A multiregional assessment of transnational pathways of introduction

Chris M. McGrannachan[1], Shyama Pagad[2] and Melodie A. McGeoch[3]

[1]Manaaki Whenua – Landcare Research, 231 Morrin Rd, St. Johns, Auckland, 1072, New Zealand; [2]Invasive Species Specialist Group, Species Survival Commission, International Union for Conservation of Nature, University of Auckland, 1072 Auckland, New Zealand; [3]Department of Ecology, Environment and Evolution, School of Life Sciences, La Trobe University, Melbourne 3086, Australia

Corresponding author: *Chris M McGrannachan* (mcgrannachanc@landcareresearch.co.nz)

Abstract

Information on the pathways by which alien taxa are introduced to new regions is vital for prioritising policy and management responses to invasions. However, available datasets are often compiled using disparate methods, making comparison and collation of pathway data difficult. Using a standardised framework for recording and categorising pathway data can help to rectify this problem and provide the information necessary to develop indicators for reporting on alien introductions. We combine the Convention on Biological Diversity's Pathways Categorisation Scheme (CPC) with data compiled by the Invasive Species Specialist Group (ISSG) to report on multiregional trends on alien introduction pathways over the past 200+ years. We found a significant increase in the documented number of multiregional alien introduction events across all pathways of the CPC's three hierarchical levels. The 'escape' pathway is the most common documented pathway used by alien taxa. Transport stowaways via shipping-related vectors are a rapidly increasing contribution to alien introductions. Most alien introduction events were of unknown pathway origin, highlighting the challenge of information gaps in pathway data and reiterating the need for standardised information-gathering practices. Combining the CPC framework with alien

introduction pathways data will standardise pathway information and facilitate the development of global indicators of trends in alien introductions and the pathways they use. These indicators have the potential to inform policy and management strategies for preventing future biological invasions and can be downscaled to national and regional levels that are applicable across taxa and ecosystems.

Keywords: Aichi Target 9, alien taxa, Convention on Biological Diversity, introduction event, introduction pathway, propagule pressure

Introduction

Expansion and increased intensity of global trade and human movement has exacerbated global species invasions (Essl et al. 2015, Early et al. 2016). Worldwide increases in the number of alien species are likely to continue (Seebens et al. 2017), meaning it is crucial that the pathways by which alien species are transported and introduced to new locations, and how these change in relative importance over time, are identified, understood and better managed (Essl et al. 2015, Chapman et al. 2017). Pathways of introduction are the means by which alien species are transported intentionally or unintentionally outside of their natural geographic range (Richardson et al. 2010, Turbelin et al. 2017). A pathway approach to risk assessment for invasive alien species focuses primarily on identifying introduction pathways to (i) develop early detection and preventative strategies, with the aim to reduce or eliminate the propagule pressure of alien species (Faulkner et al. 2016, Padayachee et al. 2017, Pergl et al. 2017), and (ii) to prioritise investment in managing pathways responsible for the highest propagule loads or particular high risk species (McGeoch et al. 2016). This approach is particularly important in the absence of species-specific data, or when suitable control efforts for individual species are unachievable (Hulme et al. 2008, Padayachee et al. 2017). Accounting for introduction pathways is therefore fundamental for developing relevant management and policy strategies that minimise the introduction, spread and impact of alien species (Hulme et al. 2008).

Efforts to categorize alien species via their pathways of introduction have culminated in the development of a standardised pathway categorisation framework (Harrower et al. 2017). Using this framework, pathways of introduction and spread are classified as intentional or unintentional and encompass three introduction mechanisms: the importation of a commodity, the arrival via a transport vector (through a dispersal corridor resulting from human activity), and the natural spread from a neighbouring region where the species is alien

(UNEP 2014, Essl et al. 2015). The foundation of this framework is the six pathway introduction categories (release, escape, transport-contaminant, transport-stowaway, corridor and unaided) originally proposed by Hulme et al. (2008), which encompass 32 specific vectors of introduction (for example, agriculture, horticulture and ship ballast water). This 'Convention on Biological Diversity (CBD) Pathways Categorisation' (CPC) (*sensu* Harrower et al. 2017) incorporates standardised terminology and guidelines for pathway categorization and is applicable at a global scale and across different taxonomic groups (Harrower et al. 2017, Tsiamis et al. 2017). The CPC has now been validated by application to alien introductions at national (South Africa; Faulkner et al. 2016), continental (Europe; Pergl et al. 2017, Tsiamis et al. 2017) and global scales (167 cities worldwide; Padayachee et al. 2017). Importantly, the intention of this scheme is, *inter alia*, to assist global reporting as well as country Parties to the CBD to respond to the Strategic Plan for Biodiversity 2011-2020 (UNEP 2014). In particular, this is relevant to achieve and report on Aichi Target 9 by 2020, such that *invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated and measures are in place to manage pathways to prevent their introduction and establishment* (Convention on Biological Diversity 2010). Whereas monitoring pathways of invasion was not included in the previous global indicator framework for invasive alien species (McGeoch et al. 2010), doing so has now become central to reporting on policy targets for biological invasion (McGeoch and Jetz 2019).

Developing information on pathways introductions using a standardised framework is currently a priority for several reasons. First, preventing the introduction and spread of alien and potentially invasive species is the first line of defence in the management of biological invasions. Managing the early stages of the invasion process (i.e. transport and introduction) that focus on prevention is more cost-effective than reactive, post-introduction management of species (Leung et al. 2002, Rout et al. 2011, Kumschick and Richardson 2013).

Nonetheless, management, policy and research that targets the transport and introduction stages of invasion remain relatively underrepresented compared to the invasion stages of establishment and spread (Puth and Post 2005, Early et al. 2016, Chapman et al. 2017).

Second, information on the pathways of species introductions has not, to date, been consolidated into a readily available or accessible form (Saul et al. 2017). Harmonising and identifying discrepancies between data sources is crucial for informing alien species policy and management (Seebens et al. 2020). For example, a recent comparison of European pathway data between the European Alien Species Information Network (EASIN) and the CPC revealed that the pathway subcategories of ~ 5,500 alien species registered with EASIN did not directly align with CPC subcategories (Tsiamis et al. 2017). These types of discrepancies can compound the already high level of uncertainty when identifying and assigning pathways to individual species introductions, particularly for unintentional pathways (e.g. transport-contaminant; transport-stowaway) that may be inadequately documented (Essl et al. 2015).

Third, information on introduction pathways contributes directly to biosecurity policy and regulations, including regulating the criteria for the import and trade of alien species (Burgiel et al. 2006, Leung et al. 2014, Hulme 2015). For example, a blacklist (banned from importation) or whitelist (permitted importation) approach has been adopted by many countries as a response to the global trade in ornamental nursery stock, which is the primary means of introduction of alien plants (Dehnen-Schmutz 2011, Essl et al. 2011, Hulme et al. 2017). Pathway information informs prioritisation of biosecurity interventions by identifying pathways that pose relatively high invasion risk in terms of both propagule load (Brockerhoff et al. 2014) and high risk species (Pergl et al. 2017, Roy et al. 2014) and further informing the development of preventative management strategies and policy at multiple scales (Pyšek et al. 2011, Faulkner et al. 2016). However, few comprehensive pathway-focused policies have

been implemented at any administration level, and those that are in place tend to target the release and escape pathways (Essl et al. 2015).

Finally, information on pathway changes over time can, with appropriate modelling and interpretation (McGeoch and Jetz 2019), be used to develop indicators for reporting on alien introduction trends (Rabitsch et al. 2016, Wilson et al. 2018). While the importance of some pathways can remain constant over several decades (e.g. shipping), other pathways (e.g. horticulture) may increase in importance (Ojaveer et al. 2017, Zieritz et al. 2017). These changes may reflect updated legislation for the importation of species, or the increasing global trade of certain commodities (Zieritz et al. 2017, Seebens et al. 2018), and are important for monitoring the effectiveness of biosecurity policy and implementation, such as Aichi Biodiversity Target 9 as well as Sustainable Development Goal 15.8 (Rabitsch et al. 2016).

To date, pathway analysis has been conducted for specific regions (e.g. South Africa, Europe; Faulkner et al. 2016, Pergl et al. 2017), environments (e.g. urban; Padayachee et al. 2017), taxonomic groups (e.g. invertebrates, plant pests; Chapman et al. 2016, Houghton et al. 2016) or specific pathway(s) (Kumschick et al. 2016, Tingley et al. 2018). Although several assessments have shown changes in pathways of invasion over time (Rabitsch et al. 2013, Ojaveer et al. 2017, Zieritz et al. 2017), these are restricted to specific taxonomic groups or geographic locations (but see Rabitsch et al. 2016). Building on these regional and taxon-specific efforts, here we conduct a cross-taxonomic, multiregional analysis of information available on transnational introduction pathways, that incorporates all major groups, environments and pathways, to quantify decadal trends in invasion reported via these pathways since 1800. We use a hierarchical, standard categorisation of pathways (Harrower et al. 2017) so that the results may in future be appropriately modelled, compared, downscaled to regions and countries, and form a baseline for future reporting of trends in

invasion pathways. We specifically ask (1) are recorded invasive alien species introductions largely intentional or unintentional? (2) What pathways of introduction and spread are responsible for alien species introductions? (3) What vectors are alien species using to move about?

Methods

Data used

Introduction records compiled from the Global Register of Introduced and Invasive Species (GRIIS) by the ISSG were used as the underlying data for the analysis of pathway trends. The GRIIS dataset provides verified and annotated country checklists of alien and invasive species (Pagad et al. 2018). In addition to species names, each record includes taxonomy, the environment/system in which the species occurs, the provenance/origin of the species, evidence of impact (yes/no), date of introduction or first record, type of introduction, pathways of introduction, mechanism of impact, and references for source information. GRIIS Version 2016.2 includes draft checklists for all 196 countries that are party to the CBD.

Data for 18746 introduction events, involving 4832 alien species in 101 countries, and occurring between the years 1300 and 2017, were available and adequate to conduct a pathways assessment (Fig. 1 – map). Here we define an introduction event as a recorded introduction of an alien species in a country outside of its native range. Each introduction event included the date of first introduction or first record of a species and contained data on either all or some of the following information types: (1) introduction being intentional or unintentional (i.e. ‘pathway type’); (2) ‘pathway category’ (escape, release, transport as contaminant or stowaway, corridors, unaided or unknown); (3) vectors (further details of specific vectors within each pathway category, (i.e. ‘pathway subcategory’). The data include

157 Animalia, Bacteria, Chromista, Fungi, Plantae, Protozoa and Virus taxa. The 101 countries
158 cover six regions: Africa, Asia, Europe, North America, Oceania and South America (Figure
159 2; Table S1). These countries encompass a range of different sizes, development status and
160 climatic regions and thus are geographically representative of global data.

161 A further 5113 species are known to be introduced to the selected 101 countries via
162 known pathways but were not included in analysis as they do not have authoritative
163 information on dates of introduction or first record. These species were therefore excluded
164 and we concentrated on the 4832 species for which the date of introduction in these 101
165 countries is known. The total number of introduction events currently estimated is ~ 98422,
166 involving ~ 10800 species (including the 5113 species mentioned above). These events,
167 besides known invasive species, include weeds, agricultural pests and diseases, and other
168 non-invasive aliens for which no pathway information or dates of introduction are known.

169 Information and data on pathways of introduction were extracted during 2016/2017
170 from sources used to compile national checklists (see Pagad et al. 2018 for information on the
171 general data collation and entry process). Information sources ranged from scientific peer-
172 reviewed literature, databases, reports both published and unpublished and research data.
173 Textual information describing pathways of introduction were documented and then reviewed
174 for categorisation. These categories were inserted into the data collection templates. Because
175 the CPC is relatively new, some of the information from the data sources used pathway
176 terminology that did not fully align with the CBD framework. In these cases, it was necessary
177 to interpret the pathways within the CBD framework, using literature-based pathway
178 information as a guide. This enabled all data to be compiled using the standard categorisation
179 of pathways endorsed by the Parties to the CBD (UNEP 2014). These categories were
180 inserted into the data collection templates.

Information on dates of introduction or first record and information related to the three levels of the pathway hierarchy for the actual introduction event were recorded - pathway type, pathway category and pathway subcategory. Each introduction event was temporally classified using centuries and decades as classifiers (Appendix S1). First introduction records were aggregated by decade beyond 1800. Decadal scales are appropriate because there is often a lag between detection and reporting events. All records prior to 1800 were aggregated as 'Pre-1800'. Records from the most recent decade were classified as '2011 plus'.

Pathway categorisation

We used the definitions and descriptions of introduction pathways contained in Harrower et al. (2017). This document is the most up-to-date guideline for interpreting the definitions of the CPC and provides examples of the CBD Pathways Categorisation's application to species information (Harrower et al. 2017). The definitions and descriptions were revised and modified by a panel of experts, using comparisons of the CPC pathway descriptions to descriptions used in (1) the Global Invasive Species Database (GISD), (2) the Delivering Alien Invasive Species Inventories for Europe (DAISIE) database, (3) the Great Britain's Non-Native Species Information Portal (GBNNSIP) database, and (4) the EASIN information platform (Harrower et al. 2017). Of particular benefit is the distinction between pathway subcategories that appear to overlap. For example, the 'Contaminant on Plants' subcategory seemingly overlaps with the 'Contaminant nursery material' and 'Transportation of habitat material' subcategories. The Harrower et al. (2017) guideline defines and describes the difference between these pathways and treats them in a prescribed order of precedence for category allocation. For example, the 'Contaminant on plants' subcategory is defined to contain all contaminants on plants that are not related to the nursery trade, where 'Contaminated nursery material' is given precedence over 'Contaminant on plants' (Harrower

et al. 2017). Despite some shortcomings of the CPC framework, particularly the uncertainty involved in interpreting some subcategories (Faulkner et al. 2020, Pergl et al. 2020), it is a reliable framework with which to report on introduction trends at a transnational level. The CPC framework is still relatively new (2014) and its further development and adoption will facilitate its use as a standardised tool for reporting on alien introductions (Pergl et al. 2020).

Analysis of trends

For pathway types (i.e. intentional or unintentional introductions), we report trends in terms of both total recorded introduction events for each decade, as well as cumulative introduction events documented between 1800 and 2017. Pathway categories are reported as total number of introduction events per decade for each category. We also report cumulative introduction events for pathway categories, using 1970 as a baseline year. This date was chosen for its comparability with the 1970 baseline used for CBD global biodiversity indicators in Butchart et al. (2010). The dominant pathway subcategories are reported as cumulative introduction events from 1800 to 2017.

We used generalized linear models (negative binomial distribution with log link function) to quantify changes in the recorded number of introduction events over time (introduction events ~ decade). This was conducted at all introduction pathway levels (pathway type, pathway category, pathway subcategory). For subcategories, only the pathways with more than 100 introduction events (n = 18 subcategories) were considered.

Results

Pathway types

There was a total of 8172 (43.59%) intentional and 10574 (56.41%) unintentional documented introduction events of alien species across the 101 countries (Table 1). Since 1800, steady and significant increases in both documented intentional and unintentional introduction events have occurred (Table 2; Figure 3a, b). From 1800 to 1900, both pathway types showed similar cumulative increases in introduction events, but with more documented intentional introduction events than unintentional events (Figure 3b, Table 3). Post 1900, the overall number of documented unintentional introductions per decade was higher than intentional introductions (Figure 3a, b; Table 3). Decadal increases in documented introduction events ranged between 5.79 % (1800 – 1810) and 23.15 % (1860 – 1870) for intentional introductions and between 7.19 % (1800 – 1810) and 24.68 % (1890 – 1900) for unintentional introductions (Table 3). The average decadal increase in intentional and unintentional introductions was 13.12 % and 15.29 %, respectively (Table 3). The decade of 1991 – 2000 had more documented introduction events than any other decade in the time series (Figure 3a).

Pathway categories

The documented number of introduction events for each pathway category has increased significantly per decade since 1800 (Table 2; Figure 4a). The 'escape' pathway is the most prevalent pathway by which species introductions are known to occur (37.84 %), followed by 'unknown' pathway introductions (32.19 %; Table 1; Figure 4a). Post 1970 trends show both escape and unknown pathways increased dramatically in cumulative number of introduction events, with 3177 and 2350 additional events, respectively, occurring between 1970 and 2017 (Figure 4b). This is equivalent to 81.38 % (escape) and 58.14 % (unknown) of the total number of pre-1970 documented introduction events. The remaining five pathway categories had fewer cumulative introduction events compared to escape and unknown pathways, the highest being 'transport-contaminant' (1982 events by 2017) and the lowest 'unaided' (148

255 events by 2017; Figure 4c). Of these five pathways, 'transport-stowaway' showed the
256 steepest cumulative increase in introduction events post 1970 (Figure 4c).

257 **Pathway subcategories**

258 The 18 pathway subcategories with more than 100 introduction events since 1800 ranged
259 from 109 to 7203 records (Table 1). The top 18 subcategories were representative of all
260 pathway categories. 'Unknown' was the pathway subcategory associated with most
261 documented introduction events (7203; 38.42 %), followed by three subcategories from the
262 escape pathway: 'horticulture' (3581; 19.10 %), 'agriculture' (1193; 6.36 %) and
263 'aquaculture/mariculture' (1010; 5.39 %; Table 1; Figure 5a). Many of the subcategories
264 showed sharp rates of increase, particularly from the beginning of the twentieth century,
265 including 'hitchhikers on ships', 'ship ballast water', 'ship hull fouling' and 'interconnected
266 waterways' (Figure 5b, c; Figure S1a). In comparison, most subcategories from the escape
267 pathway (except horticulture) had slower cumulative introduction rates, including
268 'agriculture', 'aquaculture/mariculture', 'forestry', 'ornamental purpose other than
269 horticulture' and 'pet/aquarium species'. All but one subcategory ('release in nature for use')
270 significantly increased in introduction events per decade since 1800 (Table 3).

271 **Discussion**

272 We used the CBD pathways categorisation framework and a multiregional dataset
273 encompassing a range of taxonomic groups to report on decadal changes in introduction
274 pathways reported for alien species since 1800. We highlighted the significant increase of
275 documented events for almost every pathway at each of the three hierarchical levels of the
276 CPC. Unintentional introductions have increased over intentional introductions since the
277 beginning of the twentieth century. However, 'Escape' – an intentional pathway - is the most
278 common pathway category documented, particularly for vectors related to plant and aquatic

cultivation. This shows that intentional pathway vectors are still an important source of alien introductions. The vast majority of documented introduction events, however, have an unknown vector (38.42 %), which emphasises the high level of uncertainty involved in categorising and managing alien species introduction pathways.

Accidental and deliberate introduction events

Prior to the twentieth century, the cumulative rate of increase for both intentional and unintentional introduction events documented were virtually identical (Figure 3b). The beginning of the twentieth century saw unintentional surpass intentional introductions, a trend that has continued up to the present. The increase in unintentional introductions is likely due to the rise in international trade, which is widely acknowledged as an important factor in allowing alien species to successfully establish in novel geographic regions (Levine and D'Antonio 2003, Perrings et al. 2005, Yemshanov et al. 2012, Chapman et al. 2017). In particular, the accidental transport of inconspicuous taxa, such as fungi, microorganisms, pathogens and invertebrates are often associated with global trade, including live plant imports and importation via shipping (Brockerhoff and Liebhold 2017, Chapman et al. 2017, Okabe et al. 2017). Studies from multiple regions including Europe (Chapman et al. 2017, Pergl et al. 2017, Saul et al. 2017), Asia (Hong et al. 2012, Okabe et al. 2017), the US (Liebhold et al. 2012) and the Antarctic (Osyczka et al. 2012, Houghton et al. 2016) have found that these taxonomic groups are more often associated with unintentional pathways. Increases in trade volume and the subsequent rise in accidental introductions of alien species may counteract existing national biosecurity and phytosanitary measures (Brockerhoff and Liebhold 2017). It is therefore important to improve measures for monitoring unintentional introduction pathways to effectively address the ongoing occurrence of accidental alien introductions. Interestingly, although unintentional introductions surpassed intentional

303 introductions, escape (an intentional introduction pathway category) had most associated
304 introduction events (excluding unknown events). This highlights that the prevention and
305 management of intentional introductions are of equal importance to those of unintentional
306 introductions, especially given that the impact realised by alien taxa has been associated more
307 frequently with intentional than unintentional introductions (Pergl et al. 2017).

308 **Introduction pathway categories and their vectors**

309 Our findings corroborate previous studies of alien introduction pathways in several ways.
310 First, 'escape' is overall the most common documented pathway category by which alien
311 species are introduced (Turbelin et al. 2017). Second, 'transport-stowaway' is becoming an
312 increasingly important introduction pathway, particularly for marine stowaways (Zieritz et al.
313 2017). Finally, records of introduction events via unknown pathways are prevalent in existing
314 databases and presents an ongoing problem for assessing alien introductions (Katsanevakis
315 and Moustakas 2018). Our global perspective takes into consideration alien species from
316 multiple taxonomic groups but supports similar findings from studies focussing on specific
317 taxonomic groups or regions.

318 Escape was the most prevalent pathway, with records almost doubling between 1970
319 and the present (Figure 4b). Escape has been identified as the most frequent introduction
320 pathway across all taxa at global (Turbelin et al. 2017) and national (South Africa; Faulkner
321 et al. 2016) scales, for plants at country- (Czech republic; Pyšek et al. 2011; USA; Lehan et
322 al. 2013) and city-scales (Padayachee et al. 2017) and for both plants (Pergl et al. 2017) and
323 vertebrates in Europe (Saul et al. 2017, Roy et al. 2019) and globally (Saul et al. 2017, van
324 Kleunen et al. 2018). Our results corroborate these findings at a multiregional level and
325 emphasise the ongoing need for better containment procedures and greater public awareness

of the risks involving escaped organisms, particularly ornamental plants (Ricciardi et al. 2017, Saul et al. 2017, van Kleunen et al. 2018).

Horticulture is the most important vector of alien plant introductions (Turbelin et al. 2017, van Kleunen et al. 2018) and was the pathway subcategory with the largest and fastest increase in introduction events (Figure 5a). Agriculture was the second most important pathway subcategory and is also recognised as an important contributor to alien plant introductions (Mack and Erneberg 2002, Richardson et al. 2003). Both horticulture and agriculture are pathway subcategories specific to plants (Harrower et al. 2017) and their combined, high proportion of recorded introductions in the dataset (see Table 1) supports previous studies that show escape (from horticulture or agriculture) is an important pathway for plants.

The importance of escape as an introduction pathway for faunal species is reflected by the high number of introduction events attributed to escape from aquaculture/mariculture (e.g. fish farms) compared with the pet/aquarium trade. Aquaculture/mariculture had the third most introduction events, while records attributed to the pet/aquarium trade remained relatively stable across the assessed time-period (Figure 5a). Aquaculture was found to be the highest contributing pathway to freshwater alien species introductions in Europe (Nunes et al. 2015) and an important pathway for alien invasions of European seas (Nunes et al. 2014). The ecological impacts of invasion via aquaculture can be severe (Naylor et al. 2001, Keller et al. 2011) and given the aquaculture sector is one of the fastest growing global primary industries (Teletchea and Fontaine 2014), it is also likely that alien introductions via this pathway will continue to rise.

Vectors of the transport-stowaway category were among those with largest growth in alien introductions since 1970 (Figure 5b). In particular, there was a sharp rise in the post-1970 introduction of marine stowaways as hitchhikers on ships, in ship ballast water or as

ship hull fouling, which saw 67 %, 62 % and 67 %, respectively. The importance of marine/aquatic pathways is also reflected in the sharp rise in introduction events by interconnected waterways since 1970 (Figure S1a). These increases in alien introductions are likely due to the continued expansion of tourism and international shipping (Early et al. 2016, Turbelin et al. 2017). The introduction of marine and freshwater alien taxa via shipping-related transport has been confirmed as an important source of ongoing propagule pressure in many parts of the world, including the Mediterranean region, Northwest Europe, the Northeast Pacific and Australia (Tingley et al. 2017, Zieritz et al. 2017, Anil and Krishnamurthy 2018).

A key challenge in attempting to decipher trends in alien introductions is uncertainty in the specific pathways used by species (Katsanevakis et al. 2013, Essl et al. 2015). This is particularly problematic for unintentional introductions via transport contaminants or stowaways, and for smaller organisms such as marine invertebrates that are at a higher risk of going unnoticed or undocumented (Essl et al. 2015, Ojaveer et al. 2017, Zieritz et al. 2017). The results shown here demonstrate the problem clearly: the total number of introduction events where a pathway category was unknown far exceeded all other known pathway categories (Figure 4b-c). The exception to this was the ‘escape’ pathway, an intentional pathway category that surpassed the number of unknown introduction events (Figure 4b). Furthermore, ‘unknown’ was the highest-ranked pathway subcategory in terms of the number of introduction events and was almost double that of the second-ranked subcategory (Horticulture; Table 1). These results corroborate previous studies that have demonstrated and highlighted the risk that uncertainty poses to introduction pathway datasets and trends (Zenetos et al. 2017, Katsanevakis and Moustakas 2018).

There are several reasons why uncertainty in pathway identification and trends occurs. Often, the lack of historical introduction records (i.e. pre-mid twentieth century; Ojaveer et al.

2017) can result in gaps in datasets that can particularly impact the interpretation of introduction temporal trends (McGeoch et al. 2010, Katsanevakis et al. 2013, Galil et al. 2018). Usually this occurs due to decreased scientific effort or reduced awareness of the need to record alien species introductions (Ojaveer et al. 2017).

In many cases, multiple pathways are equally tenable as the cause of alien species introductions to a new region (Minchin 2007). This makes assigning the correct pathway difficult and decisions may be entirely based on the interpretations or assumptions of assessors (Zenetos et al. 2012). In other instances, the species' ecology may be used to infer an introduction pathway (Zenetos et al. 2012). A representative example of this is the introduction of marine species into the Mediterranean Sea via the Suez Canal. Several pathway vectors could feasibly be responsible for new introductions into the Mediterranean, including species as hitchhikers on ships, through ship ballast water or hull fouling, or through natural, unaided dispersal (Katsanevakis et al. 2013). These types of uncertainty can potentially over- or under-emphasise certain pathways, causing trends to be misrepresented at both global and regional scales. Using a confidence score in allocating pathways may provide a cautionary approach to the compilation of pathway data that helps identify which species, pathways or regions are particularly susceptible to uncertainty (Essl et al. 2015). A focus on improving monitoring of these identified species, pathways or regions may aid efforts to alleviate uncertainty in pathway data. Confidence scores have been successfully integrated into other alien-focused, standardised frameworks, such as the Environmental Impact Classification of Alien Taxa (EICAT; Blackburn et al. 2014, Hawkins et al. 2015) and have recently been used in assessing alien introduction pathways in Europe (Pergl et al. 2020).

The compilation of pathway data from multiple countries or regions can also be a source of uncertainty. Data is often unavailable in many countries, due to a lack of adequate monitoring, data collection efforts or funding (Latombe et al. 2017). Compiling data at

national or regional levels usually requires a well-established network of contacts and managing these networks can expend a great deal of time and effort (Zenetos et al. 2017). Furthermore, having multiple pathway data sources will result in multiple ways in which the data is formatted, leading to discrepancies between data. Enacting a standardised framework such as the CPC to filter and arrange pathway data will ensure that trends in introductions of alien species are reported accurately. This is crucial if pathways of introduction are to be considered as an accurate indicator for alien species invasions (Wilson et al. 2018). Given that trends in pathway introductions change over time and across regions, the accuracy and standardisation (or lack thereof) of data can greatly benefit or hinder monitoring and biosecurity efforts (McGeoch et al. 2016, Latombe et al. 2019).

Developing indicators from standardised pathway data is necessary for accurate reporting of alien introduction trends. These indicators can then be used to identify the shortcomings in invasive alien species management and policy targets and help improve legislation for dealing with biological invasions (McGeoch et al. 2010, Hulme 2015). Predictive tools such as risk assessments and horizon scanning can incorporate pathway indicators to better estimate the susceptibility of regions to invasion and identify those species that will pose the greatest introduction threat (Hulme 2015, Rabitsch et al. 2016). The continual input of new pathway data will be needed to ensure that indicators remain up to date and to prevent policy decisions relying on historical pathway patterns (Latombe et al. 2019). Given that the Strategic Plan for Biodiversity 2011-2020 is coming to an end, and the 2021-2030 phase is about to begin, the development and testing of pathway indicators for tracking invasive alien species trends becomes increasingly urgent (Rabitsch et al. 2016).

Conclusions

425 We propose that the CBD Pathway Categorisation framework is a suitable tool for providing
426 standardised information on alien introduction pathways. This information can then be used
427 to report on pathway trends and their changes across time, taxa, habitats and geographic
428 scales. However, the high number of cases where introduction pathways are unknown will
429 remain a significant challenge to the reporting and documentation of alien introductions
430 (Latombe et al. 2019). Despite this, the CPC framework can enable countries to improve
431 recording and reporting of alien introductions and assist in developing strategies to reduce the
432 impacts of alien introductions beyond the Strategic Plan for Biodiversity 2011-2020.
433

434 **Acknowledgements**

435 MAM acknowledges support from the Australian Research Council (DP200101680).

436 **References**

437 Anil AC, Krishnamurthy V (2018) Ship-mediated marine bioinvasions: need for a
438 comprehensive global action plan. ASEAN Journal on Science & Technology for
439 Development 35: 17-24. https://doi.org/10.29037/ajstd.468

440 Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z,
441 Mrugała A, Nentwig W, Pergl J, Pyšek, Rabitsch W, Ricciardi A, Richardson DM,
442 Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher, S (2014) A unified
443 classification of alien species based on the magnitude of their environmental impacts.
444 PLoS Biology 12: e1001850. https://doi.org/10.1371/journal.pbio.1001850

445 Brockerhoff EG, Kimberley M, Liebhold AM, Haack RA, Cavey JF (2014) Predicting how
446 altering propagule pressure changes establishment rates of biological invaders across
447 species pools. Ecology 95: 594-601. https://doi.org/10.1890/13-0465.1

448 Brockerhoff EG, Liebhold AM (2017) Ecology of forest insect invasions. Biological
449 Invasions 19: 3141-3159. https://doi.org/10.1007/s10530-017-1514-1

450 Burgiel S, Foote G, Orellana M, Perrault A (2006) Invasive alien species and trade:
451 integrating prevention measures and international trade rules. Center for International
452 Environmental Law and Defenders of Wildlife (Washington DC).

453 Butchart SHM, Walpole M, Collen B, van Strien A, Scharlemann JPW, Almond REA, Baillie
454 JEM, Bomhard B, Brown C, Bruno J, Carpenter KE, Carr GM, Chanson J, Chenery
455 AM, Csirke J, Davidson N, Dentener F, Foster M, Galli A, Galloway JN, Genovesi P,
456 Gregory RD, Hockings M, Kapos V, Lamarque J-F, Leverington F, Loh J, McGeoch
457 MA, McRae L, Minasyan A, Hernández Morcillo M, Oldfield TEE, Pauly D, Quader
458 S, Revenga C, Sauer JR, Skolnik B, Spear D, Stanwell-Smith D, Stuart SN, Symes A,

459 Tierney M, Tyrrell TD, Vié J-C, Watson R (2010) Global biodiversity: indicators of
460 recent declines. Science 328: 1164-1168. doi:10.1126/science.1187512

461 Chapman D, Purse BV, Roy HE, Bullock HE (2017) Global trade networks determine the
462 distribution of invasive non-native species. Global Ecology and Biogeography 26:
463 907-917. https://doi.org/10.1111/geb.12599

464 Convention on Biological Diversity (2010) Quick guide to the Aicihi Biodiversity Targets. 9.
465 Invasive species prevented and controlled. Retrieved from
466 https://www.cbd.int/doc/strategic-plan/targets/T9-quick-guide-en.pdf

467 Dehnen-Schmutz K (2011) Determining non-invasiveness in ornamental plants to build green
468 lists. Journal of Applied Ecology 48: 1374-1380. https://doi.org/10.1111/j.1365-
469 2664.2011.02061.x

470 Early R, Bradley BA, Dukes JS, Lawler JJ, Olden JD, Blumenthal DM, Gonzalez P, Grosholz
471 ED, Ibañez I, Miller LP, Sorte CJB, Tatem J (2016) Global threats from invasive alien
472 species in the twenty-first century and national response capacities. Nature
473 Communications 7: 12485. https://doi.org/10.1038/ncomms12485

474 Essl F, Bacher S, Blackburn TM, Booy O, Brundu G, Brunel S, Cardoso A-C, Eschen R,
475 Gallardo B, Galil B, García-Berthou E, Genovesi P, Groom Q, Harrower C, Hulme
476 PE, Katsanevakis S, Kenis M, Kühn I, Kumschick S, Martinou AF, Nentwig W,
477 O'Flynn C, Pagad S, Pergl J, Pyšek, Rabitsch W, Richardson DM, Roques A, Roy
478 HE, Scalera R, Schindler S, Seebens H, Vanderhoeven S, Vilà M, Wilson JRU,
479 Zenetos A, Jeschke JM (2015) Crossing frontiers in tackling pathways of biological
480 invasions. BioScience 65: 769-782. https://doi.org/10.1093/biosci/biv082

481 Essl F, Nehring S, Klingenstein F, Milasowszky N, Nowack C, Rabitsch W (2011) Review of
482 risk assessment systems of IAS in Europe and introducing the German-Austrian Black

List Information System (GABLIS). Journal of Nature Conservation 19: 339-350. https://doi.org/10.1016/j.jnc.2011.08.005

Faulkner KT, Hulme PE, Pagad S, Wilson JRU, Robertson MP (2020) Classifying the introduction pathways of alien species: are we moving in the right direction? NeoBiota 62: 143-159. https://doi.org/10.3897/neobiota.62.53543

Faulkner KT, Robertson MP, Rouget M, Wilson JRU (2016) Understanding and managing the introduction pathways of alien taxa: South Africa as a case study. Biological Invasions 18: 73-87. https://doi.org/10.1007/s10530-015-0990-4

Galil BS, Marchini A, Occhipinti-Ambrogi A (2018) East is east and West is west? Management of marine bioinvasions in the Mediterranean Sea. Estuarine, Coastal and Shelf Science 201: 7-16. https://doi.org/10.1016/j.ecss.2015.12.021

Harrower CA, Scalera R, Pagad S, Schönrogge K, Roy HE (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission. https://www.cbd.int/doc/c/9d85/3bc5/d640f059d03acd717602cd76/sbstta-22-inf-09-en.pdf

Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Vilà M, Wilson JRU, Genovesi P, Blackburn TM (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Diversity and Distributions 21: 1360-1363. https://doi.org/10.1111/ddi.12379

Hong K-J, Lee J-H, Lee G-S, Lee S (2012) The status quo of invasive alien insect species and plant quarantine in Korea. Journal of Asia-Pacific Entomology 15: 521-532. https://doi.org/10.1016/j.aspen.2012.06.003

507 Houghton M, McQuillan PB, Bergstrom DM, Frost L, van den Hoff J, Shaw J (2016)
508 Pathways of alien invertebrate transfer to the Antarctic region. Polar Biology 39: 23-
509 33. https://doi.org/10.1007/s00300-014-1599-2

510 Hulme PE (2015) Invasion pathways at a crossroad: policy and research challenges for
511 managing alien species introductions. Journal of Applied Ecology 52: 1418-1424.
512 https://doi.org/10.1111/1365-2664.12470

513 Hulme PE, Bacher S, Kenis M, Klotz S, Kühn I, Minchin D, Nentwig W, Olenin S, Panov V,
514 Pergl J, Pyšek P, Roques A, Sol D, Solarz W, Vilà M (2008) Grasping at the routes of
515 biological invasions: a framework for integrating pathways into policy. Journal of
516 Applied Ecology 45: 403-414. https://doi.org/10.1111/j.1365-2664.2007.01442.x

517 Hulme PE, Brundu G, Carboni M, Dehnen-Schmutz K, Dullinger S, Early R, Essl F,
518 González-Moreno P, Groom QJ, Kueffer C, Kühn I, Maurel N, Novoa A, Pergl J,
519 Pyšek P, Seebens H, Tanner R, Touza JM, van Kleunen M, Verbrugge LNH (2017)
520 Integrating invasive species policies across ornamental horticulture supply chains to
521 prevent plant invasions. Journal of Applied Ecology 55: 92-98.
522 https://doi.org/10.1111/1365-2664.12953

523 Katsanevakis S, Moustakas A (2018) Uncertainty in marine invasion science. Frontiers in
524 Marine Science 5: 38. https://doi.org/10.3389/fmars.2018.00038

525 Katsanevakis S, Zenetos A, Belchior C, Cardoso AC (2013) Invading European Seas:
526 Assessing pathways of introduction of marine aliens. Ocean & Coastal Management
527 76: 64-74. https://doi.org/10.1016/j.ocecoaman.2013.02.024

528 Keller RP, Geist J, Jeschke JM, Kühn I (2011) Invasive species in Europe: ecology, status,
529 and policy. Environmental Sciences Europe 23. https://doi.org/10.1186/2190-4715-
530 23-23

531 Kumschick S, Devenish A, Kenis M, Rabitsch W, Richardson DM, Wilson JRU (2016)
532 Intentionally introduced terrestrial invertebrates: patterns, risks, and options for
533 management. Biological Invasions 18: 1077-1088. https://doi.org/10.1007/s10530-
534 016-1086-5

535 Kumschick S, Richardson DM (2013) Species-based risk assessments for biological
536 invasions: advances and challenges. Diversity and Distributions 19: 1095-1105.
537 https://doi.org/10.1111/ddi.12110

538 Latombe G, Canavan S, Hirsch H, Hui C, Kumschick S, Nsikani MM, Potgieter LJ, Robinson
539 TB, Saul W-C, Turner SC, Wilson JRU, Yannelli FA, Richardson DM (2019) A four-
540 component classification of uncertainties in biological invasions: implications for
541 management. Ecosphere 10: e02669. https://doi.org/10.1002/ecs2.2669

542 Latombe G, Pyšek P, Jeschke JM, Blackburn TM, Bacher S, Caphina C, Costello MJ,
543 Fernández M, Gregory RD, Hobern D, Hui C, Jetz W, Kumschick S, McGrannachan
544 C, Pergl J, Roy HE, Scalera R, Squires ZE, Wilson JRU, Winter M, Genovesi P,
545 McGeoch MA (2017) A vision for global monitoring of biological invasions.
546 Biological Conservation 213: 295-308. https://doi.org/10.1016/j.biocon.2016.06.013

547 Lehan NE, Murphy JR, Thorburn LP, Bradley BA (2013) Accidental introductions are an
548 important source of invasive plants in the continental United States. American Journal
549 of Botany 100: 1287-1293. https://doi.org/10.3732/ajb.1300061

550 Levine JM, D'Antonio CM (2003) Forecasting biological invasions with increasing
551 international trade. Conservation Biology 17: 322-326. https://doi.org/10.1046/j.1523-
552 1739.2003.02038.x

553 Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of
554 prevention or a pound of cure: bioeconomic risk analysis of invasive species.

555 Proceedings of the Royal Society of London B: Biological Sciences 269: 2407-2413.
556 http://dx.doi.org/10.1098%2Frspb.2002.2179

557 Leung B, Springborn MR, Turner JA, Brockerhoff EG (2014) Pathway-level risk analysis:
558 the net present value of an invasive species policy in the US. Frontiers in Ecology and
559 the Environment 12: 273-279. https://doi.org/10.1890/130311

560 Liebhold AM, Brockerhoff EG, Garrett LJ, Parke JL, Britton KO (2012). Live plant imports:
561 the major pathway for forest insect and pathogen invasions of the US. Frontiers in
562 Ecology and the Environment 10: 135-143. https://doi.org/10.1890/110198

563 Mack RN, Erneberg M (2002) The United States naturalized flora: largely the product of
564 deliberate introductions. Annals of the Missouri Botanical Garden 89: 176-189.
565 doi:10.2307/3298562

566 McGeoch MA, Butchart SHM, Spear D, Marais E, Kleynhans EJ, Symes A, Chanson J,
567 Hoffmann M (2010) Global indicators of biological invasion: species numbers,
568 biodiversity impact and policy responses. Diversity and Distributions 16: 95-108.
569 https://doi.org/10.1111/j.1472-4642.2009.00633.x

570 McGeoch MA, Genovesi P, Bellingham PJ, Costello MJ, McGrannachan CM, Sheppard A
571 (2016) Prioritizing species, pathways, and sites to achieve conservation targets for
572 biological invasions. Biological Invasions 18: 299-314.
573 https://doi.org/10.1007/s10530-015-1013-1

574 McGeoch MA, Jetz W (2019) Measure and Reduce the Harm Caused by Biological
575 Invasions. One Earth 1: 171-174.

576 Minchin D (2007) Aquaculture and transport in a changing environment: overlap and links in
577 the spread of alien biota. Marine Pollution Bulletin 55: 302-313.
578 https://doi.org/10.1016/j.marpolbul.2006.11.017

579 Naylor RL, Williams SL, Strong DR (2001). Aquaculture – a gateway for exotic species.
580 Science 294: 1655-1656. doi:10.1126/science.1064875

581 Nunes AL, Katsanevakis S, Zenetos A, Cardoso AC (2014) Gateways to alien invasions in
582 the European seas. Aquatic Invasions 9: 133-144.
583 http://dx.doi.org/10.3391/ai.2014.9.2.02

584 Nunes AL, Tricarico E, Panov VE, Cardoso AC, Katsanevakis S (2015) Pathways and
585 gateways of freshwater invasions in Europe. Aquatic Invasions 10: 359-370.
586 http://dx.doi.org/10.3391/ai.2015.10.4.01

587 Ojaveer H, Olenin S, Narščius A, Florin A-B, Ezhova E, Gollasch S, Jensen KR, Lehtiniemi
588 M, Minchin D, Normant-Saremba M, Strāke S (2017) Dynamics of biological
589 invasions and pathways over time: a case study of a temperate coastal sea. Biological
590 Invasions 19: 799-813. https://doi.org/10.1007/s10530-016-1316-x

591 Okabe K, Masuya H, Kanzaki N (2017) Unintentional introductions of microscopic
592 organisms associated with forest insects. Biological Invasions 19: 3229-3242.
593 https://doi.org/10.1007/s10530-017-1507-0

594 Osyczka P, Mleczko P, Karasiński D, Chlebicki A (2012) Timber transported to Antarctica: a
595 potential and undesirable carrier for alien fungi and insects. Biological Invasions 14:
596 15-20. https://doi.org/10.1007/s10530-011-9991-0

Pagad S, Genovesi P, Carnevali L, Schigel D, McGeoch MA (2018) Introducing the global register of introduced and invasive species. Scientific Data 5: 170202. https://doi.org/10.1038/sdata.2017.202

Padayachee AL, Irlich UM, Faulkner KT, Gaertner M, Procheş Ş, Wilson JRU, Rouget M (2017) How do invasive species travel to and through urban environments? Biological Invasions 19: 3557-3570. https://doi.org/10.1007/s10530-017-1596-9

Pergl J, Brundu G, Harrower CA, Cardoso AC, Genovesi P, Katsanevakis S, Lozano V, Perglová I, Rabitsch W, Richards G, Roques A, Rorke SL, Scalera R, Schönrogge K, Stewart A, Tricarico E, Tsiamis K, Vannini A, Vilà M, Zenetos A, Roy HE (2020) Applying the Convention on Biological Diversity Pathway Classification to alien species in Europe. NeoBiota 62: 333-363. doi: 10.3897/neobiota.62.53796

Pergl J, Pyšek P, Bacher S, Essl F, Genovesi P, Harrower CA, Hulme PE, Jeschke JM, Kenis M, Kühn I, Perglová I, Rabitsch W, Roques A, Roy DB, Roy HE, Vilà M, Winter M, Nentwig W (2017) Troubling travellers: are ecologically harmful alien species associated with particular introduction pathways? NeoBiota 32: 1-20. https://doi.org/10.3897/neobiota.32.10199

Perrings C, Dehnen-Schmutz K, Touza J, Williamson M (2005) How to manage biological invasions under globalization. Trends in Ecology and Evolution 20: 212-215. https://doi.org/10.1016/j.tree.2005.02.011

Puth LM, Post DM (2005) Studying invasion: have we missed the boat? Ecology Letters 8: 715-721. https://doi.org/10.1111/j.1461-0248.2005.00774.x

Pyšek P, Jarošik V, Pergl J (2011) Alien plants introduced by different pathways differ in invasion success: unintentional introductions as a threat to natural areas. PloS One 6: e24890. https://doi.org/10.1371/journal.pone.0024890

621 Rabitsch W, Genovesi P, Scalera R, Biala K, Josefsson M, Essl F (2016) Developing and
622 testing alien species indicators for Europe. Journal for Nature Conservation 29: 89-96.
623 https://doi.org/10.1016/j.jnc.2015.12.001

624 Rabitsch W, Milasowszky N, Nehring S, Wiesner C, Wolter C, Essl F (2013) The times are
625 changing: temporal shifts in patterns of fish invasions in central European fresh
626 waters. Journal of Fish Biology 82: 17-33. https://doi.org/10.1111/j.1095-
627 8649.2012.03457.x

628 Ricciardi A, Blackburn TM, Carlton JT, Dick JTA, Hulme PE, lacarella JC, Jeschke JM,
629 Liebhold AM, Lockwood JL, MacIsaac HJ, Pyšek P, Richardson DM, Ruiz GM,
630 Simberloff D, Sutherland WJ, Wardle DA, Aldridge DC (2017) Invasion science: a
631 horizon scan of emerging challenges and opportunities. Trends in Ecology &
632 Evolution 32: 464-474. http://dx.doi.org/10.1016/j.tree.2017.03.007

633 Richardson DM, Cambray JA, Chapman RA, Dean WRJ, Griffiths CL, Le Maitre DC,
634 Newton DJ, Winstanley TJ (2003) Vectors and pathways of biological invasions in
635 South Africa – past, future and present. In G. Ruiz & J. Carlton (Eds.), Invasive
636 species: vectors and management strategies (pp. 292-349). Island Press (Washington
637 DC).

638 Richardson DM, Pyšek P, Carlton JT (2010) A compendium of essential concepts and
639 terminology in invasion ecology. In D.M. Richardson (Ed.), Fifty years of invasion
640 ecology: the legacy of Charles Elton (pp. 409-420). Wiley-Blackwell.
641 https://doi.org/10.1002/9781444329988.ch30

642 Rout TM, Moore JL, Possingham HP, McCarthy MA (2011) Allocating biosecurity resources
643 between preventing, detecting, and eradicating island invasions. Ecological
644 Economics 71: 54-62. https://doi.org/10.1016/j.ecolecon.2011.09.009

645 Roy HE, Bacher S, Essl F, Adriaens T, Aldridge DC, Bishop JDD, Blackburn TM, Branquart
646 E, Brodie J, Carboneras C, Cottier-Cook EJ, Copp GH, Dean HJ, Eilenberg J,
647 Gallardo B, Garcia M, García-Berthou E, Genovesi P, Hulme PE, Kenis M, Kerckhof
648 F, Kettunen M, Minchin D, Nentwig W, Nieto A, Pergl J, Pescott OL, Peyton JM,
649 Preda C, Roques A, Rorke SL, Scalera R, Schindler S, Schönrogge K, Sewell J,
650 Solarz W, Stewart AJA, Tricarico E, Vanderhoeven S, van der Velde G, Vilà M,
651 Wood CA, Zenetos A, Rabitsch W (2019) Developing a list of invasive alien species
652 likely to threaten biodiversity and ecosystems in the European Union. Global Change
653 Biology 25: 1032-1048. https://doi.org/10.1111/gcb.14527

654 Roy H, Schonrogge K, Dean H, Peyton J, Branquart E, Vanderhoeven S, Copp G, Stebbing
655 P, Kenis M, Rabitsch W, Essl F, Schindler S, Brunel S, Kettunen M, Mazza L, Nieto
656 A, Kemp J, Genovesi P, Scalera R, Stewart A (2014) Invasive alien species –
657 framework for the identification of invasive alien species of EU concern
658 (ENV.B.2/ETU/2013/0026). European Commission.

659 Saul W-C, Roy HE, Booy O, Carnevali L, Chen H-J, Genovesi P, Harrower CA, Hulme PE,
660 Pagad S, Pergl J, Jeschke JM (2017) Assessing patterns in introduction pathways of
661 alien species by linking major invasion databases. Journal of Applied Ecology 54:
662 657-669. https://doi.org/10.1111/1365-2664.12819

663 Seebens H, Blackburn TM, Dyer EF, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P,
664 van Kleunen M, Winter M, Ansong M, Arianoutsou M, Bacher S, Blasius B,
665 Brockerhoff EG, Brundu G, Capinha C, Causton CE, Celesti-Grapow L, Dawson W,
666 Dullinger S, Economo EP, Fuentes N, Guénard B, Jäger H, Kartesz J, Kenis M, Kühn
667 I, Lenzner B, Liebhold AM, Mosena A, Moser D, Nentwig W, Nishino M, Pearman
668 D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE,

669 Scalera R, Schindler S, Stajerová K, Tokarska-Guzik B, Walker K, Ward DF,
670 Yamanaka T, Essl F (2018) Global rise in emerging alien species results from
671 increased accessibility of new source pools. Proceedings of the National Academy of
672 Sciences 115: E2264-E2273. https://doi.org/10.1073/pnas.1719429115

673 Seebens H, Blackburn TM, Dyer EF, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P,
674 Winter M, Arianoustou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-
675 Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H,
676 Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Perman D, Pergl J,
677 Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R,
678 Schindler S, Štajerová K, Tokarska-Guzik B, van Kluenen M, Walker K, Weigelt P,
679 Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species
680 worldwide. Nature Communications 8: 14435.
681 https://dx.doi.org/10.1038/ncomms14435

682 Seebens H, Clarke DA, Groom Q, Wilson JRU, García-Berthou E, Kühn I, Roigé M, Pagad
683 S, Essl F, Vicente J, Winter M, McGeoch M (2020) A workflow for standardising and
684 integrating alien species distribution data. NeoBiota 59 : 39-59.
685 https://doi.org/10.3897/neobiota.59.53578

686 Teletchea F, Fontaine P (2014) Levels of domestication in fish: implications for the
687 sustainable future of aquaculture. Fish and Fisheries 15 : 181-195.
688 https://doi.org/10.1111/faf.12006

689 Tingley R, García-Díaz P, Rani Rocha Arantes C, Cassey P (2018) Integrating transport
690 pressure data and species distribution models to estimate invasion risk for alien
691 stowaways. Ecography 41: 635-646. https://doi.org/10.1111/ecog.02841

692 Tsiamis K, Cardoso AC, Gervasini E (2017). The European Alien Information Network on
693 the Convention on Biological Diversity pathways categorization. NeoBiota 32: 21-29.
694 https://doi.org/10.3897/neobiota.32.9429

695 Turbelin AJ, Malamud BD, Francis RA (2017) Mapping the global state of invasive alien
696 species: patterns of invasion and policy responses. Global Ecology and Biogeography
697 26: 78-92. https://doi.org/10.1111/geb.12517

698 UNEP (2014) Pathways of introduction of invasive species, their prioritization and
699 management. UNEP/CBD/SBSTTA/18/9/Add.1, subsidiary body on scientific,
700 technical and technological advice, eighteenth meeting, Montreal.
701 www.cbd.int/doc/meetings/sbstta/sbstta-18/official/
702 sbstta-18-09-add1-en.pdf. Decision XII/17 CBD COP12

703 van Kleunen M, Essl F, Pergl J, Brundu G, Carboni M, Dullinger S, Early R, González-
704 Moreno P, Groom QJ, Hulme PE, Kueffer C, Kühn I, Máguas C, Maurel N, Novoa A,
705 Parepa M, Pyšek P, Seebens H, Tanner R, Touza J, Verbrugge L, Weber E, Dawson
706 W, Kreft H, Weigelt P, Winter M, Klonner G, Talluto MV, Dehnen-Schmutz K
707 (2018) The changing role of ornamental horticulture in alien plant invasions.
708 Biological Reviews 93: 1421-1437. https://doi.org/10.1111/brv.12402

709 Wilson JRU, Faylkner KT, Rahlao SJ, Richardson DM, Zengeya TA, van Wilgen BW (2018)
710 Indicators for monitoring biological invasions at a national level. Journal of Applied
711 Ecology 55: 2612-2620. https://doi.org/10.1111/1365-2664.13251

712 Yemshanov D, Koch FH, Ducey M, Koehler K (2012) Trade-associated pathways of alien
713 forest insect entries in Canada. Biological Invasions 14: 797-812.
714 https://doi.org/10.1007/s10530-011-0117-5

715 Zenetos A, Çinar ME, Crocetta F, Golani D, Rosso A, Servello G, Shenkar N, Turon X,
716 Verlaque M (2017) Uncertainties and validation of alien species catalogues: The
717 Mediterranean as an example. Estuarine, Coastal and Shelf Science 191: 171-187.
718 https://doi.org/10.1016/j.ecss.2017.03.031

719 Zenetos A, Gofas S, Morri C, Rosso A, Violanti D, García Raso JE, Çinar ME, Almogi-Labin
720 A, Ates AS, Azzurro E, Ballesteros E, Bianchi CN, Bilecenoglu M, Gambi MC,
721 Giangrande A, Gravili C, Hyams-Kaphzan O, Karachle PK, Katsanevakis S, Lipej L,
722 Mastrototaro F, Mineur F, Pancucci-Papadopoulou MA, Ramos Esplá A, Salas C, San
723 Martin G, Sfriso A, Streftaris N, Verlaque M (2012) Alien species in the
724 Mediterranean Sea by 2012. A contribution to the application of European Union's
725 Marine Strategy Framework Directive (MSFD). Part 2. Introduction trends and
726 pathways. Mediterranean Marine Science 13: 328-352.
727 https://doi.org/10.12681/mms.327

728 Zieritz A, Gallardo B, Baker SJ, Britton JR, van Valkenburg JLCH, Verreycken H, Aldridge
729 DC (2017) Changes in pathways and vectors of biological invasions in Northwest
730 Europe. Biological Invasions 19: 269-282. https://doi.org/10.1007/s10530-016-1278-z

731 **Tables**

732 **Table 1:** Summary of introduction pathways and their documented introduction events.

733 Bracketed numbers represent the number of subcategories categorised as "other".

Total Number of Documented Introduction Events: 18746			
Introduction Pathway	**# of Documented Introduction Events**	**% of Total Documented Introduction Events**	**Rank**
Pathway Type			
Intentional	8172	43.59	2
Unintentional	10574	56.41	1
Pathway Category			
Release	1078	5.75	5
Escape	7094	37.84	1
Transport-Contaminant	1982	10.57	3
Transport-Stowaway	1581	8.43	4
Corridors	828	4.42	5
Unaided	148	0.79	6
Unknown	6035	32.19	2
Pathway Subcategory			
Release: Biological control	109	0.58	18
Release: Fishery in the wild	248	1.32	14
Release: Landscape/flora/fauna improvement	342	1.82	11
Release: Other subcategories (4)	110	0.59	n/a
Release: Release in nature for use	229	1.22	15
Escape: Agriculture	1193	6.36	3
Escape: Aquaculture/mariculture	1010	5.39	4
Escape: Forestry	273	1.46	13
Escape: Horticulture	3581	19.10	2
Escape: Ornamental purpose	475	2.53	7
Escape: Pet/aquarium species	288	1.54	12
Escape: Other subcategories (6)	204	1.09	n/a
Transport-contaminant: Seed contaminant	654	3.54	6
Transport-contaminant: Timber trade	190	1.01	16
Transport-contaminant: Other subcategories (8)	310	1.65	n/a
Transport-stowaway: Hitchhikers on ship/boat	412	2.20	10
Transport-stowaway: Ship/boat ballast water	447	2.38	8
Transport-stowaway: Ship/boat hull fouling	422	2.25	9
Transport-stowaway: Other subcategories (8)	82	0.44	n/a
Corridors: Interconnected waterways/basins/seas	827	4.41	5
Corridors: Other subcategories (1)	0	0.00	n/a
Unaided: Natural dispersal across borders	137	0.73	17

Unknown: Unknown	7203	38.42	1

734

735 **Table 2.** Decadal increase in documented intentional and unintentional introduction events

736 for the period 1810 to 2011.

Decade	Documented Intentional Introduction Events	Documented Unintentional Introduction Events	Intentional Decadal Growth (%)	Unintentional Decadal Growth (%)	Difference Between Intentional / Unintentional Decadal Growth Rates
Pre-1800	553	473	n/a	n/a	n/a
1810	585	507	5.79	7.19	1.40
1820	646	575	10.43	13.41	2.98
1830	772	693	19.50	20.52	1.02
1840	869	790	12.56	14.00	1.43
1850	1056	951	21.52	20.38	1.14
1860	1218	1129	15.34	18.72	3.38
1870	1500	1359	23.15	20.37	2.78
1880	1707	1636	13.80	20.38	6.58
1890	1981	1953	16.05	19.38	3.32
1900	2314	2435	16.81	24.68	7.87
1910	2587	2868	11.80	17.78	5.98
1920	2854	3316	10.32	15.62	5.30
1930	3251	3918	13.91	18.15	4.24
1940	3603	4521	10.83	15.39	4.56
1950	4009	5064	11.27	12.01	0.74
1960	4550	5773	13.49	14.00	0.51
1970	5105	6437	12.20	11.50	0.70
1980	5663	7188	10.93	11.67	0.74
1990	6516	7937	15.06	10.42	4.64
2000	7313	9279	12.23	16.91	4.68
2010	7993	10445	9.30	12.57	3.27
2011 >	8172	10574	2.24	1.24	1.00
Average	n/a	n/a	**13.12**	**15.29**	**3.10**
Std Dev.	n/a	n/a	**4.70**	**5.25**	**2.17**

737

738 **Table 3.** Trends in recoded introduction events by pathway across the period 1800 to 2017.
739 Generalized linear model results (family = negative binomial, link = log). Significant *p* values
740 ($p < 0.05$) shown in bold.

Pathway Type	Slope coefficient	Std. Error	df	*z*	*p*
Intentional	0.011	0.001	20	8.427	< **0.001**
Unintentional	0.013	0.002	20	8.568	< **0.001**
Pathway Category					
Release	0.012	0.002	20	5.764	< **0.001**
Escape	0.011	0.001	20	8.608	< **0.001**
Transport - contaminant	0.01	0.002	20	5.493	< **0.001**
Transport - stowaway	0.021	0.002	20	11.25	< **0.001**
Corridor	0.035	0.003	20	10.156	< **0.001**
Unaided	0.026	0.003	20	7.787	< **0.001**
Unknown	0.01	0.002	20	6.408	< **0.001**
Pathway Subcategory					
Release: Biological control	0.017	0.004	20	4.858	< **0.001**
Release: Fishery in the wild	0.016	0.004	20	4.253	< **0.001**
Release: Landscape "improvement"	0.012	0.002	20	5.075	< **0.001**
Release: Release in nature for use	0.001	0.002	20	0.421	0.674
Escape: Agriculture	0.004	0.002	20	2.017	**0.045**
Escape: Aquaculture/mariculture	0.028	0.003	20	8.975	< **0.001**
Escape: Forestry	0.006	0.002	20	2.858	**0.004**
Escape: Horticulture	0.009	0.001	20	7.632	< **0.001**
Escape: Ornamental purpose	0.012	0.002	20	5.429	< **0.001**
Escape: Pet/aquarium species	0.024	0.003	20	8.628	< **0.001**
Contaminant: Seed contaminant	0.01	0.002	20	5.644	< **0.001**
Contaminant: Timber trade	0.032	0.005	20	6.581	< **0.001**
Stowaway: Hitchhikers on ship/boat	0.028	0.003	20	8.316	< **0.001**
Stowaway: Ship/boat ballast water	0.021	0.003	20	7.633	< **0.001**
Stowaway: Ship/boat hull fouling	0.023	0.003	20	8.457	< **0.001**
Corridors: Interconnected waterways	0.035	0.003	20	10.155	< **0.001**

Unaided: Natural dispersal	0.025	0.003	20	7.514	< **0.001**
Subcategory unknown	0.01	0.002	20	6.408	< **0.001**

741

Figures

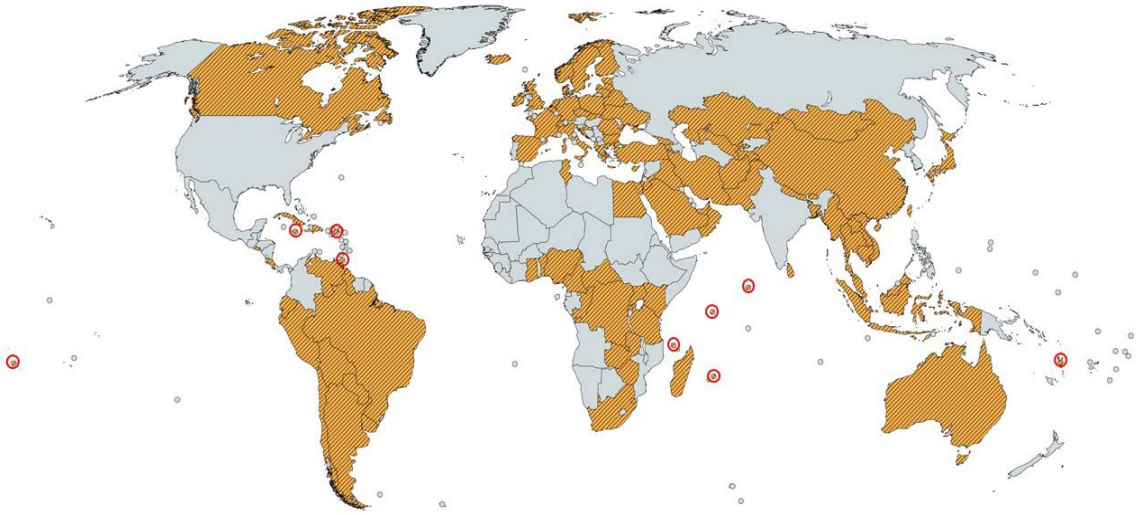


Figure 1. The 101 countries (orange) used to conduct the global pathways assessment. Red open circles indicate small island nations (n = 9) (https://mapchart.net/; accessed 30 July 2019).

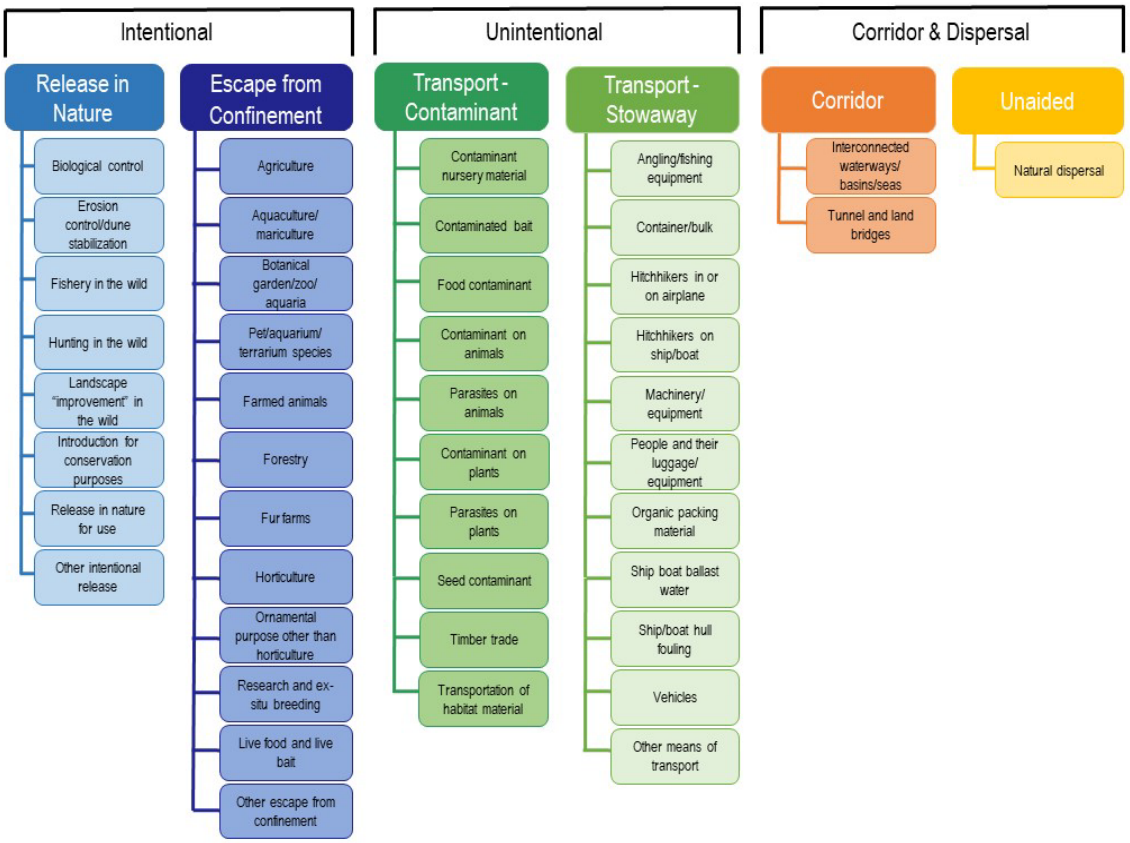


Figure 2. Overview of the hierarchical, standard categorisation of pathways. Six pathway categories and 44 pathway subcategories are broadly categorised into a) intentional transport and introduction of taxa, b) pathways of unintentional introduction and c) pathways by which taxa move to new regions, without direct transportation by humans (i.e. Pathway types). Adapted from Harrower et al. (2017).

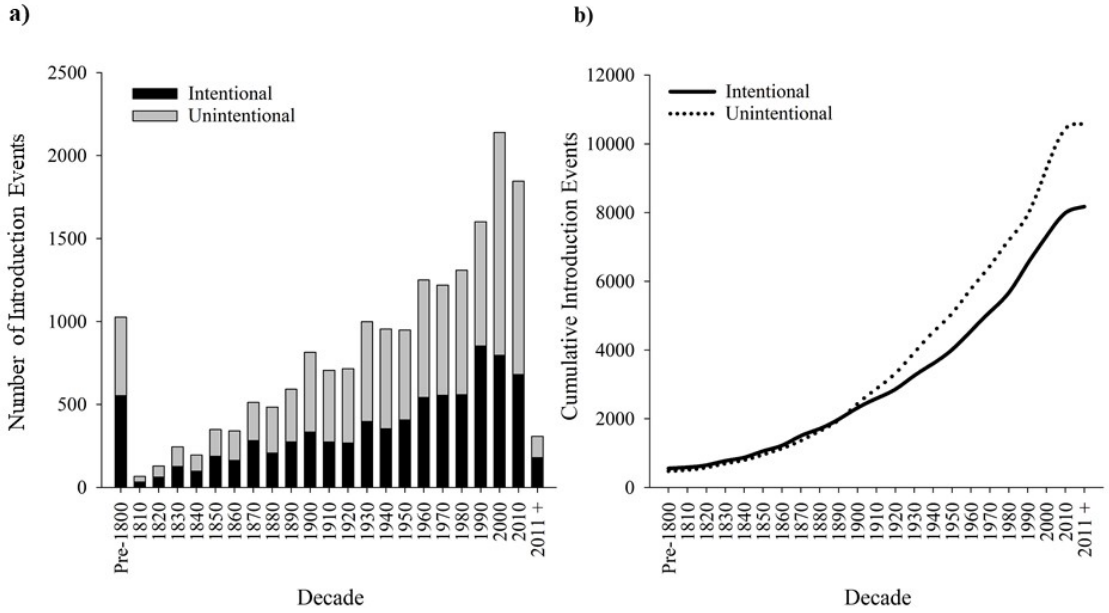


Figure 3. Decadal changes in the documented number of intentional and unintentional introductions of alien species for 101 countries. Trends in introduction events (n = 18746) involving over 4800 alien species are shown as: a) number of documented introduction events, and b) the cumulative number of documented introduction events. An introduction event in this figure represents one species introduced outside of its known native range for the first time and into one of the 101 countries in the pool.

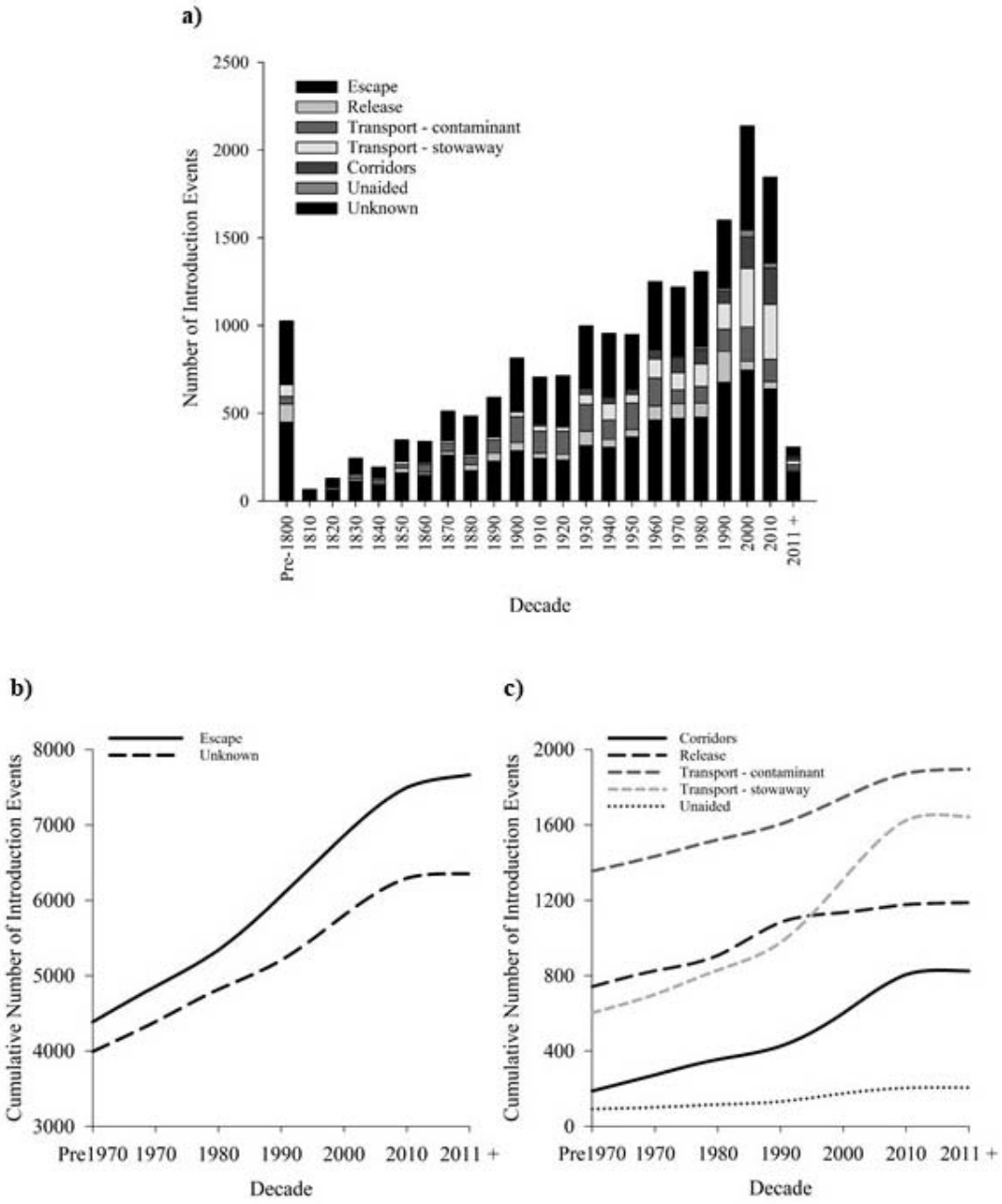
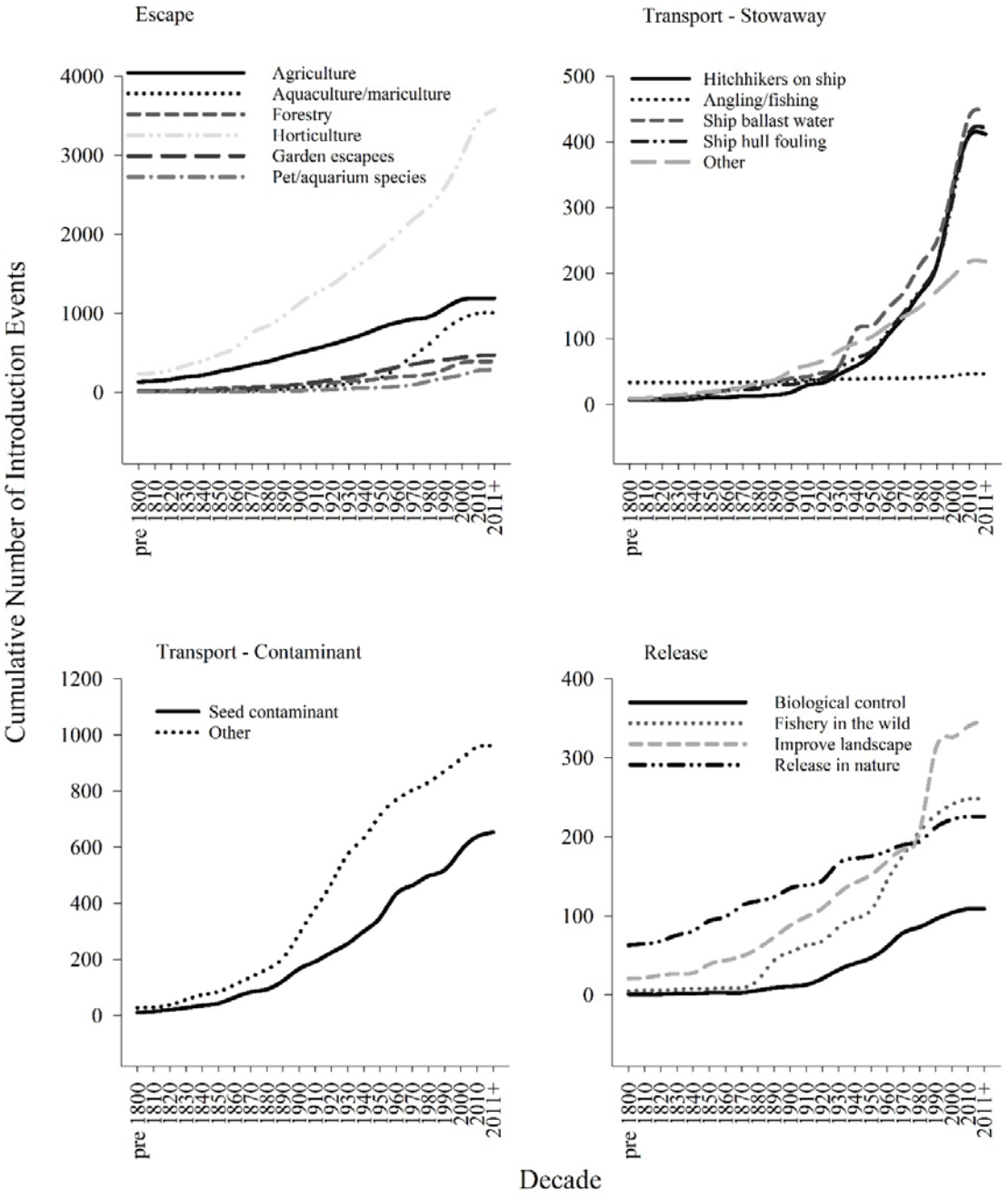


Figure 4. Changes in the six main pathway categories (as well as the number of introductions via unknown pathways). (a) The documented number of introduction events (n = 18746) of alien species per decade since 1800 for 101 countries. (b-c) Cumulative number of documented introduction events by pathway since 1970 (note different scaling on y-axes).

774



775

776 **Figure 5.** Changes in the dominant pathway subcategories across decades. Cumulative
777 number of documented introduction events (note different scales on y-axes). The 18 pathway
778 subcategories shown are those with most (> 100) introduction events (see Figure S1 for
779 Corridors: interconnected waterways/basins/seas', 'unaided: natural dispersal across borders'
780 and 'unknown' pathway subcategories not shown).