Uncertainty in invasive alien species listing
Author(s): Melodie A. McGeoch, Dian Spear, Elizabeth J. Kleynhans and Elrike Marais
Source: Ecological Applications, Vol. 22, No. 3 (April 2012), pp. 959-971
Published by: Ecological Society of America
Stable URL: http://www.jstor.org/stable/23213930
Accessed: 07-01-2016 09:39 UTC

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp
JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.
Uncertainty in invasive alien species listing

MELDIE A. McGECH,1,2,3 DIAN SPEAR,2 ELIZABETH J. KLEYNHANS,2 AND ELRIKE MARAIS2

1Cape Research Centre, South African National Parks, P.O. Box 216, Steenberg 7947 South Africa
2Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602 South Africa

Abstract. Lists of invasive alien species (IAS) are essential for preventing, controlling, and reporting on the state of biological invasions. However, these lists suffer from a range of errors, with serious consequences for their use in science, policy, and management. Here we (1) collated and classified errors in IAS listing using a taxonomy of uncertainty; and (2) estimated the size of these errors using data from a completed listing exercise, with the purpose of better understanding, communicating, and dealing with them. Ten errors were identified. Most result from a lack of knowledge or measurement error (epistemic uncertainty), although two were a result of context dependence and vagueness (linguistic uncertainty). Estimates of the size of the effects of these errors were substantial in a number of cases and unknown in others. Most errors, and those with the largest estimated effect, result in underestimates of IAS numbers. However, there are a number of errors where the size and direction of the effect remains poorly understood.

The effect of differences in opinion between specialists is potentially large, particularly for data-poor taxa and regions, and does not have a clearly directional or consistent effect on the size and composition of IAS lists. Five tactics emerged as important for reducing uncertainty in IAS lists, and while uncertainty will never be removed entirely, these approaches will significantly improve the transparency, repeatability, and comparability of IAS lists. Understanding the errors and uncertainties that occur during the process of listing invasive species, as well as the potential size and nature of their effects on IAS lists, is key to improving the value of these lists for governments, management agencies, and conservationists. Such understanding is increasingly important given positive trends in biological invasion and the associated risks to biodiversity and biosecurity.

Key words: bias; bioindicators; biosecurity; expert judgment; inventories; scientific error; species databases.

INTRODUCTION

Lists of alien and invasive alien species (IAS) are an essential tool in the management of biological invasions (Ricciardi et al. 2000, Kolar and Lodge 2001). They are widely used in risk assessments underpinning quarantine and prevention strategies, as well as in the development of appropriate and effective control methods (Wittenberg and Cock 2005). Early warning, prevention, and control measures for IAS rely heavily on information on which alien species are present in the region or country of concern, as well as their invasion status there and elsewhere. The identity and associated biology and distribution of alien species also form the foundation for developing effective practices for controlling those species that have established and spread (Rejmánek and Richardson 1996). Furthermore, governments and management agencies commonly make alien species listing decisions as the basis for implementing IAS legislation (Shine et al. 2005, Lodge et al. 2006).

Lists of alien and invasive alien (henceforth “invasive” for the sake of brevity) species have also more recently been used for reporting on biodiversity targets and indicating the status of, and trends in, biological invasions with the purpose of informing policy (Shine et al. 2005, Simberloff et al. 2005, Hulme et al. 2009). This includes the use of IAS information to measure progress towards the Convention on Biological Diversity’s 2010 Biodiversity Target to reduce threats to biodiversity (Butchart et al. 2010), as well as the European Union’s Headline Biodiversity Indicator “Trends in invasive alien species in Europe” (EEA 2010). Complete and accurate listing information is clearly important for global indicators, such as these, of the effectiveness of policy and of other responses to the IAS problem (McNeely et al. 2005, Meyerson and Mooney 2007, Stoett 2010).

In spite of their value and ubiquitous use, the compilation of invasive species lists is fraught with challenges. For example, if the number of IAS in a country is confounded by the amount of information available, the patterns observed are, at least partly, a consequence of information availability rather than actual numbers of IAS in the country (McGeoch et al. 2010). Comparisons across countries are then similarly
confounded (Pyšek et al. 2008). Furthermore, increases in IAS through time in understudied regions will likely represent increases in monitoring and recording effort and not actual trends in numbers of IAS present in a country (Crooks 2005, Caley et al. 2008). From a management perspective, incomplete or poorly contextualized alien and invasive species lists pose a biosecurity risk and may significantly reduce the effectiveness of prevention and control strategies (see Kolar and Lodge 2001). Finally, government and public trust depends on the scientific credibility of decisions guiding policy and justifying the substantial investment in IAS management interventions (McNeely et al. 2005, Stoett 2010, Hattingh 2011).

Avoiding errors in species listing processes and understanding inherent biases and inaccuracies are important for many areas in conservation biology and its application for policy development. The size and direction of sources of error that occur in IAS listing are of particular significance. Here we provide a comprehensive assessment thereof based on (1) published literature identifying and discussing such sources of error, and (2) using data gathered to estimate the number of IAS in countries as a measure of the pressure of biological invasions on biodiversity (McGeoch et al. 2010). We classify the types of uncertainty arising from these errors better to understand their origin, nature, and possible solutions, as well as to facilitate communication when dealing with IAS listing and data collation exercises (Regan et al. 2002, Walker et al. 2003). We focus on invasive alien species (defined here as that subset of alien species that has a negative ecological impact; McGeoch et al. 2010) rather than alien species per se, although the majority of errors are similarly relevant to alien listing processes, regardless of the biological definition used. This assessment is the first to collate, classify, and estimate the effects of IAS listing errors, and is intended to aid future listing exercises and to improve the transparency and comparability of IAS lists.

METHODS

Errors and associated uncertainty

We first identified from the literature the potential and realized errors recognized for IAS listing. A search was conducted for published information on any errors recognized in alien and invasive species lists or in the process of compiling such lists. In total 10 errors were identified. Each of these was then classified according to Regan et al.’s (2002) “taxonomy of uncertainty,” as either epistemic (associated with knowledge of the system) or linguistic (related to scientific vocabulary) uncertainty (Table 1). Each error was then further classified into the various types of uncertainty under the two main classes: epistemic as a measurement error, systematic error, natural variation, subjective judgment, or model uncertainty; and linguistic as vagueness or context dependence (Table 1; Regan et al. 2002, Walker et al. 2003). In conducting this classification, several cases occurred where a particular error could be assigned to more than a single uncertainty type, and in some cases, was subject to a specific interpretation of the error and its relevance to IAS listing (see also Regan et al. 2002). We attempted to assign errors to uncertainty types based on factors most pertinent to the IAS listing process, although alternative interpretations and classifications are possible in some cases. We also requested three invasion biologists (not coauthors) to independently classify the errors. Based on the outcome of the independent classification and comments received, we revised and clarified the explanations of a number of the errors.

Effect of errors

Once the range of errors associated with IAS lists and the listing process had been compiled and classified into uncertainty classes and types, the effect of each of these errors was examined. This was achieved by using IAS lists compiled by ourselves to (1) identify the direction of the effect that the error has on IAS lists (e.g., inflating or underestimating species numbers), and (2) to estimate the extent or size of the effect (not statistical effect size, but rather an estimate based on available examples of the degree to which invasive species lists may be prone to the particular error). It was necessary to compile our own list because existing lists were either not sufficiently representative or systematic, the methods and definitions used to compile the lists were variable or not transparent, or the raw data were not available to us (see section below: Designation of alien species as invasive). Nonetheless, we did draw extensively on existing lists as a source of information (see Appendix A; McGeoch et al. 2010).

Data compilation for IAS lists

We compiled IAS data using a “documented evidence” approach (Sutherland et al. 2004), i.e., using information in peer-reviewed literature, reference books, and electronic databases on alien and invasive species that cited scientific literature (see Appendix A; McGeoch et al. 2010). We refer to this as the DE-IAS (documented evidence IAS) list. A stratified-random set of 57 countries was selected for which DE-IAS country lists were compiled (representative of different country sizes, climatic regions, continents, and degrees of economic development (Appendix B; see McGeoch et al. 2010 for methods). Taxa included were alien vascular plants, birds, fish, amphibians, mammals, and marine organisms.

Presence and impact information on species in each of the 57 countries were obtained directly from the primary scientific literature, as well as from reference books and electronic databases on alien and invasive species that cited scientific literature (Appendix A). ISI Web of Science and Google Scholar were also searched for species introduction and ecological impact information for all taxa. Keywords used in these searches to compile
country lists were “invasive,” “alien,” “nonindigenous,” “introduced,” “exotic,” and species and country names. The indigenous geographic range of a species was accepted as the indigenous distribution range provided by electronic databases and reference books (Appendix A). A conservative approach was adopted, classifying species as indigenous if there was uncertainty in their indigenous geographic range.

**Designation of alien species as invasive**

Using this information, a formal, systematic decision-making process was followed for the inclusion of each species onto the DE-IAS list for a particular country (Fig. 1), i.e., to designate an alien species as invasive in that country. This process was adopted to ensure that species inclusion was as standardized, transparent, and repeatable as possible (Pullin and Stewart 2006). Three evidence-based criteria were used to designate established alien species as invasive in a particular country (Fig. 1), and the 57 DE-IAS country lists were compiled using these criteria. A species was included in the DE-IAS country list if it met any one of these three criteria, and the criterion by which it was included is recorded as follows:

- **Criterion 1** Alien species that had a demonstrated impact on indigenous biodiversity in the country in question; for example, via hybridization, competition, predation, change in fire regimes, or altered food web dynamics (Spear and Chown 2009; Vilà et al. 2010). This criterion was considered the most robust evidence of invasiveness at the country level.

- **Criterion 2** Alien species that had an extensive distribution range, are very abundant, or had a high population growth rate in the country. Widespread and abundant alien species were assumed to impact biodiversity (see Pyšek and Hulme 2005, Vilà et al. 2010) via (1) the displacement of individuals of indigenous species, and (2) the alteration of ecosystem functioning (e.g., nutrient cycling, shade, and water cycling) of the system that they invade. This criterion was considered to provide some evidence of alien species invasiveness at the country level.

- **Criterion 3** Invasive elsewhere, i.e., the established alien species was invasive anywhere else (other than the country in question) in the introduced range of the species based on criterion one or two. “Invasiveness elsewhere” has been demonstrated to be a strong (albeit not perfect) predictor for the likely invasiveness of an alien species at a new location (Reichard and Hamilton 1997, Duncan et al. 2003), and history of invasion success has been found to be related to likelihood of establishment (Hayes and Barry 2008). However, there are certainly instances where species are invasive in some regions of their introduced range and not in others (e.g., see Reichard and Hamilton 1997). This criterion was thus considered the least robust of the three criteria used. Freshwater fish, mammals, birds, amphibians, and marine organisms were evaluated based on all three criteria (Fig. 1), and plants on criterion 3 only (due to the prohibitive number of searches required [~18 012] in the latter case). Plants were thus used in only a subset of the analyses as appropriate.

Once this process had been completed, the collated DE-IAS list (i.e., across all 57 countries) included 2871 records of 542 species (316 vascular plant, 101 marine organisms, 44 freshwater fish, 43 mammal, 23 bird, and 15 amphibian species), with presences and absences assigned for each of these species per country. This data set was then used to estimate the effect of as many of the 10 listing errors as was possible.

**Quantifying the effects of errors from the compiled data**

To assess the effect of the three criteria described above on the “documented number of IAS per country” (i.e., to estimate the effect of errors 4 and 6; Table 1), the IAS data were expressed for (1) all three criteria (impact, spread, and invasive elsewhere) and (2) criterion 1 only (demonstrated impact in a particular country). The total number of IAS for these two data sets was compared using a Wilcoxon matched-pairs test (Statistica 8.0; Statsoft 2008), to determine if using indirect evidence of invasiveness (i.e., criterion 3; Fig. 1) contributed significantly to the total number of listed species (to estimate the effect of error 4a; Table 1). The proportion of species in the DE-IAS list (none of which were themselves double counted as a consequence of not recognizing synonyms) that had synonyms was also calculated (error 1; Table 1).

To determine the relative consequences of using documented evidence vs. specialist judgments in compiling lists of DE-IAS (although they are often used to supplement incomplete data, such judgments have been shown to be error prone; Burgman 2004), 23 DE-IAS lists were assessed by a selection of 19 different country and/or taxon specialists (e.g., the full bird list by an alien bird specialist, and the plant list for Kenya by a Kenyan alien plant specialist; Appendix C). Specialists were considered to be persons who had published on the subject (i.e., alien species of a particular taxon in a particular country or region) and whose principle employment or academic career involved this subject area. Specialists were asked to agree (A, true positive) or disagree (B, false positive, assuming here that the specialist is correct) with the inclusion of each species on the DE-IAS list, or to state that they did not know (C), based on their knowledge of the negative impact of each species on biodiversity. They were also asked to add species to the DE-IAS list that in their opinion should be considered invasive, but that were not on the DE-IAS list provided to them (D, false negative, assuming here that the specialist is correct). Results were collated across country lists for particular taxa, and across taxa for particular countries to calculate medians for components A–D. Kruskall-Wallis tests were used to identify if there were significant differences in the numbers of species listed using the two approaches (documented vs. specialist judgment) for different
Table 1. Errors in lists of invasive alien species (IAS).

<table>
<thead>
<tr>
<th>Errors</th>
<th>Explanation</th>
<th>Uncertainty classes (E, L) and types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Human error</td>
<td>Erroneous information in lists and databases, that can also be perpetuated (Pyšek 2003), e.g., misidentification of species, not recognizing synonyms and other errors in data entry (Isaac et al. 2004).</td>
<td>E; measurement error</td>
</tr>
<tr>
<td>2) Incomplete information searches</td>
<td>If searches of data sources are not comprehensive, this results in incomplete lists.</td>
<td>E; measurement error</td>
</tr>
<tr>
<td>3) Species identification</td>
<td>Alien species are misidentified as a result of taxonomic uncertainty, such as undescribed species or taxa where the systematics have not been fully resolved (Ruiz et al. 2000, Pyšek 2003, Pyšek et al. 2008, Carlton 2009, Galil 2009).</td>
<td>E; systematic error†</td>
</tr>
<tr>
<td>4) Survey information on presence, extent, and population dynamics outside of indigenous range</td>
<td>a) Information on the establishment and spread is required to designate alien species as invasive (Pyšek et al. 2004). Insufficient survey information results in failure to recognize invasive species. As survey data increase, invasive species are more likely to be recognized. b) Invasive alien species assemblages are dynamic and require regular surveys (see Plate 1) to maintain accurate species counts and information on distribution and population size (Crooks 2005).</td>
<td>E; systematic error as a result of lack of knowledge E; natural variation‡</td>
</tr>
<tr>
<td>5) Resolution of data and scaling of &quot;alien range&quot;</td>
<td>a) Overestimation due to the coarse resolution of alien species distribution maps or geographic listings, e.g., marine organisms listed by marine ecoregions that encompass multiple countries (Hulme 2003, Molnar et al. 2008). b) Extralimital species (i.e., species introduced outside their natural geographic range within a geopolitical area) are often not recognized as invasive or potentially invasive and are thus not considered or included in the listing process (Richardson et al. 2000, Pyšek et al. 2004, Guo and Ricklefs 2010).</td>
<td>E; systematic error as a result of lack of knowledge L; context dependence</td>
</tr>
<tr>
<td>6) Data and knowledge not documented</td>
<td>Data are not available in the form of publications (books and primary literature), electronic, or online databases (Simpson et al. 2006), i.e., evidence may exist (and specialists may recognize invasive alien species), but this has not yet been documented, or existing documentation is outdated (Carlton 2009). This may result, for example, from the time delay between discovery and publication. Eradicated or extirpated species may also remain on species lists for the same reason (Richardson et al. 2000).</td>
<td>E; systematic error as a result of lack of (documented) knowledge</td>
</tr>
<tr>
<td>7) Documented data and knowledge not readily or widely accessible</td>
<td>Information in gray literature is not readily or widely accessible (Simpson et al. 2006). There are language barriers to information and data transfer. A wide range of data sources and forms exist, and data are not always sufficiently well collated, i.e., there is often no single comprehensive data source that encompasses either a broad range of taxa and/or regions.</td>
<td>E; systematic error as a result of lack of knowledge</td>
</tr>
<tr>
<td>8) Baseline information on indigenous range</td>
<td>Inadequate indigenous range information (Richardson et al. 2000, Pyšek 2003), such as cryptogenic species (Carlton 1996), resulting in subjective interpretation (based on a scarcity of evidence and with a random outcome) of species as being either alien or not.</td>
<td>E; subjective judgment as a result of lack of knowledge</td>
</tr>
<tr>
<td>9) Research on biodiversity impact</td>
<td>As a result of limited information on the biodiversity impact of alien species, predictors of invasiveness result in incorrect listing decisions, e.g., risk assessment models or predictor variables (such as the use of &quot;invasiveness elsewhere&quot; in Fig. 1, which is not a perfect predictor of invasiveness locally (Reichard and Hamilton 1997).</td>
<td>E; model uncertainty as a result of lack of knowledge</td>
</tr>
</tbody>
</table>
Table 1. Continued.

<table>
<thead>
<tr>
<th>Errors</th>
<th>Explanation</th>
<th>Uncertainty classes (E, L) and types</th>
</tr>
</thead>
<tbody>
<tr>
<td>10) Species designation as invasive</td>
<td>a) A wide range of alternative definitions exist for alien and invasive species, and the adoption of alternative definitions results in differences in IAS lists (Valery et al. 2008, Richardson et al. 2011). b) Scientists use a range of different approaches to designating aliens as invasive (Richardson et al. 2000, Pyšek et al. 2004, Valery et al. 2008); their decisions are often experience based, and in the absence of evidence-based knowledge may vary substantially between specialists (Burgman 2001, Cook et al. 2010).</td>
<td>L: vagueness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E: subjective judgment</td>
</tr>
</tbody>
</table>

**Note:** The uncertainty class is shown as epistemic uncertainty (E) or linguistic uncertainty (L), with further descriptions of subcategories (types) of these uncertainties, following Regan et al. (2002).

† Although we classify taxonomic uncertainty as a form of systematic error, Regan et al. (2002) also consider it to be a subtle form of uncertainty related to the “indeterminacy of theoretical terms” (i.e., linguistic), where usage of a term may change over time as a consequence of advances in knowledge, such as taxonomic revisions and reclassifications.

‡ Natural variation as a form of epistemic uncertainty in extreme cases becomes ontological uncertainty, i.e., inherent, persistent variability renders systems highly unpredictable, and although this probabilistic feature of biological invasions can be better understood (epistemic), it cannot be changed or removed (ontological) (Walker et al. 2003).

taxonomic groups and countries. The omission error (false negative fraction, i.e., underestimated fraction of IAS) was calculated for each list ([D/(A + D)], as were disagreement ([B/(A + B + C)]) and agreement fractions (one-agreement fraction) (Fielding and Bell 1997). These results were used to estimate the effect of errors 5a, 6, 8, and 10b (Table 1).

To evaluate the contributions to country and taxon lists made by the range of different data sources, the number of records (species by country) from each source was counted (to estimate the effect of errors 1, 7, and 10; Table 1). Often individual records had multiple sources because the information was repeated across two or more sources. The Global Invasive Species Database (GISD) was used as the baseline (because it has the broadest geographic and taxonomic coverage), and other electronic databases and information sources (Appendix A) were used to supplement this. The results therefore show how many alternative information sources were required to obtain data across a spectrum of taxa and countries.

**Results**

Errors and associated uncertainty

The 10 error sources identified from the literature related in many cases to inadequate information on the

![Species inclusion in country lists](image)

**Fig. 1.** Systematic decision-making process by which species were included in the documented evidence-based invasive alien species (DE-IAS) country lists (SxC lists), i.e., the criteria used to designate an alien species as invasive. Definitions of the criteria are: criterion 1, ecological impact in country; criterion 2, evidence for significant increase in range and/or abundance in country; criterion 3, present in country, with ecological impact evidence from elsewhere in the world.
identity (including systematics), presence, abundance, range, and impact of IAS (Table 1). Other errors refer to incomplete IAS lists as a consequence of inaccessible or difficult to access information on particular IAS taxa, and in particular countries or parts of the world. These result either from information being unpublished, language barriers to information access, information available across a wide array of disparate sources (lack of data collation), and information not always being electronically available. Eight of the 10 errors were largely epistemic (i.e., relate to knowledge and its acquisition via measurement), and the remaining two had elements of both epistemic and linguistic uncertainty (Table 1). The latter include differences in decisions as a consequence of multiple approaches to defining and designating IAS, experience-based rather than evidence-based decisions (error 10), and uncertainty related to historical and current species distributions (error 5) (Table 1). Three of the errors resulted from more than a single type of uncertainty (errors 4, 5, and 10; Table 1).

**Effect of errors**

It was possible to calculate estimates for eight of the 10 species listing errors in Table 1 using the DE-IAS information. These estimates are summarized in Table 2, re-ordered, and grouped under the seven uncertainty types (Table 1).

**Measurement error.**—Measurement errors have a range of effects on the number of IAS listed, with incomplete searches underestimating, and synonyms likely to overestimate the numbers of listed species (Table 2). The misidentification of alien species may result from human error (error 1; Table 1), in which case it is a form of measurement error, but could also be a consequence of unresolved systematics of a taxon (Table 1). In the latter case, it could be considered a form of systematic error (see next section, error 3; Table 1), because species identifications are likely to be consistent (nonrandom), based on current taxonomic knowledge. The effects of species misidentification and incomplete information searches on IAS listing could not be estimated from available data (Table 2), but the latter is assumed to be small where searches are systematic and thorough (Pullin and Stewart 2006), as was the case here. Synonyms were found for 89.9% of the 542 species in the DE-IAS list. The maximum potential for error in IAS listing as a consequence of synonyms is thus high, albeit unlikely given that it is common practice to check for synonyms.

**Systematic error and natural variation.**—Lack of survey information on identity, abundance, distribution, and population dynamics results in underestimates of the number of IAS (Table 2; see Plate 1). Across birds, mammals, amphibians, freshwater fish, and marine organisms, only 5.0% of country records were included based on information on spread (and none on population size information, criterion 2; Fig. 2). Of the total number of records for taxa in Fig. 2 (226 species, 1088 records), only 21.87% were included based on evidence of impact in the country (criterion 1, 16.63%), or evidence of rapid range expansion somewhere in their introduced range (criterion 2, 5.24%). This means that the large majority of records (78.13%) for these were included in the DE-IAS country lists based on evidence of impact elsewhere (criterion 3; Fig. 1).

In 1% of cases, species in the DE-IAS country lists were considered to be absent from the country in question by specialists (i.e., nonindigenous range designation error) (error 5a, but see also error 8; Table 2). Bias as a result of this error is also partly a consequence of natural variation, because fluctuations in abundance and distribution are inherently difficult to measure comprehensively. However, it was not possible to estimate the effect of natural variation on IAS lists (error 4b; Table 2).

Additional IAS were suggested by specialists in 17 of the 23 country and taxon lists assessed (i.e., with an omission error fraction of 31% on average (0.31 ± 0.30 [mean proportion ± SD]), median = 0.18, n = 23; Table 2, Fig. 3). Specialists assessed 1022 species records and suggested 455 additional species (406 of which were plants).

There was also no single comprehensive data source available to compile DE-IAS lists for any single taxon or country (Fig. 4). CAB International’s Crop Protection Compendium (CABI-CPC) contributed most country records (1332 [46.4%] of 2871), although it deals exclusively with crop pests, largely plants (Fig. 4). By comparison, although the Global Invasive Species Database (GISD) covers all taxa, it underrepresented some taxa and regions. For example, marine organisms and plants were particularly underrepresented in GISD, and regional (DAISIE) and taxon-specific (FishBase) databases provided significant complimentary information (Fig. 4). Overall, GISD contributed 49.6% of the total number of species records (n = 269/542).

**Subjective judgment.**—Inadequate information on species indigenous ranges also results in subjective judgments that could either inflate or underestimate (as in the case of the DE-IAS because species were designated indigenous in uncertain cases) numbers of species (error 8, but see also error 5a; Table 2).

On average, the level of agreement between DE-IAS lists and specialists was 78% (0.78 ± 0.23 [mean proportion ± SD], median = 0.84, n = 23; Fig. 3). There was significantly lower agreement (Fig. 3a) by specialists with the DE-IAS bird lists than with other taxonomic groups (H = 8.357, P = 0.038), and the strongest agreement was for the mammal lists (Fig. 3a). Similarly, agreement between specialists and the DE-IAS lists tended to be lower for the United Kingdom than for South Africa and New Zealand (Fig. 3b). There were, however, also large differences in the outcomes of different specialists assessing the same list. For example, omission error estimates ranged between 11% and 57% for South African plants (n = 3 specialists), between 6%
and 31% for South African fish (n = 3), and agreement levels ranged between 40% and 82% for New Zealand birds (n = 2).

**Model uncertainty.**—The comparative shortage of studies on biodiversity impact at the country level results in a form of model uncertainty (at least with the DE-IAS approach), because species designation as invasive then has to rely on imperfect predictors, in this case “invasive elsewhere” (criterion 3; Fig. 1), of whether a species is invasive in a particular country or not (Fig. 2, Table 1; Hayes and Barry 2008). Across the DE-IAS country lists generated, only a small proportion of
records could be included based on evidence of biodiversity impact by the species in the countries in which they were present (criterion 1; Fig. 1, Fig. 2). If this most rigorous criterion was the only one used in the listing process, the number of records of particular species in particular countries would have been reduced by 78.1% (across birds, freshwater fish, mammals, amphibians, and marine organisms), and resulted in 36.8% of the 57 countries having no IAS listed for the taxa examined (significant difference between number of records using criterion 1 vs. using all criteria; \( Z = 6.51, P < 0.0001 \)).

**Vagueness and context dependence.**—No estimates of the size of the effect of linguistic uncertainty could be calculated with the available data (errors 10a, 5b; Table 2).

In summary, not only is there a wide range of sources of error, but estimates of the size of the potential effects of these were substantial in a number of cases (\( >10\% \)) and unknown in others (Table 2). In most cases, the error was likely to result in an underestimate in numbers of IAS, particularly for those errors that were estimated to have the greatest effect (inadequate survey, range and impact information, and undocumented and inaccessible information; errors 6–7, 9–10; Table 2). The two errors that may overestimate numbers of species on IAS lists are both estimated to, with the necessary corrective action, have comparatively minor effects (errors 1, 5a; Table 2). Differences of opinion between specialists are potentially large, and do also not have a clearly directional or consistent effect on the size and composition of IAS lists (errors 6, 10b; Table 2).

**DISCUSSION**

Uncertainty in the listing of invasive alien species clearly has multiple sources. Nonetheless, the majority are epistemic in nature, and in most cases, result from either a lack of knowledge or from measurement error. Seven of the 10 errors identified in IAS listing occur as a primary consequence of a lack of information. Insufficient data on the identity, distribution, and impacts of IAS is particularly problematic. For example, in Europe, considered to be one of the most historically intensively studied regions for IAS, a targeted investment (via

---

**Fig. 2.** Rank–species richness curves for the total number of invasive alien birds, mammals, freshwater fish, amphibians, and marine organisms in 57 countries, using records included based on the three designation criteria (see Methods; *Designation of alien species as invasive*: documented ecological impact [criterion 1], spread [criterion 2], and invasive elsewhere [criterion 3]). “All criteria” equals the sum of records included based on all three criteria \( (n = 1088) \); “Impact” equals records with country-specific evidence of impact \( (n = 181) \); and “Impact and spread” equals the sum of records included based on both impact and spread criteria \( (n = 238) \).

**Fig. 3.** Median percentage of concordance between invasive alien species (IAS) lists produced using documented evidence (DE-IAS) vs. those modified based on specialist opinion: (a) taxa and (b) countries. Abbreviations are: A, agreement between DE-IAS and specialist opinion; B, disagreement between DE-IAS and specialist opinion; C, specialist does not know; and D, species added by specialist. Bars do not total 100% because the median of the percentages in each category was used. Numbers above the bars represent the number of specialists, with numbers in parentheses representing the number of (a) countries or (b) taxonomic groups if this number is different from the number of specialists.
DAISIE (2009) increased the numbers of aliens for the region several fold (Hulme et al. 2009). However, documented evidence on the ecological impacts of IAS was available for only 11% of these species (while not all alien species have ecological impacts, this percentage is considered likely to be an underestimate; Vilà et al. 2010). Similarly, Jenkins et al. (2007) estimated that impact information is available for only 13% of animals imported to the United States. Furthermore, amongst alien invertebrates in Europe, 14.5% are considered cryptogenic (Roques et al. 2009), i.e., have unknown biogeographical history, and thus, cannot be designated as either native or alien (Richardson et al. 2011). While it could be argued that knowledge of IAS is comparatively better than that for alien species per se (IAS are most likely to receive attention as a consequence of their significant impacts on the environment and economy; Pyšek et al. 2008), McGeoch et al. (2010) showed that only 10% of a random sample of countries examined could be considered to have adequate information on IAS. In spite of exponential growth in the field of invasion biology over the last several decades (Richardson et al. 2011), lack of knowledge clearly remains the largest source of uncertainty in IAS listing, and in the majority of instances, results in an underestimate of the number of IAS in a country, region, or environment.

This lack of knowledge has a range of consequences, all of which are likely to hinder IAS prevention and control efforts. Lack of knowledge results in species being misidentified, alien species not being recognized, their incipient threat not appreciated, or the level of risk being incorrectly categorized. While improvements in taxon-specific knowledge are unlikely to make a large contribution to invasion theory (Pyšek et al. 2008), such species-specific information is critical for effective management. Using only direct evidence of invasiveness (criterion 1; Fig. 1), 21 of the 57 countries examined in this study would have had no listed invasive animal species, illustrating the significant effect of information gaps on listing exercises. Geographic biases in data and knowledge are perhaps most serious because information shortages are greatest in countries least able to afford the impacts of IAS and their management (Pyšek et al. 2008, McGeoch et al. 2010). Geographic gaps in IAS knowledge exposes both data-rich and data-poor countries to greater introduction risk via the import and export of goods and produce and uneven investment in sanitary and phytosanitary measures (Perrings et al. 2010).

A further consequence of inadequate data on IAS is that decisions often have to rely on the input and opinion of specialists (Cook et al. 2010). Expert input in alien and invasive species listings and risk assessments has been widely used to supplement information where documented knowledge gaps exist, as well as to collate and review IAS information, and thus, to make listing decisions. One of the most notable instances is DAISIE (2009) that drew on the substantive body of expertise in Europe (over 1500 experts from ~90 countries) to, inter alia, create an inventory of alien species that threaten the region (Hulme et al. 2009). Indeed, Burgman (2004) states that “listing decisions are a form of risk assessment supported largely by expert judgment.” Expert judgments are, however, themselves susceptible to error (for example, as a result of limits to experience, memory, attitude to risk, value-laden opinions, and overconfidence; Açıkkaya et al. 2000, Burgman 2001, 2004). The quantitative comparison of documented, evidence-based IAS lists with specialist judgments in this paper illustrates not only that documented IAS information underestimates IAS numbers, but that in several instances judgments differed substantially between specialists. The number of independent specialist assessments for specific taxon–country combinations in this study was comparatively low (between 1 and 9). However, levels of difference in opinion between specialists of around 30–60%, similar to those found here for IAS listing, are not uncommon (Burgman et al. 2005).
2001). The size of this effect is likely to be lower in better known regions and for better known taxa than when the opposite is true. However, it is in poorly known regions and for poorly known taxa where listing decisions are most reliant on expert judgment.

To maximize the substantial potential benefit to be gained from specialist contributions to listing exercises, Burgman (2004) provides a list of 30 recommendations for improving the reliability, transparency, and credibility of expert contributions to the listing process. An important element of these recommendations is the use of models, systems, definitions, and structured rules to improve the transparency and repeatability of listing decisions. One example thereof is the process applied here (see also McGeoch et al. 2010), where an explicit framework for decision making is applied to each species considered for addition to the IAS list (Fig. 1). Other important elements include training and awareness and deliberate consideration of potential biases and reasons underlying wrong judgments and differences in opinion (Burgman 2004).

Related to data shortages and reliance on specialist input, is the difficulty associated with accessing information. This may result from information being outdated or not readily available (e.g., not electronically available) or accessible (e.g., information available in a range of languages, limiting its broad accessibility beyond the targeted language group), and sometimes as a result of the lag period between discovery and documentation. For example, only an estimated 43% of IAS databases identified are available online, and only 46% in the United States allow unrestricted access (Crall et al. 2006). This is a form of systematic uncertainty to which IAS information appears particularly prone. A substantial part of the problem is the plethora of databases that exist both within and across countries and regions, including taxon- (e.g., Invasive Plant Species of the World; Weber 2003), environment- (e.g., Database of Global Marine Invasive Species Threats), geographic- (e.g., Delivering Alien Invasive Species Inventory for Europe; DAISIE 2009), and purpose-specific databases (e.g., Invasive Plant Atlas of New England; IPANE) established to provide an early detection network for the state (Simpson et al. 2009). There are over 300 data sets on alien species in the United States alone (Crall et al. 2006), and 259 electronically accessible databases are listed by the Global Invasive Species Information Network (available online).4

Many calls have been made and several initiatives have attempted to collate alien and invasive species information across these divides (Ricciardi et al. 2000, Simpson 2004), such as the Global Invasive Species Database (GISD, De Poorter 2009) and Global Invasive Species Information Network (GISIN), that provide a platform through which a range of participating IAS databases may be accessed (De Poorter 2009). Nonetheless, as the results shown here demonstrate, generating globally and taxonomically representative lists of IAS remains a challenge. Ongoing efforts to make IAS

4 http://www.gisinetwork.org/documents/
information accessible online and to achieve IAS information sharing and data standardization will therefore significantly facilitate prevention and early detection efforts globally (DAISIE 2009, de Poorter 2009, Simpson et al. 2009).

Walker et al. (2003) draw the distinction between “uncertainty due to a lack of knowledge” (epistemic) and “uncertainty due to variability inherent in the system under consideration” (ontogenetic). Interestingly, although the invasion process itself is inherently probabilistic in nature (with introduction, survival, establishment, and spread rates all being difficult to measure, estimate, and predict; Wonham and Pachepsky 2006, Lockwood et al. 2007), uncertainties in the IAS listing process are currently almost exclusively epistemic (with additional elements of linguistic uncertainty following the Regan et al. [2002] taxonomy). Other types of uncertainty that have nothing to do with lack of knowledge include context dependence and vagueness (i.e., linguistic rather than epistemic uncertainty). The implications of linguistic uncertainty on IAS listing emerged as possibly the least well understood uncertainty class, with no available estimates of the size of the effect of vagueness (in the definition and designation of alien and invasive species), or context dependence (extralimital species being invasive and their underrepresentation in IAS lists).

Vagueness arises from scientific vocabulary that allows “borderline cases” (Burgman 2001), which for IAS means that some species can neither be clearly designated as either IAS or as non-IAS. Using the argument of Regan et al. (2002), there is, therefore, no straightforward answer to how many IAS there are, and it is further complicated by multiple alternative definitions of IAS (Lockwood et al. 2007, Richardson et al. 2011). This type of uncertainty should, as far as possible, be eliminated in advance of the listing process (although it will not be possible to eliminate entirely), and a range of possibilities for doing so, such as probabilities, fuzzy sets, and assigning degrees of membership, have been proposed (Burgman 2001, Regan et al. 2002). The second form of linguistic uncertainty (i.e., context dependence) arises from failure to specify, and thus, to recognize the geographic context of what makes an alien species alien. For example, extralimital species tend to be underrepresented on IAS lists because the observation units (context) for such lists are often geopolitical (national or sub-national) rather than biogeographic (Olden 2006, Spear and Chown 2008).

Key tactics for reducing uncertainty in the IAS listing process that emerged from the assessment conducted here, each of which would address a range of the 10 errors, thus include: (1) ongoing and expanded (especially geographically) investment in IAS research and monitoring (particularly taxonomy, abundance, distribution, and impact; McNeely et al. 2005, Pyšek et al. 2008, Vilá et al. 2010); (2) support for regional and global efforts to improve information accessibility via inventory and collation of IAS information (including global synonymic checklists) and making these available electronically (Graham et al. 2008, DAISIE 2009, Simpson et al. 2009); (3) adoption of measures to improve the transparency, repeatability, and communication of listing methods (McGeoch et al. 2006), along with standardized use of terms and concepts (Richardson et al. 2011); (4) improving the procedures for expert contributions to the process (Burgman 2001, 2004); (5) greater attention given to understanding the location, level, nature, and size of the effect of linguistic uncertainty on the IAS listing process (Burgman 2001, Regan et al. 2002, Walker et al. 2003).

CONCLUSION

Uncertainty will never be eliminated from the invasive alien species listing process (Burgman 2004). However, by better understanding the origin, nature, and size of the effect of the full range of types of uncertainty that affect the process, concrete steps can be taken to deal with them where possible (see the five tactics recommended in the previous paragraph), and to acknowledge them where not (Akçaşakaya et al. 2000). In so doing, the quality and value of the IAS listing process for policy makers and managers will be greatly improved (Butchart et al. 2010, McGeoch et al. 2010). Target 9 of the Aichi Biodiversity Targets (adopted as part of the 2011–2020 Strategic Plan for Biodiversity by the Convention on Biological Diversity’s Conference of Parties; UNEP 2011) relates specifically to invasive alien species, and will require ongoing IAS listing towards the identification and prioritization of invasive species. Contributions such as this, to better understand the sources and effects of errors in IAS listing, are likely to improve estimates of biological invasion and to identify ways of doing so such that resources may be channeled to this end.

ACKNOWLEDGMENTS

The Global Invasive Species Programme and DST-NRF Centre for Invasion Biology funded this research. S. L. Chown, J. Lee, L. Foxcroft, N. J. van Wilgen, and members of GISP’s Expert Working Group on IAS Indicators, as well as two anonymous referees, are thanked for their constructive comments. We thank the various agencies for database access (especially CAB International), the persons who contributed to the specialist assessments, and ISSG, Piero Genovesi, and Shyama Pagad for assistance with taxon and country data collation.

LITERATURE CITED


Supplemental Material

Appendix A

Electronic databases and reference texts used to compile the documented evidence-based invasive alien species (DE-IAS) lists (Ecological Archives A022-053-A1).

Appendix B

Stratified, random selection of 57 countries for which a documented-evidence based approach was used to compile invasive alien species lists (Ecological Archives A022-053-A2).

Appendix C

Country and taxon specialist combinations that assessed the documented evidence-based invasive alien species (DE-IAS) lists (Ecological Archives A022-053-A3).