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Global indicators of biological invasion: species numbers, biodiversity impact and policy responses

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ABSTRACT

Aim Invasive alien species (IAS) pose a significant threat to biodiversity. The Convention on Biological Diversity's 2010 Biodiversity Target, and the associated indicator for IAS, has stimulated globally coordinated efforts to quantify patterns in the extent of biological invasion, its impact on biodiversity and policy responses. Here, we report on the outcome of indicators of alien invasion at a global scale.

Location Global.

Methods We developed four indicators in a pressure-state-response framework, i.e. number of documented IAS (pressure), trends in the impact of IAS on biodiversity (state) and trends in international agreements and national policy adoption relevant to reducing IAS threats to biodiversity (response). These measures were considered best suited to providing globally representative, standardized and sustainable indicators by 2010.

Results We show that the number of documented IAS is a significant underestimate, because its value is negatively affected by country development status and positively by research effort and information availability. The Red List Index demonstrates that IAS pressure is driving declines in species diversity, with the overall impact apparently increasing. The policy response trend has nonetheless been positive for the last several decades, although only half of countries that are signatory to the Convention on Biological Diversity (CBD) have IAS-relevant national legislation. Although IAS pressure has apparently driven the policy response, this has clearly not been sufficient and/or adequately implemented to reduce biodiversity impact.

Main conclusions For this indicator of threat to biodiversity, the 2010 Biodiversity Target has thus not been achieved. The results nonetheless provide clear direction for bridging the current divide between information available on IAS and that needed for policy and management for the prevention and control of IAS. It further highlights the need for measures to ensure that policy is effectively implemented, such that it translates into reduced IAS pressure and impact on biodiversity beyond 2010.

Keywords

Biological invasions, Convention on Biological Diversity 2010 Biodiversity Target, environmental legislation, invasive alien species, Red List Index, species richness.

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INTRODUCTION

Invasive alien species (IAS) pose a significant threat to biodiversity. Moreover, compelling evidence exists, based on global trade and movement patterns, that the magnitude of this threat is increasing globally (Hulme, 2009). Invasive alien species alter ecosystem processes (Raizada *et al.*, 2008), decrease native species abundance and richness via competition, predation, hybridization and indirect effects (Blackburn *et al.*, 2004; Gaertner *et al.*, 2009), change community structure (Hejda *et al.*, 2009) and alter genetic diversity (Ellstrand & Schierenbeck, 2000). In Europe, for example, the large majority of the most invasive species reduce diversity and change community structure, whereas a smaller percentage directly harm threatened species (Vilá *et al.*, 2009). Increases in the number and spread of alien species appear to be strongly associated with substantial increases in the extent and volume of trade and transport, particularly over the last 25 years (Levine & D'Antonio, 2003; Ruiz & Carlton, 2003; Hulme *et al.*, 2009). Whereas global trends in trade and movement are clear, related patterns of the extent of biological invasion, their impacts on biodiversity and societal responses to these impacts remain poorly quantified at a global scale. The Convention on Biological Diversity's (CBD) 2010 Biodiversity Target (UNEP, 2002a), and the associated Invasive Alien Species Indicator under the focal area 'Threats to biodiversity' (UNEP, 2005, Walpole *et al.*, 2009), presents one of the first concerted and globally coordinated efforts to do so.

The 2010 Biodiversity Target is *to achieve by 2010 a significant reduction in the current rate of biodiversity loss at the global, regional and national level, as a contribution to poverty alleviation and to the benefit of all life on Earth* (UNEP, 2002a). Only nine of the 22 biodiversity indicators within the CBD framework are currently considered to be fully developed with well-established methods (Walpole *et al.*, 2009). Several of the other indicators remain under development in preparation for reporting on the 2010 Target (e.g. indicators of trends in genetic diversity, fragmentation of ecosystems and biodiversity for food and medicine) (Walpole *et al.*, 2009). The IAS indicator was also considered to fall in this category, because while a range of indicators of IAS have previously been proposed, developed and applied, these have been at regional, national or finer scales. Measures used include, for example, percentage of land surface area covered by alien plant species, and area and density of weeds under active management (McGeoch *et al.*, 2006). Hence there is no fully developed set of IAS indicators that combine data, derived from a standard set of methods, across species groups, ecosystems and regions.

In the context of the 2010 Biodiversity Target commitment, IAS indicators are needed to track trends in the impact that IAS have on biodiversity (UNEP, 2004; Donnelly *et al.*, 2007). They should also track the degree to which policy and management targets for IAS have been met (McGeoch *et al.*, 2006). The CBD framework goal relevant to IAS is to *control threats from invasive alien species* and the two targets are to (1) *control pathways for major potential alien invasive species* and to (2) *have management plans in place for major alien species that threaten ecosystems, habitats or species* (UNEP, 2005). Indicators are thus needed to monitor (i) the size or extent of the threat posed by IAS (pressure), (ii) the impact of IAS on biodiversity (state) and (iii) the progress towards reducing the threat (via policy or management interventions) (response). These indicators thus conform to the influential pressure-state-response model for environmental reporting (OECD, 1993) that is now widely used (Donnelly *et al.*, 2007) (Fig. 1). Through the 2010 Biodiversity Indicators Partnership (http://www.twentyten.net), the Global Invasive Species Programme was tasked with facilitating this development. An analysis of potential measures for these indicators and available (or pragmatically collectable) datasets led to four indicators being

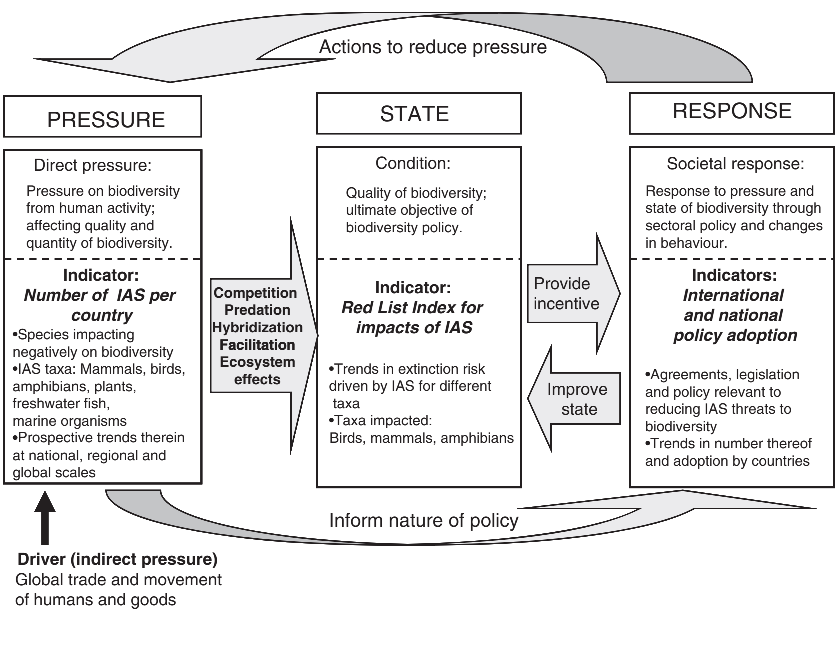

Figure 1 Pressure-state-response model of the invasive alien species (IAS) indicators for reporting on the 2010 Biodiversity Target.

prioritized, and we present the outcome of their development and expression here.

For trends in the number of IAS per country, a pilot assessment examining data availability and data quality demonstrated that there is currently inadequate information for expressing globally representative and readily interpretable trends for this indicator [although a selection of individual and regional case studies exist, most notably cumulative number of alien species in Europe since 1900 (EEA, 2009)]. Therefore, 'the documented number of IAS per country' was determined as a baseline measure. To measure the impacts of IAS on biodiversity, we used the 'Red List Index for the impacts of IAS' (Butchart *et al.*, 2005). This shows changes over time in the extinction risk of all bird, mammal and amphibian species worldwide driven by IAS, integrating the negative impacts of invasions and the positive impacts of successful conservation action tackling IAS. Two response indicators were developed to track trends in the development and adoption of (a) international policy and (b) national legislation relevant to the prevention and control of IAS. Comprehensive policy, at both national and international levels, is essential for ensuring coherent and effective planning and implementation of measures to curb alien species invasion (Shine *et al.*, 2005). The change through time in the number of IAS-relevant international agreements and their adoption by countries, as well as the development of legislation at national level, thus demonstrates the rate at which countries have come to recognize IAS as a significant problem and have formalized their intention to manage them.

Here, we present these indicators in a pressure-state-response framework and use them to: (i) quantify and report on status and trends in invasive alien species globally and (ii) evaluate whether the 2010 Biodiversity Target has been met for this well-recognized threat to biodiversity.

METHODS

Numbers of documented Invasive Alien Species (IAS)

For pragmatic reasons, we determined the number of documented IAS for a stratified random sample of countries (57, representing ~30% of countries signatory to the CBD; Appendix S1). 'Country' was used as the unit for which lists were compiled, because this is the scale at which data are generally available, and because this is the unit most relevant to evaluating and monitoring the effectiveness of the CBD (McGeoch *et al.*, 2006). To minimize bias in the outcome, we adopted a stratified-random approach to selecting the subset of countries such that they were representative of different country sizes, climatic regions, continents and development status (assessed using the Human Development Index (HDI), UNDP (2007)) (Appendix S1). Only countries that are both members of the United Nations and party to the CBD were considered in the population from which countries were selected for this indicator (n = 173).

Relevant electronically available databases were used to compile species lists (Appendix S2). In addition, primary and secondary literature searches were conducted to supplement these lists (Appendix S2). All information gained from the use of database and literature sources thus constitutes lists of IAS compiled using a 'published data' approach to populating the indicator.

Six groups of species were included in the indicator: mammals, birds, amphibians, freshwater fish, vascular plants and marine organisms (including algae, corals, invertebrates and fish). These taxa represent terrestrial, freshwater and marine environments, and data on these taxa were considered to be comparatively most comprehensive and readily available and as a result represent the best-case scenario for taxonomic representation when used to populate the indicator (Appendix S2).

Alien species were included in the list only if they were considered to be invasive. Because the focus for the 2010 Biodiversity Target is alien species that pose a threat to biodiversity, the CBD Conference of Parties definition of an IAS was used, i.e. *a species outside of its [indigenous geographic] range whose introduction and/or spread threatens biodiversity* (UNEP, 2002b). To ensure, as far as possible, comparability across taxa and countries, it was necessary to adopt standard criteria for the designation of species as invasive (Appendix S3).

Because alien and IAS data availability is well known to vary globally, an independent measure of research effort and information availability (termed 'data availability') was compiled for each country, using a combination of previously published estimates of research effort on alien species by region (major continents and their surrounding islands; see Pyšek *et al.*, 2008) and information provided in Third National Reports to the CBD (Appendix S4). On this basis, countries were classified as either data deficient, intermediate or data rich (Appendix S4).

Trends in the impact of IAS on biodiversity

Red List Index values (RLIs) were calculated for birds, mammals and amphibians using data from the IUCN Red List (http://www.iucnredlist.org). Specifically, the number of species in each Red List category and the number changing categories between assessments as a result of genuine improvement or deterioration in status (category changes owing to improved knowledge or revised taxonomy are excluded; see Butchart *et al.*, 2004, 2005, 2007 for further detail). For each genuine category change, the primary driver (threat or threat mitigated) was identified. RLIs were then calculated to show, in a stacked area chart, the contribution of each threat to the overall deterioration in the status of species (for full details, see Appendix S5). The RLI shows changes in the overall extinction risk of sets of species, with RLI values relating to the proportion of species expected to remain extant in the near future without additional conservation action. An RLI value of 1.0 equates to all species being categorized as Least Concern, while an RLI value of zero indicates that all species have gone Extinct.

Trends in international agreements and national policy adoption

Ten multi-national agreements (international conventions, organization agreements and organization guidelines) were used to quantify trends in the adoption of IAS-relevant international policy [e.g. through promoting the regulation of pathways of introduction of IAS and controlling IAS *in situ* (Shine *et al.*, 2005)] (Appendix S6). All countries party to the CBD ($n = 191$) were included in the calculation of this indicator, again based on the rationale that data for this subset of countries are generally most readily available and appropriate for reporting and monitoring progress under the banner of the CBD (of which the 2010 Biodiversity Target is a result).

For each of the 191 countries party to the CBD, any national legislation relevant to controlling IAS was identified [using, for example, national websites, National Reports to the CBD, and the Food and Agriculture Organization (FAO) database (FAO legal office http://faolex.fao.org/)]. Legislation that was potentially relevant to alien species was examined for relevance to the prevention or control of IAS. If the legislation was found to be relevant, the year of enactment was noted. Legislation was considered relevant to the prevention of alien species introductions or to control of IAS if it applied to multiple taxonomic groups and was not exclusively intended to protect agriculture. If two separate sets of legislation within a country covered plants and animals, the date of the more recent legislation was used. In addition, a measure of national policy adoption was calculated as the number of policy categories (maximum 5) in existence in a country, i.e. (1) legislation on control, (2) legislation on prevention, (3) a national IAS strategy and a National Biodiversity Strategy and Action Plan (as required by the CBD, United Nations (1993)) that included requirements for the (4) prevention and (5) control of IAS (Appendix S7).

Analysis

The relationship between the number of documented IAS, country area, land mass type (continental or island), latitude, HDI and data availability was examined using a generalized linear model with a log-link function (STATISTICA, StatSoft Inc., Tulsa, OK, USA). Marine organisms were excluded, because country area was not an appropriate predictor for this group. To examine the relationship between the pressure and response indicators (i.e. the lower arrow in Fig. 1), generalized linear models were also used to examine the relationships between the number of documented IAS per country (with a log-link function), international agreements (number to which the country is party) and national policy adoption.

RESULTS

Numbers of documented IAS per country

The number of documented IAS per country ranged from 9 (Equatorial Guinea) to 222 (New Zealand), including 2871 country by species records. There was a total of 542 species that were documented as invasive aliens across the 57 countries examined, including 316 vascular plant, 101 marine, 44 freshwater fish, 43 mammal, 23 bird and 15 amphibian species (Fig. 2). In all taxa, the frequency distributions of IAS richness were strongly right skewed, with the majority of countries falling in the lowest richness class (and a mean (±SD) of 50.36 ± 44.59 IAS per country). However, by far the greatest proportion of countries in the lowest richness class are

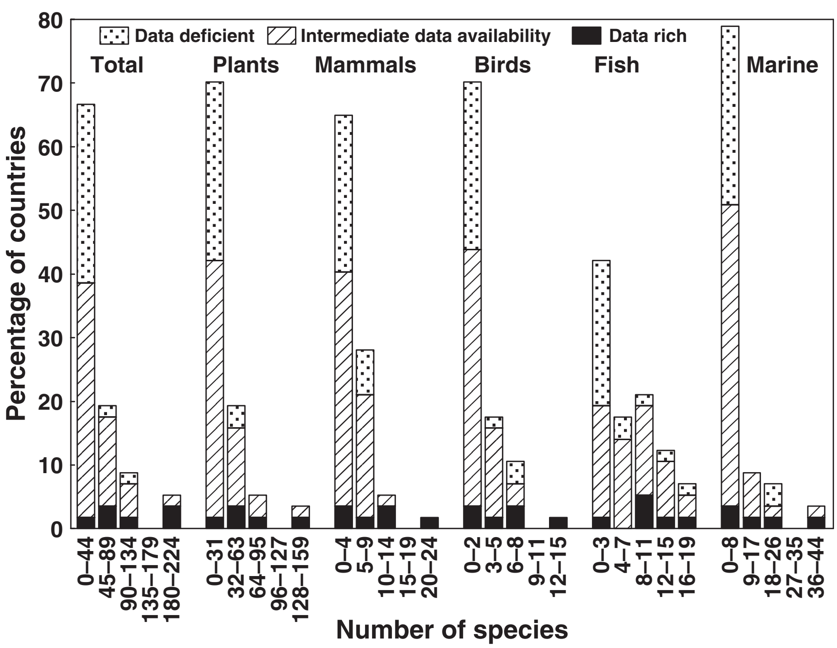

Figure 2 Frequency distributions of the number of Invasive alien species (IAS) across countries ($n = 57$) with different degrees of data adequacy ($n = 18$ data deficient (DD), $n = 33$ intermediate (IDA) and $n = 6$ data rich (DR) countries). (Vascular plants, mammals, birds, freshwater fish and marine organisms; amphibians not shown individually here because of low frequencies.)

considered either data deficient or only intermediate in data availability (as assessed independently of the data used to populate the indicator) (Fig. 2). The few data-rich countries were fairly evenly distributed across the full range of species richness categories (Fig. 2). This was true for total richness and for individual taxonomic groups.

The number of documented IAS per country was significantly explained by country area (positive, d.f. = 1, χ^2 = 18.43, P < 0.0001), HDI (positive, d.f. = 1, χ^2 = 9.56, P < 0.01), land mass type (island > continent: d.f. = 1, χ^2 = 9.24, P < 0.01) and data availability (d.f. = 2, χ^2 = 6.23, P < 0.05) (d.f. = 49, deviance explained = 74.14%). The interaction between land mass type and data availability was also significant (d.f. = 2, χ^2 = 21.87, P < 0.0001), with data-deficient and data-rich islands having more IAS than data-deficient and data-rich countries on continents. Latitude was not significant (P = 0.61) and was excluded from the final (earlier) model. Although HDI and the independent measure of data availability were themselves correlated, 'data availability' significantly increased the explanatory power of the model (Analysis of Deviance, d.f. 4, χ^2 = 232.27, P < 0.0001).

Although larger countries and islands have more IAS than smaller countries and countries on continents, data availability clearly affects IAS richness with significantly fewer documented IAS in data-deficient compared with data rich countries (Fig. 3a). Data-rich countries all had HDI's of greater than 0.8, whereas intermediate and data deficient-countries were represented by a broad range of HDI's (Fig. 3b).

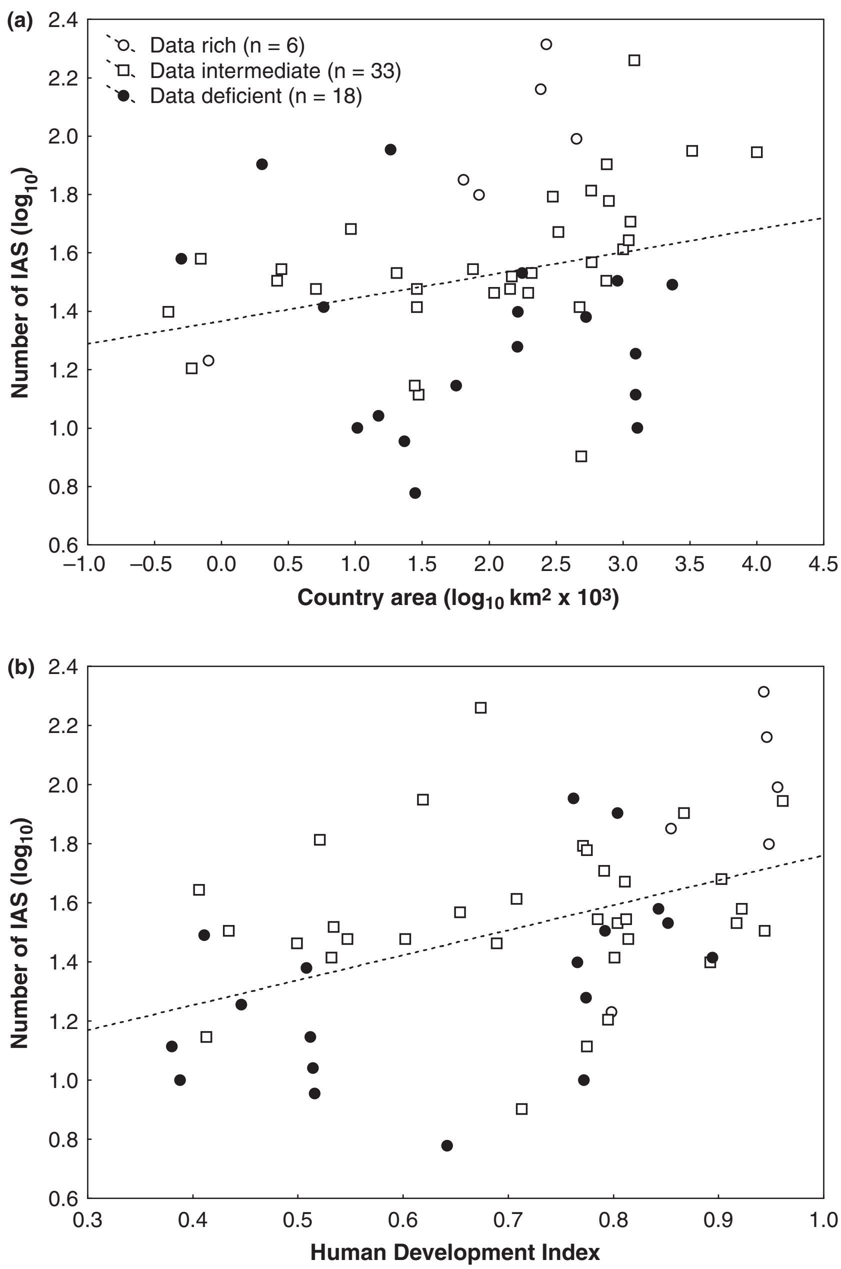

Figure 3 Relationships between the documented number of invasive alien species (IAS) per country, (a) country area and (b) the Human Development Index, showing the distribution of countries based on an independent assessment of data availability, i.e. rich, intermediate and deficient (fitted lines for illustration only, statistics provided in text).

Trends in the impact of IAS on biodiversity

RLIs for the impacts of IAS on birds, mammals and amphibians all show that the extinction risk of these groups has increased over time (i.e. their overall status has deteriorated) specifically as a consequence of the impacts of IAS (Figs 4–5). For each group, although some species have improved in status sufficiently to be downlisted to a lower category of threat on the IUCN Red List (as a consequence primarily of successful control or eradication of IAS; 11 birds, five mammals and one amphibian), many more species qualified for uplisting to higher categories of threat owing primarily to negative impacts of IAS (31 birds, 9 mammals and 205 amphibians; Fig 4; Appendix S8). IAS were also secondary drivers for an additional suite of deteriorating species that qualified for uplisting (23 birds, 14 mammals and 41 amphibians) and for a smaller suite of species that improved in status and qualified for downlisting (9 birds, 2 mammals and 0 amphibians). The overall decline in the RLI would nonetheless have been 11% worse for birds and 4.6% worse for mammals had conservation action tackling IAS not resulted in improvements in the status of some species.

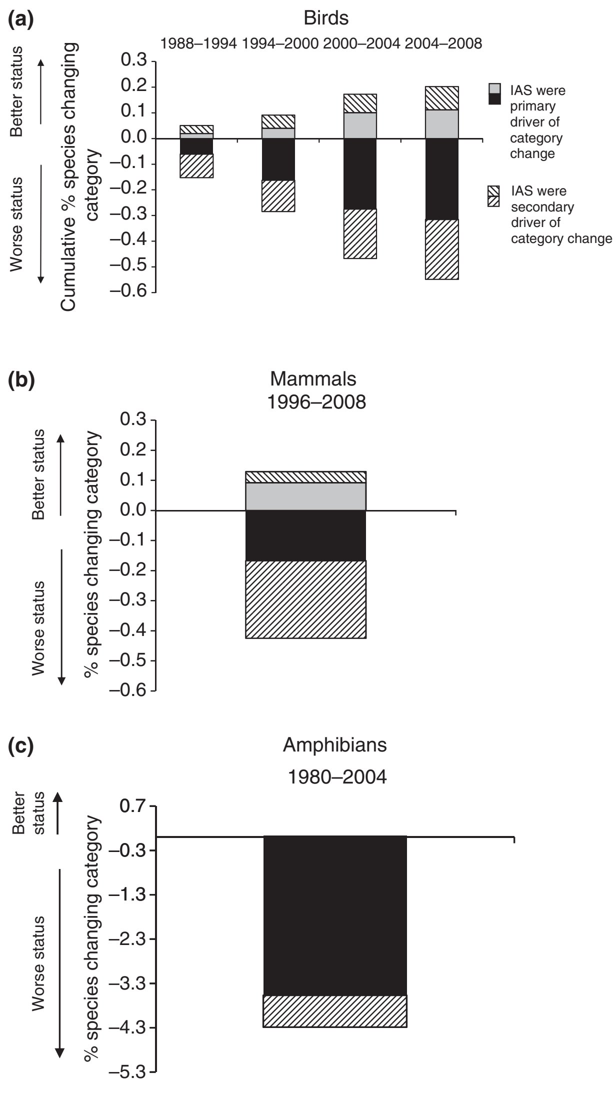

Figure 4 Number of (a) bird, (b) mammal and (c) amphibian species (expressed as a cumulative percentage of all species in each group) undergoing genuine IUCN Red List category changes driven by the impacts of invasive alien species (IAS). This includes impacts leading to deterioration in status (< 0.0) and conservation measures (such as control or eradication of IAS) leading to improvements in status (> 0.0). Solid bars show category changes for which IAS were the primary driver, hatched bars show category changes for which they were a secondary driver. Time periods refer to the intervals between comprehensive reassessments of all species in each group; n = 9,857 extant bird, 5,412 mammal and 5,718 amphibian species at start of period.

The relative importance of IAS as a driver of trends varied between groups. Agriculture was a more important driver for birds and mammals, with hunting and logging also more significant than IAS for mammals, but for amphibians, IAS were by far the most important driver (Fig. 5). For birds, it is noteworthy that the percentage of all genuine positive category changes (i.e. improvements in status) that were primarily or secondarily driven by IAS ranged from 33 to 75% in each period (and comprised 53% over the whole period). This compares to 10–45% in each period for genuine negative category changes (i.e. deteriorations in status), and 24% over the whole period. The proportions of status changes driven by IAS were significantly different between positive and negative category changes in each period (χ^2 = 15.74, d.f. = 2, P < 0.0001). In other words, a disproportionately large number of conservation successes resulted from successful conservation action tackling IAS (Appendix S8).

Trends in international agreements and national policy adoption

There has been an exponential increase in both the number of international agreements relevant to the control of IAS since 1951 (in particular since the 1970s) (r = 0.84, P < 0.001), as well as in the number of countries party to these agreements (r = 0.92, P < 0.001) (Fig. 6a). This increase is especially marked since the origin of the CBD in 1992, especially in the number of signatory countries (Fig. 6a). Therefore, both the number of global agreements relevant to the control of IAS and the number of countries signatory to these agreements have increased over the last four decades.

Only 55% of countries signatory to the CBD have IAS-relevant national legislation (Fig. 6b). The number of countries with national legislation relevant to IAS has nonetheless increased since the late 1960s, with a sharp increase apparent after the establishment of the CBD in 1992 (Fig. 6b).

The documented IAS richness of countries was significantly positively related to the number of international agreements to which the country was signatory (d.f. = 1, χ^2 = 26.64, P < 0.001) (Fig. 7a). There was also a significant difference in documented IAS richness between countries with different levels of policy adoption, and countries with the greatest policy

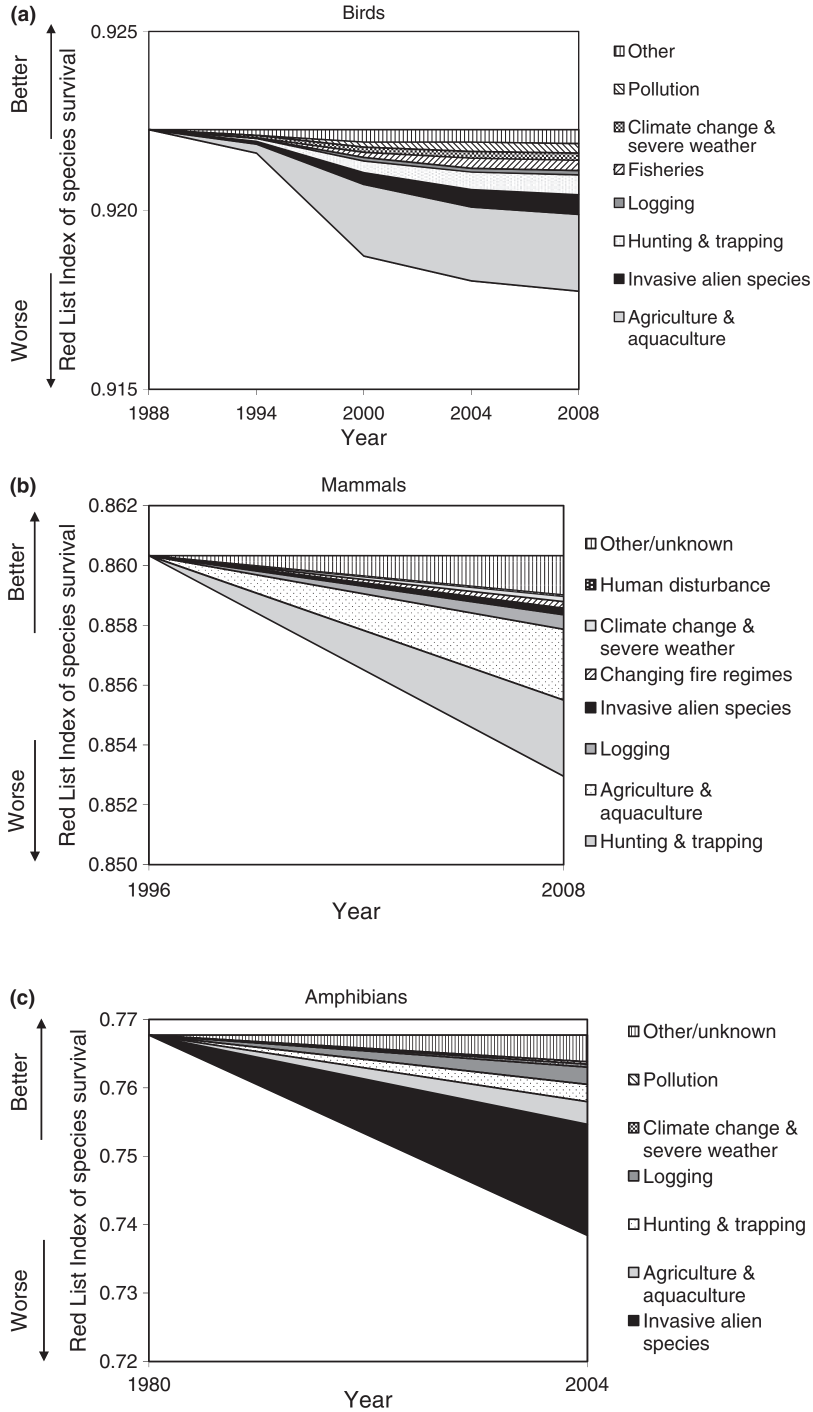

Figure 5 Red List Index (RLI) for (a) birds, (b) mammals and (c) amphibians showing trends driven by the impacts of invasive alien species (IAS) compared with trends driven by other factors, for the proportion of species expected to remain extant in the near future without additional conservation action; n = 9,785 non-data deficient extant bird, 4,555 mammal and 4,417 amphibian species at start of period. The differently shaded bands illustrate the contribution of different drivers to the overall decline in the RLI over the relevant period.

adoption score had significantly more species than those with lower scores (d.f. = 4, $\chi^2 = 31.22$, $P < 0.001$) (Fig. 7b).

DISCUSSION

Over 500 alien species, for which there is demonstrated evidence of negative biodiversity impact, were found across the globally representative set of countries examined. Furthermore, this is a significant underestimate for these countries, because the value of the indicator was positively affected by an independent measure of research effort and information availability and negatively by the development status of the country. At the same time, the Red List Index clearly shows that IAS pressure is driving declines in biodiversity, with all indications that the overall impact on species is increasing. The policy response trend to this problem has nonetheless been positive for the last several decades, at both national and international levels. Policy adoption at national level has been

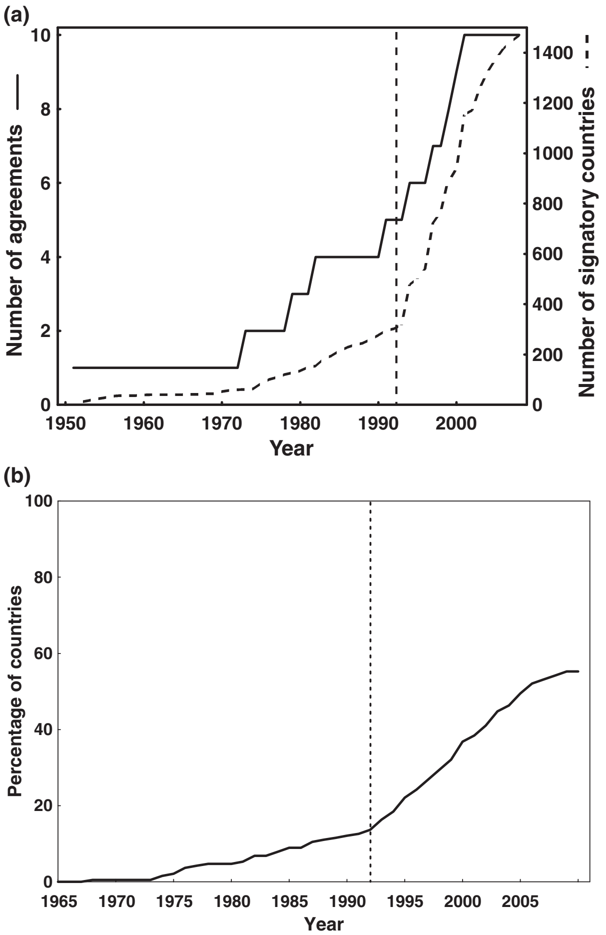

Figure 6 Trends in international agreements and national policy relevant to the prevention or control of Invasive alien species (IAS). (a) The number of international agreements (solid line) relevant to reducing threats to biodiversity from IAS (excluding the Convention on Biological Diversity that was enacted in 1992 – dashed line) and the cumulative number of countries (dotted line) party to those agreements, 1951–2008. (b) Adoption of national legislation relevant to the prevention or control of IAS for 191 countries reporting to the Convention on Biological Diversity (1967–2008).

greatest in those countries with the largest number of documented IAS. Therefore, IAS pressure has apparently driven the policy response. There is also evidence of individual conservation successes via the control of IAS and resulting improvements in the conservation status of some species. However, there is currently no evidence to suggest that policy adoption has brought about any overall decline in biodiversity impact (see Fig. 1). For this indicator of threat to biodiversity, the 2010 Biodiversity Target has thus not been achieved.

Interpretations, limitations and developments needed

Invasion pressure

The number of documented IAS per country was, perhaps unsurprisingly, shown to be affected by country development status and information availability. The number of IAS may be affected by country development status in at least two ways: 1. Low HDI (development status) is likely to be associated with low investment in research and data collation and hence few documented IAS (McNeely *et al.*, 2005). 2. Low-HDI countries may have lower volumes of international trade and transport [a well-known driver of alien species introductions (Hulme, 2009)] and hence fewer IAS. Nonetheless, controlling for such factors affecting data quality, it was possible to reconstruct well-established ecological relationships from the IAS pressure indicator. Support was provided for the well-known species–area relationship (larger countries have more IAS) (Palmer, 2006; Stohlgren *et al.*, 2006; Hulme, 2008), as well as the comparative severity of invasion on islands compared with continents (Blackburn *et al.*, 2004).

While the baseline provided by this indicator is a necessary precursor for future tracking of trends in the number of IAS per country, the question thus remains: are trends in alien species invasion increasing globally? In the region of the world with the highest quality and longest and most detailed historical record of alien species introductions, i.e. Europe, the number of new alien species establishing has increased steadily over the last century (Lambdon *et al.*, 2008; EEA, 2009; Hulme *et al.*, 2009). Similar trends have been demonstrated elsewhere in a range of cases examined for particular taxa at finer scales, for example non-indigenous species establishing in the Great Lakes (USA) (since 1810; Ricciardi, 2001); exotic species establishing in the San Francisco estuary (since 1850; Cohen & Carlton, 1998); numbers of non-indigenous snails and slugs in Hawaii (since 1830; Cowie, 1998) and invertebrate plant pests in Great Britain (since 1970; Smith *et al.*, 2007). While these trends are generally positive, they do represent alien species, rather than the smaller subset of those species that significantly harm biodiversity (although numbers of alien and invasive species are not unrelated; Rejmánek & Randall, 2004; Stohlgren *et al.*, 2008). In addition, it is often difficult to know when introductions occur, and the point at which species become invasive (Rodriguez-Cabal *et al.*, 2009), and unless good historical records of introduction, establishment and discovery are available (such as for Europe), observed trends may be both confounded and subject to misinterpretation (Davis, 2009; Lockwood *et al.*, 2009). Apparent trends in alien species introduction often conflate species establishment, population dynamics, sampling effort and the discovery process. As such, inferring changes in introduction rates directly from existing data sets is commonly not possible (Costello & Solow, 2003; Wonham & Pachepsky, 2006).

There are a number of reasons why the 'number of documented IAS per country' is likely to underestimate the number of IAS driving biodiversity loss. First, in addition to information inadequacies for some countries, there is a significant lag between the discovery of a new IAS and documentation of information on its biodiversity impact (Pyšek *et al.*, 2003; Shine *et al.*, 2009). In future, therefore, an approach that integrates published evidence with expert

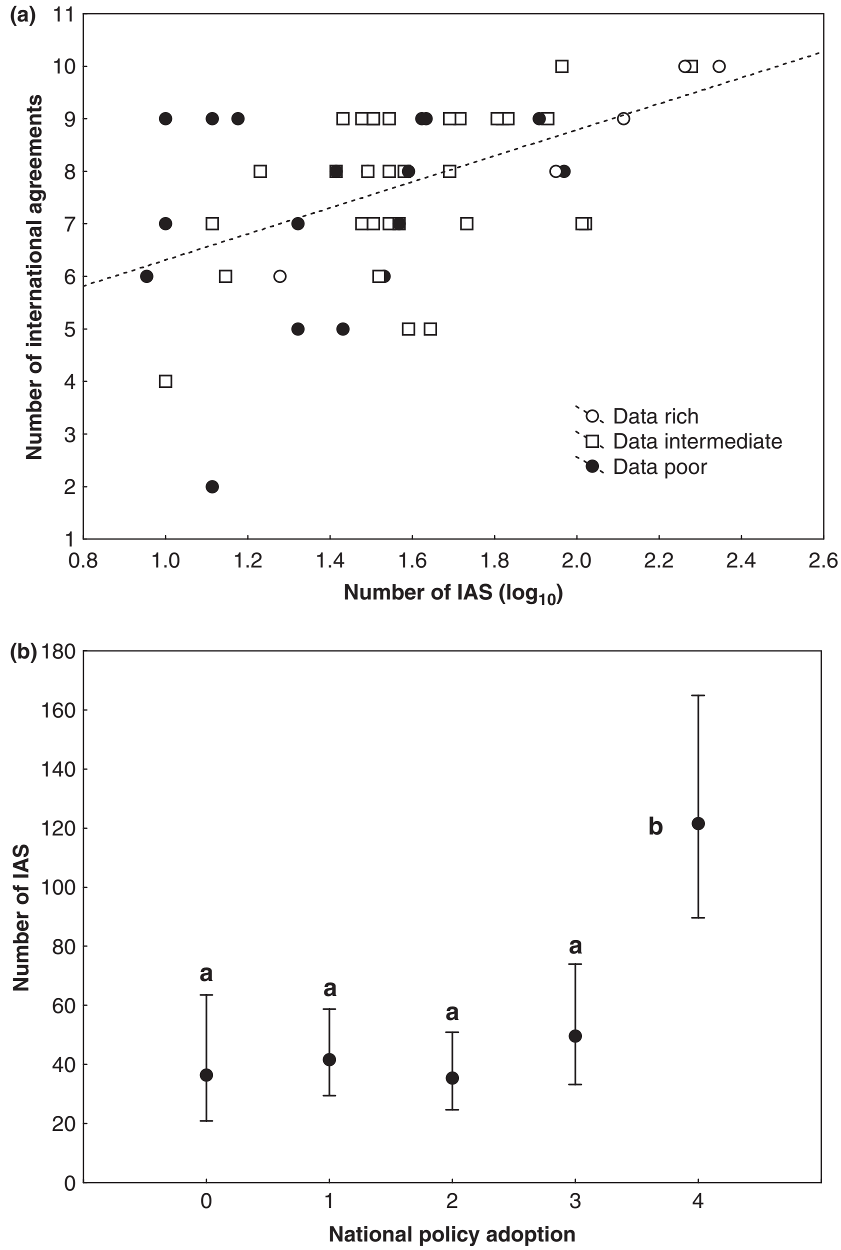

Figure 7 Relationship between pressure and response indicators. a) Relationship between the number of documented invasive alien species (IAS) in a country and the number of IAS-relevant international agreements to which that country is signatory (dashed line for illustration only, see text for statistics). b) Mean (±95% C.I.) number of documented IAS in countries with different levels of national policy adoption (0, none; 4, extensive, Appendix S7). Means with different letters are significantly different at $P < 0.05$.

opinion, such as the assessments conducted for DAISIE (Drake, 2009), is worth exploring.

Post 2010, further investment should be given to expanding this indicator to include all countries and additional taxa (e.g. reptiles). Also, subject to ongoing improvements in IAS knowledge (Pyšek *et al.*, 2008) and the accommodation of biases inherent in retrospective alien and invasive species accumulation trends (Costello & Solow, 2003; Wonham & Pachepsky, 2006), trends in the number of IAS may be constructed over time. While number of IAS was selected as the currently most feasible pressure indicator for reporting on the 2010 Biodiversity Target, it remains a comparatively indirect measure of the size and extent of the IAS problem. More direct measures include, for example, the extent of invasion, coverage, density, population size, biomass or the per capita impact of IAS (Parker *et al.*, 1999). Although resource intensive, data demanding and more readily achievable at finer scales, the possibility of using such measures for future global reporting of IAS pressure on biodiversity should be explored.

Impact on biodiversity

There are numerous examples of how the impact of IAS has been successfully tackled through eradication or control to reduce the extinction risk of native species. For example, the successful eradication of goats and sheep in 1997–1998 and cats in 1999 from Natividad island off the Pacific coast of Mexico reduced mortality dramatically in Black-vented Shearwater *Puffinus opisthomelas* (which is largely restricted to the island when breeding) qualifying the species for downlisting from Vulnerable to Near Threatened on the IUCN Red List by 2004 (BirdLife International, 2008). Similarly, control of Red Fox *Vulpes vulpes* in south-western Australia in the last decade has allowed the population of the endemic Western Brush Wallaby *Macropus irma* to recover sufficiently for it to be downlisted to Least Concern.

However, such successes are outweighed by the number of species deteriorating in status as a consequence of the impacts of IAS. For example, Yellowhead *Mohoua ochrocephala*, a bird endemic to New Zealand, was very seriously affected by rat outbreaks in 1999–2000, with two populations going extinct and three more having significant population crashes. By 2000, the rate of decline is suspected to have exceeded 50% over ten years, qualifying the species for uplisting from vulnerable to endangered (BirdLife International, 2008). Similarly, the pathogenic chytrid fungus that was entirely unknown until 1998 has been implicated in the decline and extinction of many amphibian populations around the globe (Berger *et al.*, 1998; Stuart *et al.*, 2004). Current available evidence suggests that chytridiomycosis is a novel pathogen being spread around the world by unidentified carriers (which may include humans, exotic fishes, African Clawed Frogs *Xenopus laevis* and other animals) (Rachowicz *et al.*, 2005).

The RLI integrates these positive and negative impacts and shows that the net effect of IAS has been negative in all taxonomic groups studied to date (birds, mammals and amphibians), with declines dating back as far as trends are available (1988, 1996 and 1980, respectively). IAS are the most significant driver of declines in amphibians, but while they are a substantial driver of the deteriorating extinction risk of birds and mammals, the impacts of agriculture have been more important for these groups.

No other globally representative indicator of the impacts of IAS on biodiversity is available to date. However, while the RLI has global scope and coverage, it is not particularly sensitive to small-scale changes in the status of species (as picked up by population trend-based indicators). This is because the Red List categories are relatively broad, so species may have to undergo fairly substantial changes in population or range size to cross the thresholds for a higher or lower category, and hence to contribute to trends in the index (Butchart *et al.*, 2004, 2005). Many threatened species (as well as Near Threatened and Least Concern species) are likely to be undergoing declines driven by IAS, but at a rate that is too slow to qualify them for uplisting to higher Red List categories. Hence, while a substantial proportion of all species of birds, mammals and amphibians may be declining owing to IAS, only 0.5–4% of species in each of these groups deteriorated in status sufficiently substantially during the last two decades to qualify for uplisting to higher categories of threat. In other words, at a population level, the impacts of IAS may be even greater than illustrated by the RLI. It is also worth noting that such percentages imply substantial rates of species loss over the medium to long term.

At present, RLIs showing the impacts of IAS are available only for birds, mammals and (in a preliminary form) amphibians. The latter will be updated in the next few years, and RLIs will also soon be available for cycads (1994–2009) and corals (1996–2008), with baseline data points available for several other taxa. These and the groups already comprehensively assessed for the global Red List need to be regularly reassessed to allow the RLIs to be produced and updated. This is important to provide a taxonomically more representative indicator and to show the impacts of IAS on a broader suite of biodiversity.

Policy response

The international policy indicator, albeit an indirect measure of control and management response, shows that the majority of countries have signalled their 'intention' to address the threat from IAS (albeit reflecting such intention outside of the CBD's own provisions on IAS). The national policy adoption indicator, however, demonstrates that only about half (55%) of the countries have taken the step of implementing appropriate national legislation on IAS towards meeting these international commitments. It is also apparent that even countries with legislation often have inadequate IAS strategies, insufficient IAS management plans and ineffective implementation of such plans. Numerous reasons (such as lack of capacity) underpin these deficiencies (Shine *et al.*, 2005; McGeoch *et al.*, 2006). Policy responses cannot be equated with management effectiveness, and in future, more proximate measures of the latter are desirable. There are also currently insufficient data on sub-targets (i.e. controlled pathways and species management plans in place) at national level to determine whether these have been met. The responsibility for addressing this lies with countries party to the CBD, where after data may be collated across countries to express a global indicator that more closely reflects these sub-targets for IAS in the CBD framework.

A parallel assessment conducted across 41 mega-diverse countries found little noticeable effort by countries to integrate planning for IAS, with only a subset of countries involved in regional co-operation on IAS (Stoett, 2009). Moving forward, actions to promote national-level policy adoption are required, along with the development and reporting of operational management activities at national, regional and global levels. For some IAS, control or eradication will be difficult or prohibitively expensive to achieve. However, prevention and early detection remain viable and effective options for a broad range of taxa (McNeely *et al.*, 2005).

Countries that were data deficient tended to be those with lower levels of development, and as a consequence are those less well equipped to prevent the introduction, and to control existing populations, of IAS (McNeely *et al.*, 2005; Shine *et al.*, 2005). The relationship between the pressure and response indicators thus clearly demonstrates the link between economic development and a country's capacity to manage the IAS problem, reaffirming the call to better integrate poverty alleviation and biodiversity conservation agendas (Sachs *et al.*, 2009). Biological invasion provides a particular challenge to such integration, with suggested reductions in trade barriers likely to exacerbate the alien propagule pressure underlying observed increasing trends in alien species introductions (Perrings *et al.*, 2005; Hulme *et al.*, 2009).

CONCLUSION

The development and population of IAS indicators for 2010 were strongly directed by considerations of existing and readily available data, rather than primarily by what may be ideal measures for reporting on the status and trends in IAS beyond 2010. Indeed, the measures and indicators presented here draw attention to the divide between the information that is available on IAS and that which is most valuable for policy and management (see also Mooney & Mace, 2009). We hope that the indicators will boost efforts to address these shortcomings beyond 2010. The assessment of the relative roles of geography, levels of development and data availability in determining IAS numbers may be used to inform future policy-making and capacity-building efforts, particularly with the future inclusion of more countries in the pressure indicator.

With improvements in data availability and collation, future indicators may also include more direct measures, such as extent of invasion (cover or density), per capita impacts of IAS, numbers of IAS with management plans and numbers of IAS successfully eradicated or controlled. The cost of investment in providing IAS information to support policy ranges, for example, from the €3.4 million total cost of the DAISIE project (encompassing 2122 alien species and 27 EU member states) (Drake, 2009; Shine *et al.*, 2009) to €84 thousand for the project that populated the IAS species component of the global indicator reported here (encompassing 57 countries and ~2900 records). Such investment is substantially smaller than the estimated annual cost associated with the impact and control of IAS (e.g. exceeding €12 billion/year in Europe) (McNeely *et al.*, 2005; European Commission, 2008). For all four indicators presented here, the data will be made publically available soon, with the RLI data being accessible through the IUCN Red List (http://www.iucnredlist.org) and data for the other three indicators being accessible via the Global Invasive Species Programme Website (http://www.gisp.org). We encourage the scientific community and others to contribute information to these datasets to keep the indicators up to date and as accurate as possible.

The global IAS indicator demonstrates that there has not been a significant reduction in the current rate of biodiversity loss, at least not for species threatened by IAS. While it is widely expected that we will also have failed to meet the 2010 Biodiversity Target more generally (Collen *et al.*, 2009; Mooney & Mace, 2009; Walpole *et al.*, 2009), it is the outcome of indicators such as these that provide the evidence and insight for plotting a way forward. To reduce biodiversity loss after 2010, considerably greater investment is needed in effective implementation of management interventions to reduce the spread, and control existing populations, of IAS.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Countries and selection method used for the pressure indicator.

Appendix S2 Databases and reference texts used.

Appendix S3 Designation of alien species as invasive.

Appendix S4 Independent measure of data availability per country.

Appendix S5 The Red List Index.

Appendix S6 Relevant international agreements.

Appendix S7 National policy adoption.

Appendix S8 Trends in the impact of invasive alien species (IAS) by taxon.

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BIOSKETCH

This research team worked together with the specific purpose of producing the invasive alien species indicator for reporting on the 2010 Biodiversity Target. Melodie McGeoch and Stuart Butchart have a particular interest in the development and use of indicators in conservation. Author contributions: M.M. and S.B. led the project, with conceptual contributions from D.S. and E.M; the writing was led by M.M.; all authors contributed to data collection, collation and analysis.

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