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Classifying the introduction pathways of alien species: are we moving in the right direction?

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Abstract

Alien species are introduced to new regions in many different ways and for different purposes. A number of frameworks have been developed to group such pathways of introduction into discrete categories in order to improve our understanding of biological invasions, provide information for interventions that aim to prevent introductions, enable reporting to national and international organisations and facilitate the prediction of threats. The introduction pathway classification framework proposed by the Convention on Biological Diversity (CBD) as a global standard is comprised of six main categories and 44 sub-categories. However, issues have arisen with its implementation. In this position paper, we outline five desirable properties of an introduction pathway classification framework – it should be compatible (i.e. the level of detail of the categories is similar to that of the available data), actionable (i.e. categories link to specific interventions), general (i.e. categories are applicable across the contexts that are of interest (e.g. taxa, habitats and regions)), equivalent (i.e. categories are equivalent in their level of detail) and distinct (i.e. categories are discrete and easily distinguished) – termed the CAGED properties. The six main categories of the CBD framework have all of the CAGED properties, but the detailed sub-categories have few. Therefore, while the framework has been proposed by the CBD as a global standard and efforts have been made to put it into practice, we argue that there is room for improvement. We conclude by presenting scenarios for how the issues identified could be addressed, noting that a hybrid model might be most appropriate.

Keywords
biological invasions, biosecurity, Convention on Biological Diversity, framework, introduction effort, invasion biology, mode of introduction, propagule pressure

Introduction

Information on how and why alien species are introduced to new regions provides the foundation for pre- and at-border management strategies that aim to prevent the introduction of harmful species (Hulme et al. 2008; Hulme 2015). However, alien species can be introduced through a vast number of introduction pathways and, as there are limited resources available to manage introductions, important pathways must be identified and prioritised (Hulme et al. 2008; Essl et al. 2015; Essl et al. 2020). A number of frameworks have been developed to aggregate the immense number of introduction pathways into discrete categories (Essl et al. 2015). These introduction pathway classification frameworks (hereafter simply frameworks) are used in analyses that improve our understanding of biological invasions, provide information for interventions that aim to prevent introductions, enable reporting to national and international organisations and facilitate the prediction of threats. The different frameworks were developed for use in different contexts and they differ with respect to the way in which they were developed and in their level of detail. For example, there are six main categories and 20 sub-categories in the framework used by the European Alien Species Information Network (EASIN), which supports European states by providing information for policy and management (Tsiamis et al. 2017); the framework developed by Wilson et al. (2009) comprises six categories and aims to improve understanding of the underlying properties of pathways and the consequences for invasion success; and the framework developed by Hulme et al. (2008) has six categories and was developed to provide information for decisions on existing regulatory instruments.

Based on the framework of Hulme et al. (2008), a hierarchical framework was developed to assist countries to achieve Aichi Biodiversity Target 9 of the Convention on Biological Diversity (CBD), specifically the requirement to identify and manage pathways of introduction (https://www.cbd.int/sp/targets/, CBD 2014; Essl et al. 2015; Scalera et al. 2016; Harrower et al. 2018). This framework (hereafter referred to as the CBD framework) was proposed by the CBD as a global standard (CBD 2014). With six main categories and 44 sub-categories, the CBD framework is very detailed (Fig. 1). The six main categories of the CBD framework, which were adopted from the framework of Hulme et al. (2008), were developed by classifying pathways, based on three shared attributes: the degree of human involvement, the means of transport and the means of subsequent introduction (Hulme et al. 2008). In contrast, the 44 sub-categories of the CBD framework were developed by comparing and incorporating existing frameworks [including those used by the Global Invasive Species Database (GISD), the Centre for Agriculture and Bioscience International's (CABI) Invasive Species Compendium and the Delivering Alien Invasive Species Inventories for Europe (DAISIE) consortium].

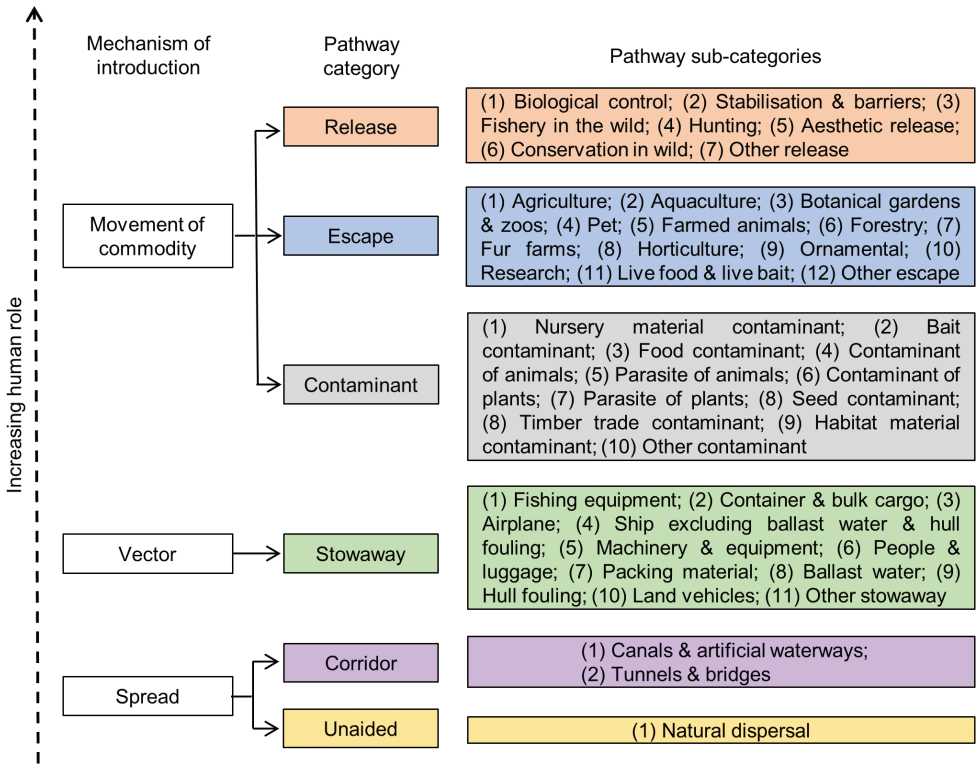

Figure 1. The introduction pathway classification framework proposed by the Convention on Biological Diversity (CBD 2014). The nomenclature proposed in Harrower et al. (2018) has been implemented. The mechanisms of introduction and main categories were adopted from the framework developed by Hulme et al. (2008).

Assessments that have attempted to apply the CBD framework have highlighted implementation issues (Saul et al. 2017; Tsiamis et al. 2017; Zenetos 2017; van Wilgen and Wilson 2018; Pergl et al. 2020). For instance, the sub-categories cannot accommodate all data and some sub-categories overlap and are indistinguishable. Subsequent to the launch of the CBD framework, guidelines were produced which clarified the definitions of the framework's main categories and sub-categories and proposed small adjustments to the framework's nomenclature and structure to address some of the areas of confusion and uncertainty (Harrower et al. 2018, for details see Appendix I: Fig. A1). To date, the guidelines and the proposed changes do not appear to have been officially recognised by the CBD.

Despite these issues, the development of the framework and its recognition by the CBD was an important step towards the global implementation of a shared terminology and classification framework for pathways (Rabitsch et al. 2016, but see Paap et al. 2020). Parties to the CBD have been encouraged to make use of the framework (Essl et al. 2015) and efforts have been made to implement it. Data in existing databases have been re-classified using the CBD framework (Saul et al. 2017; Tsiamis et al. 2017; van Wilgen and Wilson 2018; Pergl et al. 2020), its terminologies have been included in the vocabularies of global data standards (Groom et al. 2019), it has been used in national

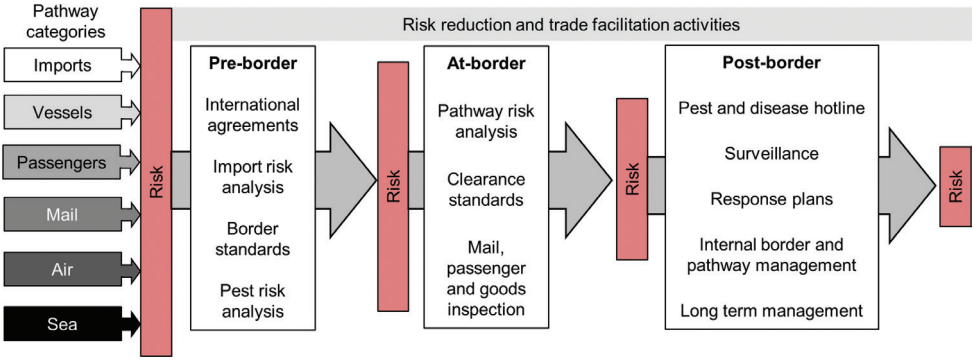

Figure 2. The six pathway categories recognised by New Zealand's biosecurity surveillance system. These categories are linked to the location of biosecurity pressures and interventions (see Suppl. material 1: Fig. S1). Figure redrawn from Ministry of Agriculture and Forestry (MAF) Biosecurity New Zealand (2008).

level reporting (Wilson et al. 2018) and is employed in the system (NOTSYS) used by member states of the European Commission to report new observations of invasive species that are of Union concern (https://easin.jrc.ec.europa.eu/notsys). However, some countries still make use of their own frameworks. For example, New Zealand's biosecurity surveillance system uses a framework that comprises six pathway categories (Fig. 2). This framework, unlike others, does not consider the degree of human involvement when classifying introductions into pathway categories, but introductions are instead classified based on the location of biosecurity interventions. This approach means that intentional and accidental introductions can be classified into the same pathway category.

In this position paper, we discuss why introduction pathway classification frameworks are needed and identify the desirable properties that these frameworks should have in order to achieve their stated purpose. Based on these properties, we assess the main categories and sub-categories of the CBD framework and the framework used by New Zealand's biosecurity surveillance system. We conclude by presenting scenarios for how frameworks might be improved in future.

The purpose of introduction pathway classification frameworks and their desirable properties

An ideal framework should aim to: improve our understanding of biological invasions, provide information for policy and management interventions that aim to prevent introductions, enable reporting to national and international organisations and facilitate the prediction of threats. Unfortunately, existing frameworks differ in terms of their structure and in the context for which they were developed and, thus, rarely address all four of these aims.

Frameworks have been used in retrospective analyses, whereby historical introduction data are categorised and the frequency of introductions through each of the pathways is assessed. These analyses improve our understanding of how and why alien species have been introduced in the past. Additionally, when information is included on invasion success

and impacts, these analyses can be used to explore the link between the pathway through which an organism was introduced and its likelihood of becoming invasive and causing harm (Wilson et al. 2009; Pyšek et al. 2011; Faulkner et al. 2016; Pergl et al. 2017). Many of these retrospective analyses have been performed and they have answered a wide range of questions, including how the pathways vary in their importance geographically and over time, as well as across taxonomic groups, habitats and spatial scales (Hulme et al. 2008; Pyšek et al. 2011; Katsanevakis et al. 2013; Faulkner et al. 2016; Zieritz et al. 2017). A variety of frameworks have been used for this purpose; however, frameworks with broad, inclusive categories are most useful for cross-cutting analyses, as introductions that occur in a variety of contexts can be classified within the same categories. Although such frameworks are particularly suitable for studies at a global scale (e.g. Hulme et al. 2008; Saul et al. 2017), they have also been used successfully in cross-cutting analyses at regional- (Pergl et al. 2017) and national-scales (e.g. Pyšek et al. 2011; Faulkner et al. 2016).

Frameworks are also used to direct or provide information for policies, legislation and pre- and at-border management strategies that focus on either preventing the introduction of specific priority species or managing specific pathways or vectors of concern (to reduce propagule and colonisation pressure (Lockwood et al. 2005, 2009)). Examples of these interventions include inspections at ports of entry that aim to prevent the introduction of potentially harmful species (Liebhold et al. 2006; McCullough et al. 2006) and policies that require foreign vessels entering a region to exchange and/or flush their ballast tanks with mid-ocean saltwater (Bailey et al. 2011). As it would be impossible to create different legislative instruments for the vast number of pathways that exist, frameworks with broad, inclusive categories are most useful for legislation and policy (Hulme et al. 2008). However, to provide information for direct interventions, more detailed categories that are explicitly constructed with interventions in mind may be required.

Another important role of frameworks is to assist with the standardised monitoring and reporting of biological invasions at different scales (Latombe et al. 2017; Wilson et al. 2018; Groom et al. 2019). Indeed, the CBD framework has been proposed as an explicit component of global monitoring for biological invasions and its vocabulary has been proposed as part of the Darwin Core biodiversity standards (Latombe et al. 2017; Groom et al. 2019). As pathways of introduction vary across regions and countries (Essl et al. 2015), it would be difficult to create a detailed framework that comprises the introduction pathways that are important for all regions and, therefore, frameworks with broad, inclusive categories are likely to be most useful for monitoring and reporting, particularly at the global scale.

Finally, frameworks can be incorporated in risk analyses (Kumschick et al. 2020) and horizon-scanning exercises (Matthews et al. 2014, 2017; Tsiamis et al. 2020) to make predictions concerning future invaders and their pathways of introduction and to determine what can be done to prevent future introductions. Frameworks with detailed categories are likely to be most useful for this purpose and, indeed, the detailed sub-categories of the CBD framework have been used in horizon-scanning exercises (e.g. Tsiamis et al. 2020).

In order for a framework to achieve all of these purposes, we suggest that it should have five properties, that we have termed the CAGED properties. Frameworks must be: Compatible, Actionable, General, Equivalent and Distinct (CAGED) (Table 1).

Table 1. The proposed five desirable properties that introduction pathway classification frameworks should have in order to achieve their purpose, the rationale for why each is important and examples of where the property is missing.

Property	Definition	Rationale	Examples of where the property is missing
Compatible	The level of detail of each category should be compatible with that of the available data so that it is possible to classify the available data into the categories. The level of detail of the categories must be similar to (or coarser than) that of the available data, so that pathways do not match to multiple categories.	Facilitates the classification of available data, ensures that all introductions can be classified and included in analyses and that introductions are not classified into multiple categories (which could artificially inflate the relative importance of some pathways).	It is often unclear whether a marine species has been introduced through the 'hull-fouling' or 'ballast water' sub-categories of the CBD framework. Therefore, these sub-categories are not compatible with the available data and, consequently, introductions are often classified into both sub-categories or the sub-categories are merged.
Actionable	The links between the categories and interventions need to be clear, with each category aligning with a specific intervention.	If the primary purpose of a framework is to facilitate interventions, then the structure of the framework should be based on the interventions themselves. Actionability ensures that knowledge on the pathways can be easily translated into appropriate action. If multiple pathways are managed using the same tool, then data will need to be re-interpreted to provide information for management.	Multiple sub-categories of the CBD framework pertain to the introduction of contaminants of imported plants or plant products (e.g. 'nursery material contaminant', 'contaminant of plants' and 'parasite of plants' sub-categories). These sub-categories are managed using the same tools and so data will need to be re-interpreted in order to provide information for management.
General	The framework and individual categories should be applicable across whatever contexts are of interest (e.g. regions, taxa, habitats and time periods).	Frameworks that are generalisable across taxa, habitats and regions, allow for the classification of available data in a comparable way, which enables cross-cutting analyses and reporting at global scales. It also means that the categories will likely be able to accommodate data from a wide range of pathways that will change in importance and possibly become more diverse over time. Furthermore, it is inappropriate for countries/regions to manage pathways that are not applicable to them, as this would be a waste of resources. Reporting on pathways that are not applicable could lead to the success of management being overstated.	The framework used by New Zealand's biosecurity surveillance system does not make provision for introductions where alien species spread through natural dispersal over land borders. In the New Zealand context, few alien species have arrived from other regions without human intervention (Hulme 2020), but this is one reason why the framework does not have generality at a global level. Note that species that disperse naturally through the air (e.g. seeds blown over from Australia) or sea are classified into the 'air' or 'sea' categories of the framework.
Equivalent	Categories should be equivalent in their level of detail (i.e. pathways on the same level of a framework should not be subsets of each other).	Ensures that the categories are comparable, which is vital for analyses that explore the relative importance of pathways and that inform management. If categories are not equivalent, the relative importance of some pathways could be underestimated.	The 'mail' category of the framework used by New Zealand's biosecurity surveillance system is a subset of the 'imports' category, which is on the same level of the framework. Therefore, the importance of 'imports' could be underestimated.
Distinct	Categories should be easily distinguished and discrete.	Ensures consistent interpretation by stakeholders and, therefore, the consistent classification of data. If categories are not distinct, they could be misinterpreted, data will be inconsistently classified and ultimately cross-cutting analyses will be precluded.	The difference between the 'horticulture' and 'ornamental' sub-categories of the CBD framework is uncertain since some species can be of both ornamental and horticultural value. As these sub-categories are not distinct, it is likely that classifications are inconsistent.

We have not attempted to rank or weight these properties as their relative importance will vary depending on the context for which the framework is developed, but we argue that all are required for a framework to be effective. Whether a framework possesses the CAGED properties could also vary, based on the context of interest; for instance, a framework developed for regional use could possess the CAGED properties within that context, but not at a global level. Note these properties are, we believe, discrete. For example, if introductions are described by more than one category, then the framework is too detailed and is not compatible with the available data. Nonetheless, the categories might still be applicable across different taxonomic groups, habitats,

regions and time periods and so the framework has generality. In contrast, a category could be compatible with the available data, but will not be general if it is only applicable to one type of organism, habitat or region.

Assessment of introduction pathway classification frameworks

Based on the CAGED properties, we evaluated the framework used by New Zealand's biosecurity surveillance system, the six main categories of the CBD framework and the 44 sub-categories of the CBD framework (Table 2 and for details on each framework, see Figs 1, 2). We aimed to assess whether a diverse set of frameworks exhibited the CAGED properties at a global level and so these frameworks were selected as they vary in their level of detail, in the approach followed for their development and in the political level for which they were developed (Table 2). The main categories and sub-categories of the CBD framework were assessed separately as they were developed separately, using different methods. Furthermore, assessing the levels separately meant that the usefulness of each level could be determined, and issues that are specific to each level of the framework could be identified.

Introduction pathway classification framework used by New Zealand's biosecurity surveillance system

The framework used by New Zealand's biosecurity surveillance system (Fig. 2) has some of the CAGED properties (Table 2 and, for further details, Suppl. material 1: Table S1). In particular, it was developed explicitly with biosecurity in mind and so is positioned in the context of at-border interventions (Suppl. material 1: Fig. S1). However, the categories are not equivalent in their level of detail as some categories are subsets of others (see Table 1 for an example), their compatibility with the available data will vary across regions and the framework is not general as the categories do not include introductions where alien species spread through natural dispersal over land borders (see Table 1). The framework was developed from first principles, but due to the political level for which it was developed (an island country) and the approach used (which focused on the location of biosecurity pressures and interventions), it does not have all the CAGED properties (including for the context for which it was developed).

Main categories of the CBD introduction pathway classification framework

The main categories of the CBD framework, which were adopted from the framework of Hulme et al. (2008), have all of the CAGED properties (Table 2 and, for further details, Suppl. material 1: Table S3). The links between the main categories and existing regulations are clear (Suppl. material 1: Fig. S2) and the inclusive nature of the main categories means that it is likely that it will be possible to integrate data for current and historical pathways, as well as those that will develop in the future. Furthermore, pathways from

many different regions (e.g. Pyšek et al. 2011; Faulkner et al. 2016), taxonomic groups (Faulkner et al. 2016; Padayachee et al. 2017; Pergl et al. 2017) and habitats (Padayachee et al. 2017) have been successfully classified according to the main categories and they have been used to assess changes over time (Pyšek et al. 2011; Faulkner et al. 2016). Hulme et al. (2008) is widely cited and the framework has been used by researchers from across the world working on many different issues (Wilson et al. in 2020b). The stimulus for the framework of Hulme et al. (2008) was that there was a critical need for an approach that balanced comprehensiveness with utility, in terms of both understanding the drivers of invasion and guiding the development of overarching legislation. It is, therefore, likely that the main categories of the CBD framework have the CAGED properties as they were developed from first principles and as they were specifically designed to provide information for regulations, assess risks in a variety of contexts and facilitate comparative analyses across habitats, regions and taxonomic groups (Hulme et al. 2008).

Sub-categories of the CBD introduction pathway classification framework

The sub-categories of the CBD framework (Fig. 1) have few of the CAGED properties (Table 2 and Table 3 for further details). Assessments that have used the CBD framework have highlighted that the differences between the sub-categories are unclear (Tsiamis et al. 2017; van Wilgen and Wilson 2018; Pergl et al. 2020), the information available is often not detailed enough for classification at the sub-category level (i.e. introductions match to more than one sub-category) (Tsiamis et al. 2017; Zenetos 2017; van Wilgen and Wilson 2018) and many of the sub-categories are only appropriate for specific taxonomic groups or habitats (Matthews et al. 2014; Padayachee et al. 2017). The sub-categories of the framework are also not equivalent in their level of detail as some sub-categories are subsets of others (Harrower et al. 2018). While an ef-

Table 2. Assessment of the introduction pathway classification frameworks, based on the CAGED properties. For each framework the method of development, the political level for which it was developed and level of detail is presented, together with an assessment indicating which of the five properties it possesses. As the main categories of the CBD framework were developed separately and using different methods, they were assessed separately from the sub-categories. Frameworks were partially compatible or actionable if some categories possessed the property, but not all. It is uncertain if the sub-categories of the CBD framework are distinct, as the definitions in the proposed guidelines have not been widely tested. See Table 3 for details of the scoring of the CBD framework's sub-categories.

Framework	Method of development	Political level	Number of categories	Property				
				Compatible	Actionable	General	Equivalent	Distinct
New Zealand biosecurity surveillance system	Based on the location of biosecurity pressures and interventions	Country	Six	Partially	Yes	No	No	Yes
Main categories of the CBD framework	Three pre-determined criteria	Global	Six	Yes	Yes	Yes	Yes	Yes
Sub-categories of the CBD framework	Compared and incorporated existing frameworks	Global	44	Partially	Partially	No	No	Uncertain

fort has been made to link the sub-categories to existing regulations and international management tools, for most sub-categories, pathway-specific management tools were not identified (CBD 2014) and a number of the sub-categories are managed using the same tools (see Table 3 for details). If many sub-categories are managed using the same tools, then the results from analyses using the framework will need to be re-interpreted to provide information for management (the data from various sub-categories would have to be merged) and this puts into question why such a high level of detail is required. Therefore, while the sub-categories were developed to inform specific, tailored management (Essl et al. 2015), there is little evidence that they do.

Despite their high level of detail, the sub-categories are also not likely to be appropriate for all regions. Geographically biased datasets (largely European and global datasets (e.g. GISD) that contain few data from developing regions) were used to develop the sub-categories. Consequently, it is likely that some pathways that are important in under-studied or developing regions will not fit into the detailed sub-categories of the framework. Furthermore, the data that are available will often not

Table 3. The evidence used to assess the sub-categories of the CBD introduction pathway classification framework. Presented are the CAGED properties, the outcomes of an assessment indicating which of the five properties the xsub-categories possess and the evidence.

Property	Outcome	Evidence
Compatible	Partially	The level of detail of some of the sub-categories is suitable for the classification of the available data, but published assessments have highlighted that, for some of the sub-categories, the information available is often not sufficiently detailed for classification and, consequently, pathways map on to more than one sub-category (see Tsiamis et al. 2017, Zenetos 2017, van Wilgen and Wilson 2018). For example, the level of detail required to determine whether a marine species was introduced through hull fouling or the release of ballast water is often not available (Tsiamis et al. 2017, Zenetos 2017).
Actionable	Partially	In a technical note, an effort was made to link the sub-categories of the framework to interventions (see CBD 2014). Existing international tools that are pathway-specific were only identified for 14 of the 44 sub-categories, with no pathway-specific tools identified for, for example, 'fur farms', 'contaminated bait' and 'stowaways on land vehicles' (CBD 2014). Furthermore, a number of the sub-categories are managed using the same tools. For example, the multiple sub-categories that pertain to the introduction of contaminants of imported plants or plant products are managed using the standards developed under the International Plant Protection Convention and the pre- and at-border management for all of these pathways would be similar.
General	No	Published assessments have highlighted that many of the sub-categories are only appropriate for specific taxonomic groups or habitats (see Matthews et al. 2014, Padayachee et al. 2017, Saul et al. 2017). For example, the 'horticulture' sub-category is specific to plants, while the 'airplane' sub-category is specific to the terrestrial habitat. Consequently, variations across taxonomic groups and habitats have only been assessed at the main category level (e.g. Padayachee et al. 2017, Saul et al. 2017). The sub-categories are not applicable to all regions. For South Africa, 8% of known introductions with a recorded pathway did not fit into any of the detailed sub-categories and had to be classified into the 'other' sub-categories (Suppl. material 1: Fig. S3). For some regions, introductions are often due to a few, highly prominent sub-categories, with no introductions through others (see Suppl. material 1: Fig. S3 and Matthews et al. 2014). The sub-categories are very specific and so may not be able to incorporate data for new pathways.
Equivalent	No	Sub-categories of the framework are subsets of others. For example, four sub-categories ('nursery material contaminant', 'seed contaminant', 'timber trade contaminant' and 'parasite of plants') are subsets of the 'contaminant of plants' sub-category, while the 'fur farms' sub-category is a subset of the 'farmed animals' sub-category (Harrower et al. 2018).
Distinct	Uncertain	Published assessments have highlighted that the differences between the pathway sub-categories are unclear (Saul et al. 2017, Tsiamis et al. 2017, Grousset et al. 2018, van Wilgen and Wilson 2018). For example, the difference between the 'horticulture' and 'ornamental' sub-categories is uncertain (Tsiamis et al. 2017). Consequently, in some instances, species have been assigned to pathways which are indirectly associated with introduction (although, in some cases, this is due to differing opinions on how classifications should be done (Harrower et al. 2018)), for example, pathogens introduced as contaminants of agricultural products assigned to the 'agriculture' sub-category (Qongqo 2018). Recently produced guidelines for the framework (Harrower et al. 2018) provide detailed descriptions of the main categories and sub-categories and define the pathways in relation to one another. Therefore, the differences between the sub-categories should now be clear. However, as the guidelines have not been widely tested, it is uncertain as to whether the sub-categories are distinct.

be of sufficient detail for classification. Pathways that will pose a challenge include the traditional medicine trade, which is an important pathway of introduction in South Africa (Byrne et al. 2017; Burness 2019). The traditional medicine trade in South Africa largely occurs in informal markets and it is highly unlikely that the details that are required to classify these introductions, according to the sub-categories of the CBD framework, will be available (e.g. whether the species was imported and released to be harvested later, whether it was imported in a form that is ready to be processed/consumed or whether it was farmed in controlled situations from which some individuals escaped). Even if these details were available, most of these introductions would be classified within the catch-all 'other' sub-categories of the framework, while the remaining introductions, those species that are 'farmed' for this purpose, would be classified within the 'horticulture' sub-category. This classification is not useful, as the traditional medicine trade is often informal and it would be inappropriate/ineffective to regulate and manage it in the same way as commercial horticulture. Therefore, the sub-categories of the CBD framework are not general enough to be applicable to this pathway, but they are also not compatible with the available data. While some studies have highlighted that some of the sub-categories are too detailed to be compatible with the available data (e.g. van Wilgen and Wilson 2018), further testing is required to determine the extent to which this is an issue, especially for developing regions.

The reason that the sub-categories of the CBD framework have few of the CAGED properties might be because they were not developed from first principles and were informed by geographically restricted or biased datasets. The guidelines for the framework (Harrower et al. 2018) should reduce the ambiguity of the sub-categories; however, this needs to be widely tested (see Pergl et al. 2020). It is important to note that the definitions proposed by Harrower et al. (2018) highlight that there are often subtle differences between the sub-categories. Therefore, while the proposed definitions could reduce the ambiguity of the sub-categories, for introductions to be consistently and correctly classified, users of the framework will need to invest a considerable amount of time to understand the differences between them. It remains to be seen how many countries will invest the time required.

A way forward

An introduction pathway classification framework will likely be an important tool in efforts to track progress towards meeting the Convention on Biological Diversity's post-2020 target on invasive alien species (Essl et al. 2020). However, the current CBD framework, or at least the framework's sub-categories, has few of the properties that such a framework should have (i.e. the CAGED properties). The relative importance of the CAGED properties will vary depending on the context for which a framework is developed. However, all the CAGED properties are required if frameworks that are developed in a global context (like that proposed by the CBD) are to be effective. We present four scenarios for how the identified issues could be addressed, with the aim of ensuring the development of a global level framework that has categories that are compatible, actionable, general, equivalent and distinct (i.e. CAGED).

1 Refine the current CBD framework: make adjustments as required and create a process for updating and adapting the framework so that it can better respond to the needs of the users. As the framework was developed within the last six years, there may not have been sufficient time for the framework to be adequately tested and for wrinkles to be identified and ironed out. The framework has already been put into practice and so, this would be the simplest way to move forward. As a start, the adjustments and recommendations proposed by Harrower et al. (2018) and Pergl et al. (2020) could be widely tested and adopted and the terminologies could be better aligned with those used in related fields (see Paap et al. 2020). The effort that would be required to implement any changes (i.e. the re-assignment of data) would also need to be considered. Furthermore, before being put into effect, the changes would need to be tested and widely accepted, ideally published in a peer-reviewed journal, recognised by the CBD and maintained as a standard (Wilson et al. 2020-a).
2 Develop a new framework: design a new framework that has categories that are CAGED at a global level. The development of a new framework should ideally be based on first principles and there would have to be a process to obtain consensus from the global community on interpretations of categories and their definitions (Tsiamis et al. 2017). Before adoption, the framework would need to be thoroughly tested using data from a wide range of regions, taxonomic groups and habitats. This test should involve a number of individuals from all groups of stakeholders that would apply the framework (i.e. more than one person should classify pathways using the framework) and the consistency of their classifications should be assessed. This would require a considerable amount of work and records in existing databases that have been classified using the CBD framework would have to be re-classified. This new framework would ideally be backwardly compatible with the CBD framework, though this would be undesirable if it came at the expense of the CAGED properties.
3 Develop context-specific frameworks: biological invasions are not managed at a global scale and so a single global framework may not be appropriate. For example, in South Africa, most known introductions for which a pathway was recorded have been assigned to only four of the CBD framework's sub-categories ('horticulture', 'biocontrol', 'agriculture' and 'other escape') and there were no introductions through ten of the 44 sub-categories (Suppl. material 1: Fig. S3). Therefore, in the South African context, it is inappropriate to manage many of the pathways in the CBD framework and reporting on them could be misleading. For example, there has only been one known introduction to South Africa for fur farming and so, while technically one can report that this pathway is managed, this is misleading (Table 1). The CBD framework may also not be appropriate in the context of secondary dispersal (i.e. dispersal of an alien species after introduction; but see Pergl et al. 2020) and so, a separate framework may be required to monitor and report on the movement of alien species post-border. Therefore, context-specific frameworks could be more valuable. As context-specific frameworks would make data exchanges and cross-cutting research more difficult and labour intensive, they should ideally align.
4 Use a hybrid model: Use the six main categories of the CBD framework (possibly with the recommendations of Pergl et al. (2020) and Paap et al. (2020) incorporated

following testing), but encourage countries to develop their own sub-categories (e.g. that are explicitly relevant for local management) or adapt the sub-categories so that they meet their needs. Countries could report to international organisations at the main category level, but context-specific variation would be accommodated at lower levels of the framework. This would additionally allow countries or regions (e.g. Europe) that have adopted the CBD framework to continue to use it in its entirety.

In conclusion, the main categories of the CBD framework have all of the desirable properties of an introduction pathway classification framework, but the sub-categories have few and so there is a need for improvement. Whether one of the four scenarios listed above is the best way to move forward or whether a different approach is preferable, will require further discussion. Even in the absence of most CAGED properties, all current frameworks can help to improve our understanding of biological invasions. However, to facilitate cross-cutting analyses, provide information for policy and enable reporting to national and international organisations, a classification at a higher level using a few, inclusive categories that fulfil the CAGED properties appears most appropriate. While higher level categorisation can also provide information for management interventions that aim to prevent introductions and facilitate the prediction of threats, detailed, context-specific categories may be more effective in these instances. Thus, our view is that, while it is possible to refine or fundamentally recast the CBD framework, a universal framework may simply be too general to ever be useful in specific applied contexts. As such, we believe a hybrid model – a few general categories at the global scale and context-specific sub-categories driven by local needs at a regional level – may be the most appropriate.

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Supplementary material 1

Evidence used to assess the introduction pathway classification frameworks

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Data type: Additional information

Explanation note: Evidence not included in the paper that was used to assess whether three introduction pathway classification frameworks are fit for purpose.

Link: https://doi.org/10.3897/neobiota.62.53543.suppl1

Appendix 1

Introduction pathway classification framework		Proposed revisions to the introduction pathway classification framework	
RELEASE IN NATURE	Biological control	Biological control	RELEASE
	Erosion control/dune stabilisation	**Stabilisation and barriers**	
	Fishery in the wild	Fishery in the wild	
	Hunting	Hunting	
	Landscape/flora/fauna "improvement" in the wild	**Aesthetic release**	
	Introduction for conservation purposes or wildlife management	**Conservation in wild**	
	Release in nature for use other than above	**Other release**	
	Other intentional release		
ESCAPE FROM CONFINEMENT	Agriculture	Agriculture	ESCAPE
	Aquaculture/mariculture	**Aquaculture**	
	Botanical garden/zoo/aquaria	**Botanical gardens & zoos**	
	Pet/aquarium/terrarium species	**Pet**	
	Farmed animals	Farmed animals	
	Forestry	Forestry	
	Fur farms	Fur farms	
	Horticulture	Horticulture	
	Ornamental purpose other than horticulture	**Ornamental**	
	Research and ex-situ breeding	**Research**	
	Live food and live baits	Live food and live bait	
	Other escape from confinement	**Other escape**	
TRANSPORT-CONTAMINANT	**Contaminant nursery material**	**Nursery material contaminant**	CONTAMINANT
	Contaminated bait	**Bait contaminant**	
	Food contaminant	Food contaminant	
	Contaminant on animals	**Contaminant of animals**	
	Parasites on animals	**Parasites of animals**	
	Contaminant on plants	**Contaminant of plants**	
	Parasites on plants	**Parasites of plants**	
	Seed contaminant	Seed contaminant	
	Timber trade	**Timber trade contaminant**	
	Transportation of habitat material	**Habitat material contaminant**	
	NA	**Other contaminant**	
TRANSPORT-STOWAWAY	**Angling/fishing equipment**	**Fishing equipment**	STOWAWAY
	Container/bulk	**Container/bulk cargo**	
	Hitchhikers in or on airplane	**Airplane**	
	Hitchhikers on ship/boat	**Ship excluding ballast water or hull fouling**	
	Machinery/equipment	**Machinery & equipment**	
	People and their luggage/equipment	**People & luggage**	
	Organic packing material, in particular wood packaging	**Packing material**	
	Ship/boat ballast water	**Ballast water**	
	Ship/boat hull fouling	**Hull fouling**	
	Vehicles	**Land vehicles**	
	Other means of transport	**Other stowaway**	
CORRIDOR	**Interconnected waterways/basins/seas**	**Canals and artificial waterways**	CORRIDOR
	Tunnels and land bridges	**Tunnels and bridges**	
UNAIDED	**Natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5**	**Natural dispersal**	UNAIDED

Figure A1. The introduction pathway classification framework developed for the Convention on Biological Diversity and changes, shown in bold, to the framework as recommended in guidelines produced by Harrower et al. (2018). The guidelines were written specifically to avoid making major changes to the framework. The proposed structural changes were that two overlapping sub-categories be merged and that a catch-all sub-category (called 'other contaminant') be added for contaminant introductions that do not fit into any of the detailed sub-categories.

Supplementary material 1: Evidence used to assess the pathway frameworks

Evidence for the assessment of the framework used by the New Zealand biosecurity surveillance system

Table S1. The evidence used to assess the framework used by the New Zealand biosecurity surveillance system. Presented are the CAGED properties of pathway frameworks, the outcomes of an assessment indicating which of the five properties the framework possesses, and the evidence. Categories were partially compatible as some categories possessed the property, but not all.

Property	Outcome	Evidence
Compatibility	Partially	Some categories will not be compatible with the data that are available in some regions. The framework is compatible with the data that are available in New Zealand, which has one of the best biosecurity systems in the world, and where interceptions are meticulously recorded (Ministry of Agriculture and Forestry (MAF) Biosecurity New Zealand 2008). However, in other regions, such as South Africa where interception data are not readily available (Faulkner et al. 2017), it is often not known whether a species has been intentionally imported through the mail or through other processes.
Actionability	Yes	The categories of the framework were developed in the context of at-border interventions and the links between the categories and the location of these interventions are clear (Figure S1).
Generality	No	The framework does not make provision for introductions where alien species spread through natural dispersal over land borders, and the 'sea' and 'air' categories are only applicable to certain regions, taxa or habitats (see Table S2). The categories are inclusive and so it is likely that it will be possible to integrate data for current and historical pathways as well as those that will develop in the future.
Equivalency	No	Categories are subsets of other categories. For example, goods can be imported through the mail and, therefore, the 'mail' category is a subset of the 'imports' category.
Distinctness	Yes	Assessment made by the authors based on information on the framework (see Ministry of Agriculture and Forestry (MAF) Biosecurity New Zealand 2008) and knowledge of pathways of introduction.

Table S2. The six categories of the pathway framework used by the New Zealand biosecurity surveillance system, and details on the regions, taxa and habitats for which the categories are applicable.

Category	Region	Taxa	Habitat
Imports	All	Invertebrates, vertebrates and plants (e.g. imported pets and plants, and insects and seeds in containers)	Terrestrial, freshwater and marine (e.g. terrestrial species imported for horticulture, marine or freshwater species imported for the aquarium trade)
Vessels	All	Invertebrates, vertebrates and plants (e.g. rodents that stowaway on vehicles, hull fouling invertebrates, and seeds on vehicle's tyres)	Terrestrial, freshwater and marine (e.g. rodents on vehicles, freshwater species on the hulls of ships, and marine species in ballast water)
Passengers	All	Invertebrates, vertebrates and plants (e.g. eggs of pet birds in luggage, invertebrates on fruit in luggage, and seeds in luggage)	Terrestrial, freshwater and marine (e.g. seeds in luggage, eggs of freshwater and marine pets in luggage)
Mail	All	Invertebrates, vertebrates and plants (e.g. pet reptiles and invertebrates, and seeds of garden plants)	Terrestrial, freshwater and marine (e.g. pet reptiles, and freshwater and marine plants for aquaria)
Sea	Only countries with a sea border. Not applicable to landlocked countries	Invertebrates, vertebrates and plants (e.g. marine fish, invertebrates or plants that naturally disperse from their introduced range)	Terrestrial and marine (e.g. insects transported passively on floating wood, and marine invertebrates with planktonic larvae). Not applicable for freshwater species
Air	All	Invertebrates, vertebrates and plants (e.g. birds, insects or plants that naturally disperse from their introduced range)	Terrestrial (e.g. seeds blown by the wind). Not applicable for freshwater or marine species

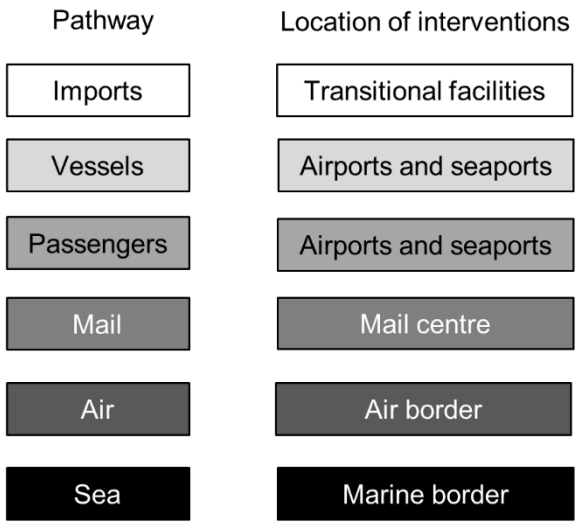

Figure S1. The six categories of the pathway framework used by the New Zealand biosecurity surveillance system, and the location of the interventions for each category (Ministry of Agriculture and Forestry (MAF) Biosecurity New Zealand 2008). The locations within airports and seaports where interventions take place will differ for vessels and passengers.

Evidence for the assessment of the main categories of the CBD framework

Table S3. The evidence used to assess the main categories of the CBD framework. Presented are the CAGED properties of pathway frameworks, the outcomes of an assessment indicating which of the five properties the categories possess, and the evidence.

Property	Outcome	Evidence
Compatibility	Yes	Compatibility does not appear to have been an issue in studies that have used the categories (e.g. Pyšek et al. 2011, Faulkner et al. 2016, Pergl et al. 2017).
Actionability	Yes	The categories were developed to inform existing regulatory instruments and the links between the categories and regulations are clear (Figure S2).
Generality	Yes	The categories were developed with universality in mind (Hulme et al. 2008) and have been successfully used in a number of published assessments to classify pathways from different regions [e.g. South Africa (Faulkner et al. 2016) and Czech Republic (Pyšek et al. 2011)], taxonomic groups (Faulkner et al. 2016, Padayachee et al. 2017, Pergl et al. 2017) and habitats (Padayachee et al. 2017). The categories are inclusive and so it is likely that it will be possible to integrate data for current and historical pathways as well as those that will develop. We found one study, a horizon scanning exercise (Matthews et al. 2017), where a category called 'other' was used instead of 'unaided'. This 'other' category was only used for a few macroinvertebrates, and this issue does not appear to be prevalent.
Equivalency	Yes	None of the categories is a subset of another category.
Distinctness	Yes	Published assessments that have used the categories have not indicated that they are ambiguous. Furthermore, when implementing the categories in published assessments (e.g. Faulkner et al. 2016), the authors found them to be distinct.

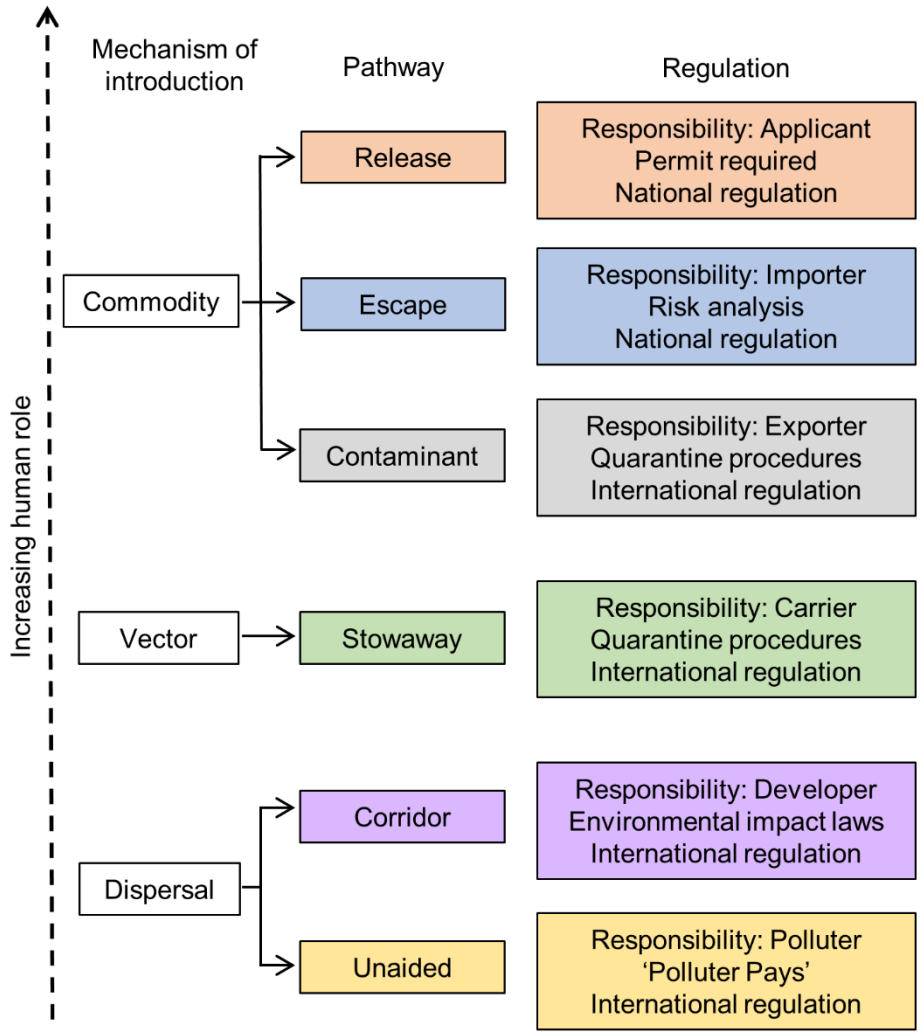

Figure S2. The pathway classification framework developed by Hulme et al. (2008). The framework recognises that an organism can be introduced to a new region through three mechanisms of introduction (the importation of a commodity, the arrival of a transport vector and the natural dispersal of an alien species) and that these mechanisms are associated with six pathway categories. The regulatory methods that are used to manage each pathway are shown. The six categories of this framework form the main categories of the framework adopted by the CBD.

Additional evidence for the assessment of the sub-categories of the CBD framework

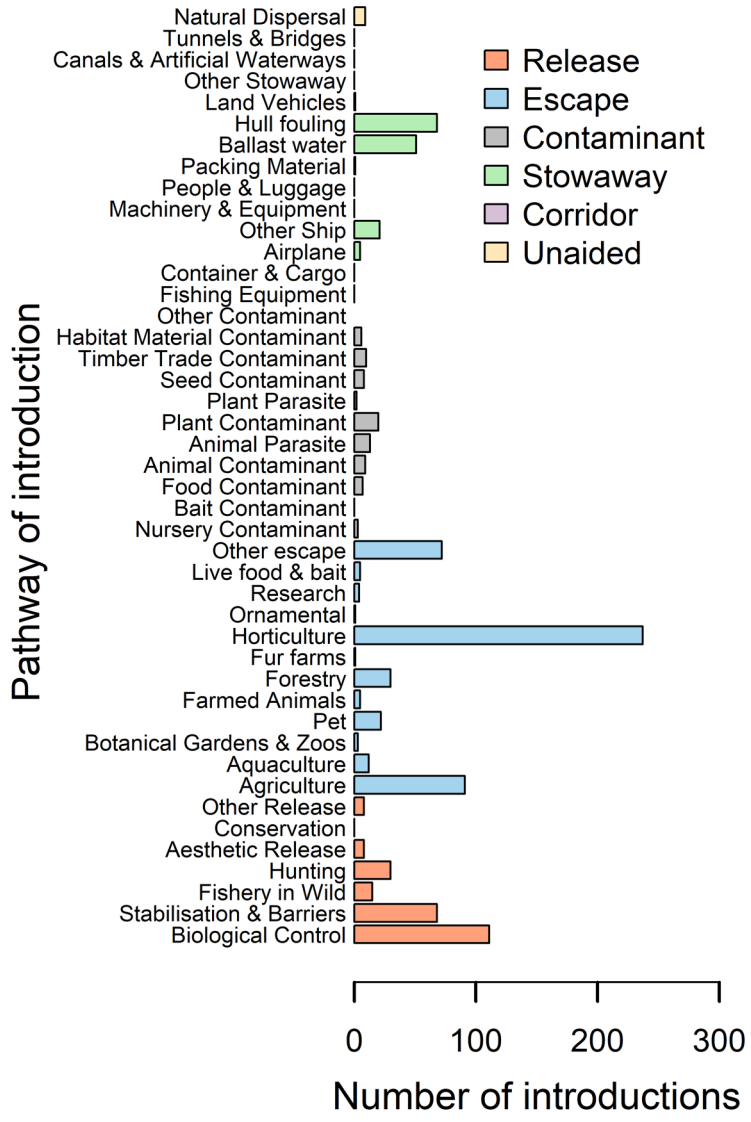

Figure S3. The number of taxa introduced to South Africa through the pathways of introduction, as classified using the sub-categories of the CBD framework. Most introductions are only through a few sub-categories, with many sub-categories having no introductions. For many alien taxa in South Africa pathway of introduction data is not available. Data from van Wilgen and Wilson (2018).

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