has the potential to establish outdoors as well as to become invasive in The Netherlands. Since terrestrial planarians have not been regularly surveyed in The Netherlands, the precise number of alien species that have already established outdoors and the exact distribution of established species are unknown.

Alien terrestrial planarians have been observed in Europe since the 19th century. *Bipalium kewense* was first observed in Kew Gardens in England in 1877 (Winsor 1983). The first report of an alien terrestrial planarian in The Netherlands in 1912 also concerns *B. kewense* (Nederlands Soortenregister 2020a). The comparison of first introduction trends in The Netherlands, France and the United Kingdom (Figure 2) indicates that the latter country may be considered an important area for primary introductions of alien terrestrial planarians that subsequently spread to other countries within Europe. The United Kingdom, Australia and New Zealand are part of the Commonwealth of Nations, a cooperation agreement, resulting in a large trade volume between those countries (Dynes et al. 2001). Another reason for the great number of records for introduced species of land flatworms in the United Kingdom and France may lie in the fact that in both countries research groups have been more active, and for longer periods of time, in the monitoring of terrestrial, alien planarians. Furthermore, the number of first observations of terrestrial planarians originating from Australia seems to increase from 1970. This may be the result of an increase in the import of plants from Australia and New-Zealand, which were very popular in the United Kingdom since the founding of the Commonwealth of Nations (H. Jones *pers. comm.*). Moreover, the availability of (historical) taxonomic knowledge to both professional experts and amateur scientists increased, as well as their time which they could spent in field biology (H. Jones *pers. comm.*). Globalization and climate change may lead to a further increase of introductions and of establishment of alien planarian species in the future (Hellman et al. 2008; Hulme 2009; Drew et al. 2010). Climate change may facilitate establishment of hitchhiking species from warmer areas, because, unlike deliberately imported species, these species prefer a warmer climate and will therefore be able to survive winters in The Netherlands in the future.

Possible impact of alien terrestrial planarians

According to literature, alien terrestrial planarian species can adversely affect native biodiversity and ecosystem functioning. However, information to quantify these effects is scarce. Effects on biodiversity and ecosystems can influence each other. Changes in biodiversity can induce changes in the functioning of the ecosystem (Verbrugge et al. 2015), which may explain the comparable risks for effects of alien species on biodiversity and ecosystems. Effects on ecosystem services are in general less quantified. Since ecosystem services are intertwined with biodiversity and ecosystem functioning, it is important to quantify the risk on effects of alien species on ecosystem services as well. On the other hand, it is difficult to state that impacts of alien species on biodiversity will translate into impacts on, for example, the functioning of ecosystems or ecosystem services. This is partly due to the limited insight in the ecological functioning of native species.

A large part of the available information about the potential effects of terrestrial planarians is anecdotal. For example, there are stories of farmers who notice that seagulls no longer follow the ploughs after the earthworm populations have been depleted due to the presence of alien terrestrial planarians. However, it is not possible to draw firm conclusions from this kind of anecdotical information. Populations of earthworm-eating birds, such as the lapwing *Vanellus vanellus* (Linnaeus, 1758), are declining in the United Kingdom and elsewhere in Europe. This is likely the result of changes in agricultural practices and not of the introduction of alien terrestrial planarians (Cannon et al. 1999), but predators of earthworms could have an additional negative impact on lapwing populations. There are ample indications, though, that earthworm species are vulnerable to predation by *A. triangulatus* (Lillico et al. 1996). As long as there is a lack of knowledge about effects on native species, it is recommended considering the precautionary principle to prevent introduction and spread of species that have been identified as posing a high probability of establishment and high risk on adverse environmental impact. Moreover, the body of knowledge on the invasion biology of terrestrial planarians is rapidly evolving. Therefore, it is recommended to regularly reassess the potential risks of species for which little information is currently available or the risk scores are uncertain.

Based on the risk assessment with the Harmonia+ protocol, the risk score of *A. triangulatus* is high (Table 2). This species is also already listed as an invasive alien species of European Union concern (European Commission 2019). *Arthurdendyus triangulatus* could have the same invasion pattern as other alien terrestrial planarians, such as *B. kewense*. *Bipalium kewense* has still not been observed outdoors, such as in gardens and parks after a long residence period in the United States (Cannon et al. 1999). On the other hand, *A. triangulatus* could be in the early stages of colonization, and is likely to be introduced from the United Kingdom or from its native regions, into continental Europe, including The Netherlands. In many cases it is impossible to deduce to what extent the increase in observations of, for example, *A. triangulatus* represents a true distribution. It is likely that due to more media attention for certain species in newspapers, magazines, websites and other media reports, more observers are aware and therefore new locations and more individuals will be observed. However, information about (alien) terrestrial planarians remains scarce, as compared to other animal groups. For example, information about the environmental factors that determine survival and reproduction are scarce. Without this information, it is also not possible to make a reasonable estimate of the potential spread of alien terrestrial planarians (Cannon et al. 1999).

Management strategies

Once an invasive alien species has established, control is often difficult, if not impossible. Therefore, the cost for controlling invasive alien species can be high (De Hoop et al. 2016). The costs of alien terrestrial planarians are mainly caused by their effect on agriculture as some of them are ferocious earthworm predators and can thus reduce earthworm densities. Quantifying these economic effects is difficult. For example, the contribution of earthworms to ecosystem services is estimated to be 1 billion euro per year in Ireland (Bullock et al. 2008). Earthworms contribute to 34% of grass biomass (Van Groenigen et al. 2014). In areas infected by alien terrestrial planarians, earthworm populations can be reduced by up to 20% (Murchie and Gordon 2013). Based on this information, introduction of *A. triangulatus* could thus result in a reduction of 6.8% in grass biomass production. Boag (2000) predicted a loss of £7 and £42 per ha (approximately €7.7 to €46.4) due to *A. triangulatus,* noting that more information was needed to give a better estimate. Extrapolations from known data estimate potential annual losses of £17 million (approximately €18.8 million) in Scotland. Currently, farmers do not associate the reduction in grass yield with earthworm reduction due to predation of alien terrestrial planarians, but with weather conditions and fertilizer problems (Roy et al. 2018).

The effects of alien terrestrial planarians in horticulture are also hardly quantified. Negative publicity of a terrestrial planarian infestation in a garden centre or nursery could potentially influence sales (Roy et al. 2018). Phytosanitary measures to reduce the risk of spreading alien terrestrial planarians will also entail costs (Alford 1998). Imports of alien terrestrial planarians from outside the EU are expected to decrease in the coming years due to generic phytosanitary legislation, such as restrictions on soil displacement, designed to prevent the import of pests and diseases. Williams et al. (2010) indicated that good hygiene at plant nurseries and horticultural suppliers is necessary to control the spread of the alien terrestrial planarians. Since good hygiene practices are already standard practice, Williams et al. (2010) estimated that only minor additional costs are associated with controlling the spread of alien terrestrial planarians. Nevertheless, additional measures are needed, such as monitoring, spreading information and communication as there is a possibility that more alien terrestrial planarians have already established in the EU.

Recommendations for further research

Although the first alien terrestrial planarian was already recorded from the United Kingdom in 1877 and in 1912 from The Netherlands, there is almost no (quantitative) information about their effects on the environment and public health in spite of their long-time occurrence. Despite the long-term presence of alien terrestrial planarians, no clear effects have been observed. In order to avoid unnecessary costs, more research and monitoring is needed to get a better insight in the distribution and impacts of alien terrestrial planarians. In particular, structural monitoring of the presence of high-risk species groups in imported potted plants and soil, as well as in nature, can be valuable to prevent or signal invasions at an early stage. Furthermore, research on species characteristics of alien terrestrial planarians, such as food sources, and linking those to the current database makes it possible to unravel relationships with species distribution status and invasiveness. This knowledge can be applied in pre-screening of alien species. Development of quantitative methods for assessing the effects and risk of alien planarian species could also help with pre-screening of alien species.

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Authors' contribution

N.W. Thunnissen: Research conceptualization, Sample design and methodology, Investigation and data collection, Data analysis and interpretation, Writing: Original Draft; S.A. de Waart: Investigation and data collection, Data analysis and interpretation, Writing: Original Draft; F.P.L. Collas: Research conceptualization, Data analysis and interpretation, Writing: Review & Editing. E. Jongejans: Data analysis and interpretation, Writing: Review & Editing; A.J. Hendriks: Acquiring funding, Data analysis and interpretation, Writing: Review & Editing; G. van der Velde: Investigation and data collection, Data analysis and interpretation, Writing: Review & Editing. R.S.E.W. Leuven: Acquiring funding, Research conceptualization, Data analysis and interpretation, Writing: Original Draft, Supervision.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Risk assessment of alien terrestrial planarian species for The Netherlands using Harmonia⁺.
Table S2. Risk assessment of *Anisorhynchodemus* sp. in The Netherlands using Harmonia⁺.
Table S3. Risk assessment of *Arthurdendyus albidus* in The Netherlands using Harmonia⁺.
Table S4. Risk assessment of *Arthurdendyus australis* in The Netherlands using Harmonia⁺.
Table S5. Risk assessment of *Arthurdendyus triangulatus* in The Netherlands using Harmonia⁺.
Table S6. Risk assessment of *Artioposthia exulans* in The Netherlands using Harmonia⁺.
Table S7. Risk assessment of *Australoplana sanguinea* in The Netherlands using Harmonia⁺.
Table S8. Risk assessment of *Bipalium kewense* in The Netherlands using Harmonia⁺.
Table S9. Risk assessment of *Caenoplana coerulea* in The Netherlands using Harmonia⁺.
Table S10. Risk assessment of *Caenoplana decolorata* in The Netherlands using Harmonia⁺.
Table S11. Risk assessment of *Caenoplana micholitzi* in The Netherlands using Harmonia⁺.
Table S12. Risk assessment of *Caenoplana purpurea* in The Netherlands using Harmonia⁺.
Table S13. Risk assessment of *Caenoplana variegata* in The Netherlands using Harmonia⁺.
Table S14. Risk assessment of *Diversibipalium multilineatum* in The Netherlands using Harmonia⁺.
Table S15. Risk assessment of *Dolichoplana striata* in The Netherlands using Harmonia⁺.
Table S16. Risk assessment of *Dolichoplana* sp. in The Netherlands using Harmonia⁺.
Table S17. Risk assessment of *Kontikia andersoni* in The Netherlands using Harmonia⁺.
Table S18. Risk assessment of *Marionfyfea adventor* in The Netherlands using Harmonia⁺.
Table S19. Risk assessment of *Obama nungara* in The Netherlands using Harmonia⁺.
Table S20. Risk assessment of *Parakontikia atrata* in The Netherlands using Harmonia⁺.
Table S21. Risk assessment of *Parakontikia coxii* in The Netherlands using Harmonia⁺.
Table S22. Risk assessment of *Parakontikia ventrolineata* in The Netherlands using Harmonia⁺.
Table S23. Risk assessment of *Platydemus manokwari* in The Netherlands using Harmonia⁺.
Table S24. GPS coordinates of Figure 3. Distribution of alien terrestrial planarian species in The Netherlands.
Table S25. Questions for interviews with experts.

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