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Taking Stock of the Assisted Migration Debate

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Review

Taking stock of the assisted migration debate

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a b s t r a c t

Assisted migration was proposed several decades ago as a means of addressing the impacts of climate change on species populations. While its risks and benefits have been debated, and suggestions for planning and management given, there is little consensus within the academic literature over whether to adopt it as a policy. We evaluated the main features of the assisted migration literature including the study methods, taxonomic groups, geographic regions and disciplines involved. We further assessed the debate about the use of assisted migration, the main barriers to consensus, and the range of recommendations put forth in the literature for policy, planning or implementation. Commentaries and secondary literature reviews were as prevalent as first-hand scientific research and attention focussed on a global rather than regional level. There was little evidence of knowledge transfer outside of the natural sciences, despite the obvious policy relevance. Scholarly debate on this topic has intensified during the last 3 years. We present a conceptual framework for evaluating arguments in the debate, distinguishing among the direct risks and benefits to species, ecosystems and society on the one hand, and other arguments regarding scientific justification, evidence-base and feasibility on the other. We also identify recommendations with potential to advance the debate, including careful evaluation of risks, benefits and trade-offs, involvement of relevant stakeholders and consideration of the complementarity among assisted migration and less risk-tolerant strategies. We conclude, however, that none of these will solve the fundamental, often values-based, challenges in the debate. Solutions are likely to be complex, con- text-dependent and multi-faceted, emerging from further research, discussion and experience.

Contents

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1. Introduction

Climate change has been predicted to threaten biodiversity in a number of ways (IPCC, 2007 and Parmesan, 2006), many of which are associated with the expected low adjustment rates of species to rapidly shifting habitat conditions (Davis and Shaw, 2001,Hulme, 2005 and Peters and Darling, 1985). Habitat destruction and fragmentation, the leading current and historical causes of biodiversity loss, may further impede population recovery, migration and range extension under climate change (Schwartz et al., 2001). Traditional conservation techniques, such as increasing suitable habitat at range margins and providing landscape corridors, may enable species to adjust their ranges more rapidly (Hunter et al., 2010 and Krosby et al., 2010). However, some have argued that these management approaches will need to be supplemented with innovative, adaptive and even "risk-tolerant" strategies (Heller and Zavaleta, 2009 and Hunter et al., 2010). One such proposed strategy is assisted migration (AM).

Assisted migration is the intentional translocation or movement of species outside of their historic ranges in order to mitigate actual or anticipated biodiversity losses caused by anthropogenic climatic change. Equivalent terms include facilitated migration, assisted colonization (Hoegh-Guldberg et al., 2008a and Hunter, 2007), managed relocation (Richardson et al., 2009), assisted range expansion (Hayward, 2009) and species translocation (Heller and Zavaleta, 2009).

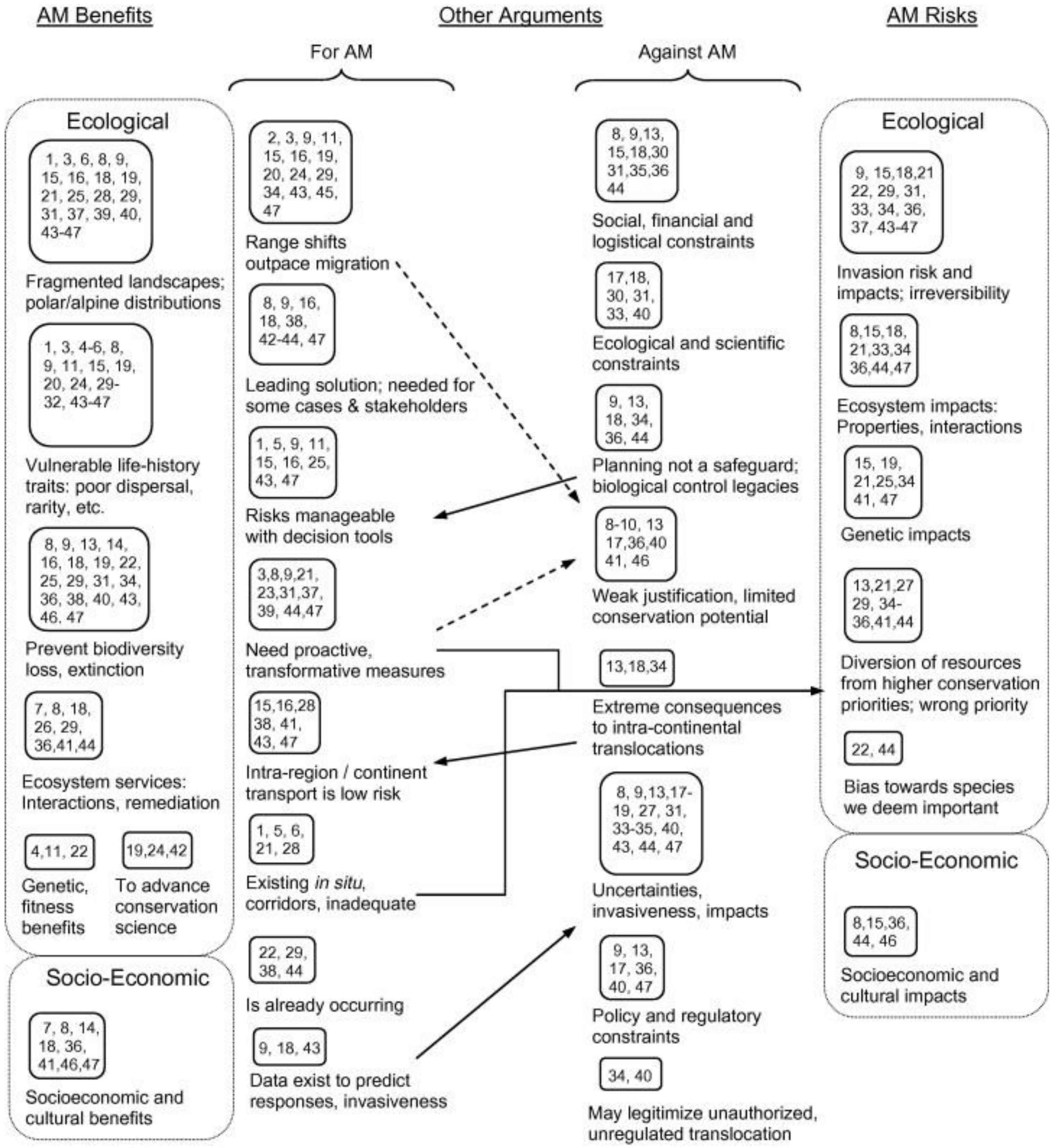
Since it was first proposed (Peters and Darling, 1985), AM has become a major topic of debate in the search for solutions to mitigate the impacts of climate change on biodiversity (McLachlan et al., 2007). Assisted migration is controversial because it conflicts with established conservation paradigms that favor maintaining the status quo of species ranges, and in situ management (Hagerman et al., 2010 and Hayward, 2009), and because of the complex scientific, policy and ethical questions that it raises. It creates conflicting conservation objectives, e.g. the preservation of single species vs. the protection of ecological communities against the risks posed by introduced species (Schwartz, 1994). Thus, AM is closely intertwined with the problem of invasive alien species (IAS). There is concern that translocated species will have similar impacts to IAS, including uncontrolled population growth and negative impacts on resident species (Ricciardi and Simberloff, 2009a). On the other hand, species translocated under AM may actually displace and help control IAS, many of which are expected to expand their populations under climate change (IPCC, 2007 and Walther et al., 2009).

A variety of approaches have been taken to provide a framework for assessing the AM debate. These range from evaluating a small set of contrasting, representative positions (McLachlan et al., 2007) to proposals for decision-making and risk assessment (e.g.,Galatowitsch et al., 2009, Hoegh-Guldberg et al., 2008a and Richardson et al., 2009). Despite this, the academic debate about the merits of AM continues (e.g. Ricciardi and Simberloff, 2009a, Ricciardi and Simberloff, 2009b, Sandler, 2010, Schlaepfer et al., 2009 and Vitt et al., 2010). Meanwhile, governmental agencies and international organizations are increasingly recommending AM as a climate change adaptation strategy (e.g., the IUCN according to Foden et al., 2008), and some groups have begun to implement AM policy and programmes (Colombo et al., 2008, McLachlan et al., 2007,Shirey and Lamberti, 2010 and Shirey and Lamberti, 2011).

At this critical juncture, an analysis of the current state of the scholarly literature on AM is timely for evaluating the state of knowledge and the range of arguments so as to provide guidance to decision-makers. While other researchers have examined specific aspects of the AM issue (e.g., plants: Vitt et al., 2010; selected positions in the debate: McLachlan et al., 2007; species valuation: Sandler, 2010; planning tools: Hoegh-Guldberg et al., 2008a; integration with other adaptations: Loss et al., 2011), and others have reviewed the literature on climate change adaptation more generally (Felton et al., 2009 and Heller and Zavaleta, 2009), this is the first comprehensive review of the scholarly literature pertaining to AM.

This review had two objectives: (1) to identify the main features of the AM literature and (2) to assess the debate about the use of AM as a climate change adaptation strategy. For the first objective, we classified the literature in terms of: study methods, geographic and taxonomic focus, and degree of transfer of knowledge from the natural sciences to other academic disciplines and non-academic sectors. For the second objective, we characterized the debate in terms of arguments for and against AM, barriers to consensus, proposals for overcoming them, and recommendations for AM research, policy or action; developed a conceptual framework to portray the competing arguments and their interrelations

(Fig. 3); and evaluated the recommendations and proposed avenues toward consensus in terms of their potential to advance the debate. It would be unrealistic to expect to resolve the debate definitively, as there will likely never be complete agreement on the use of AM. Rather, our goal was to identify recommendations with some potential, however modest, to bridge disagreements, move the scholarly debate toward greater consensus, and avoid an emerging state of paralysis in which conservation managers and policy makers find themselves unable either to embrace or reject AM as a strategy to adapt to climate change.



2. Methods

To identify the main features of the AM literature, we searched Web of Science ISI (Science Citation Index Expanded, Social Sciences Citation Index, and Arts and Humanities Citation Index), Scopus Elsevier (Life Sciences, Health Sciences, Physical Sciences, and Social Sciences and Humanities indices) and Google Scholar for relevant articles in the natural sciences, social science and humanities, without geographic or date restrictions. We accessed these on May 7, 2010 employing the search terms or strings: “assisted” or “facilitated” and “migration” or “colonization”; “translocation” or “relocation”; “artificial” and “introduction”; climate change” or “warming” or “global change” or “elevated CO_2”; “alien” or “exotic” or “invad*” or “invasi*” or “non-native” or “non-indigenous” or “introduced” same “species”. The searches produced 227 articles. We reviewed the author, title, journal name and abstract of each, along with the full text as needed. We discarded 78 as clearly irrelevant, selected those (57) that referred explicitly to AM, and added six papers found through cross-referencing, for a total of 63 articles. These ranged from articles focussed directly on AM to those mentioning it as an implication of their study. The remaining 92 articles addressed potentially relevant topics, for example, bioclimatic modeling, paleobiological reconstructions of former ranges, climate change science, or IAS, but did not mention AM in the title or abstract, or in the full-text of those we sampled, and so were not included in the analysis. Our goal was to delimit the scope of the literature conservatively, isolating those articles that engaged substantially and deliberatively with the subject.

We classified the 63 articles in terms of study method, geographic focus and taxa investigated. To give a rough sense of the transfer of knowledge from the natural sciences to other academic and non-academic domains, we classified articles in terms of economic sector addressed and academic discipline. Classification categories were derived from MacLellan (2008) and an earlier examination of the larger literature on climate change, species invasion and AM (N.K., N.H. and J.I.M. unpublished results).

The second objective of characterizing and assessing the debate over the use of AM for adaptation to climate change, involved detailed reviews of the full-text of 50 articles. Our selection was guided by the previous analysis. We identified 44 articles from our original search results, including all commentary (e.g., opinion pieces, letters, essays) and reviews, most general syntheses or reviews of climate change and biodiversity conservation, and a selection of other relevant articles captured in our search. We also included articles dealing with related topics (e.g., species reintroduction) or having high citation rates (to capture articles having the greatest impact on the debate). We read the full-text articles discarding any that were not relevant to the debate, leaving 32 articles, to which we added 18 through cross-referencing for a total of 50.

To get an overall picture of the debate, we classified each article as either (1) generally supportive of, (2) generally not supportive of, or (3) taking no clear position on AM as an option for climate change adaptation. In the category “generally supportive” we included articles either endorsing the use of AM for specified situations or suggesting that it should be considered. The category “generally not supportive” included articles opposing or expressing serious reservations about the use of AM. While this sort of exercise may carry a risk of over-simplifying a complex debate, it is useful as a first approximation of the degree of support for and opposition to AM in the scholarly literature. To get a fuller picture, it was accompanied by a fine-grained analysis of the various positions in the debate. We did this by identifying, for each article, (1) arguments in favor of and in opposition to AM ("reasons for" and "reasons against"), (2) recommendations for research, policy or action, and (3) stated barriers to consensus and proposed solutions to these obstacles. To avoid bias or oversight in selection we created a database in which we transcribed each item in the authors' words. We then classified these into like categories based on similarity of underlying position (Heller and Zavaleta, 2009). Under reasons for and against we only included reasons stated in relation to AM or in relation to translocation for species protection with mention of situations of climate change. We focused on arguments endorsed by the authors, but also included opposing arguments if these were stated in the context of acknowledging potentially relevant considerations in the debate.

We organized the reasons for and against into broad groups of similar kinds of arguments based on whether they were direct benefits or risks of AM programs to ecosystems or society. Arguments that did not consider direct risks or benefits were classified as "other arguments" for or against and included arguments about the feasibility of operationalizing AM, as well as counter-arguments, or, responses to statements made on the opposing side. For the latter, we identified the principal arguments to which they responded, to illustrate connections among pro- and con-arguments.

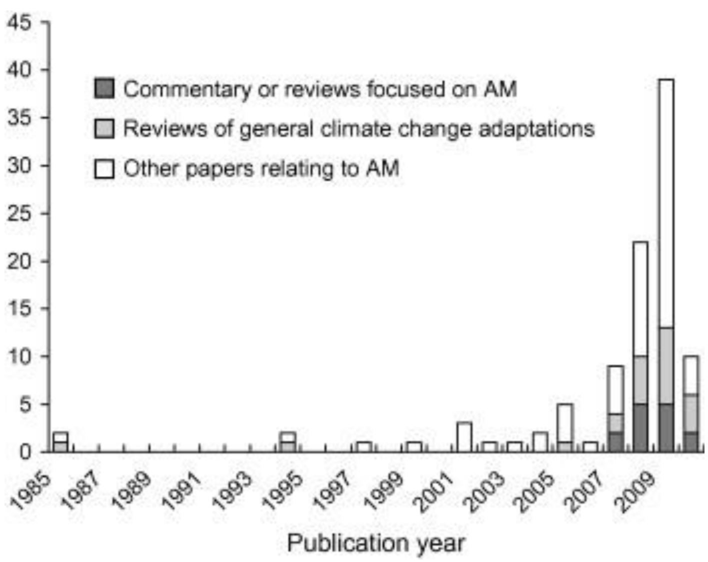
Recommendations included those pertaining specifically to AM, regardless of whether the paper was overtly in favor of AM policy or not, or, if the paper discussed more general climate change adaptations, those deemed instructive to AM policy and practice. Once recommendations were grouped based on their similarity, they were classified into five main types, reflecting the topic of concern (species and sites, law and policy, planning, implementation, approach) and then some were divided into sub-categories based on the context in which they would be carried out (e.g., research needs, selection criteria, tools or techniques, specific actions for implementation, prescriptions, etc.).

One of us [N. Hewitt] read and classified 48 of the 50 papers, also indicating how each recorded argument or recommendation was derived by the authors, with categories (1) first hand research, either empirical, experimental or modelling; (2) literature review, or (3) the authors' own thoughts, views, and opinions ("ecological reasoning"). For recommendations, N. Hewitt also summarized: (A) whether the authors provided sufficient detail and information to implement the recommendation (actionable) or whether it was a more general idea (general principal), and (B) whether the recommendation was a call for further research (information need), or a call for policy and practice activities (action) (Heller and Zavaleta, 2009, p. 16). To crosscheck results, two of us [N.H. and N.K.] identified reasons for, reasons against and recommendations for 23 of the 50 papers examined.

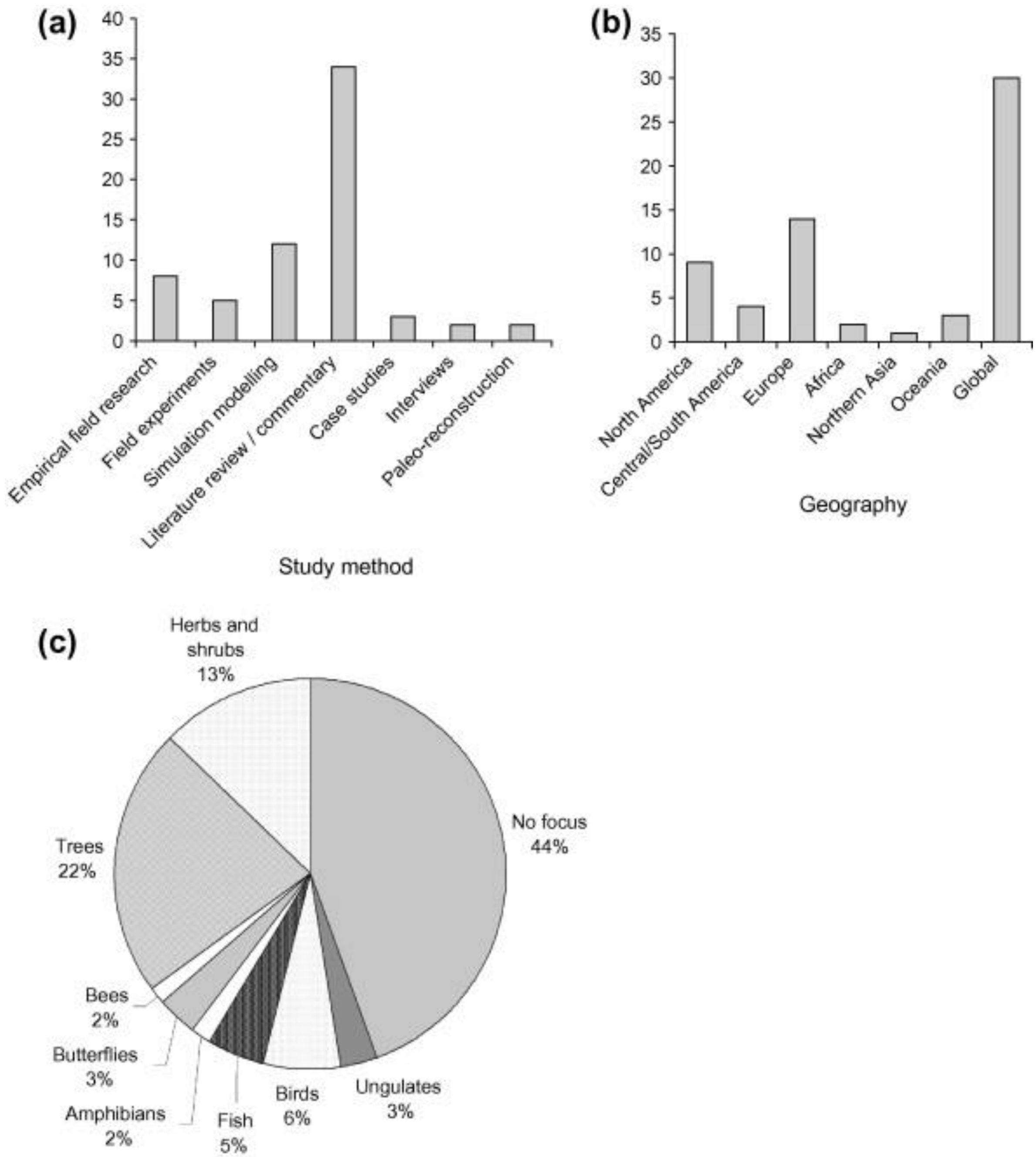
3. Results and discussion

3.1. Study methods

Assisted migration has emerged, in recent years, as a major topic of discussion in the field of climate change and biodiversity adaptations. Following a highly cited, definitive article by Peters and Darling (1985) (Supplementary data, S1), AM received little attention until 2007 when the number of articles on the topic rose dramatically (Fig. 1). Moreover, all AM-focussed commentary and reviews were published after 2006. These latter articles are a good indication that a sustained debate has emerged amongst conservation biologists on the use of AM as a strategy for conserving biodiversity in the face of climate change.



Thirty-six articles (57%) employed literature review, commentary or interviews. Thirty articles (48%) presented biophysical data based on empirical research, experimentation, models, case studies or paleobiological reconstruction (Fig. 2a), of which a sizeable number (19) recommended AM as a means of preserving the taxa examined in the face of threats to species from climate change. We might have expected to find more first-hand scientific research in the scholarly AM literature, given that a sizeable number of original studies of biophysical data capable of informing the science, policy and practice of AM exist (although Parmesan, 2006, found few well designed studies of species range shifts). Such studies were captured in our search but excluded from our analysis (e.g., general bioclimatic or species distribution modeling, paleobiological range reconstructions, case studies of invasive species distribution changes and impacts). This existing body of research on climate change impacts is a potential, largely untapped, link in the chain of science, policy and planning for AM.



3.2. Geographic and taxonomic focus

The largest proportion of articles, including all (19) AM commentary/review and general climate change adaptation articles, had a global or general geographic focus (Fig. 2b). This was not surprising given the relatively small number of articles presenting original research. Europe and North America garnered the most attention among geographic regions, most likely reflecting the concentration of researchers and funding agencies in those areas (Felton et al., 2009). Polar and alpine regions were the focus of two regional papers (Krankina et al., 1997 and Viveros-Viveros et al., 2009), and were presented as examples of regions with high extinction risk due to lack of available habitat for range translation (Hoegh-Guldberg et al., 2008a, Peters and Darling, 1985 and Rahel et al., 2008). Tropical environments also received attention, both in some regional papers (focused on Central America and Oceania) and in two general papers, one with reference to biodiversity hotspots with “disappearing” climates (Williams et al., 2007), the other in terms of opportunities for ex situ conservation in tropical botanical gardens (Chen et al., 2009).

From a taxonomic perspective, 56% of articles examined specific taxa in non-invasive contexts, the majority of which were plants, especially trees (Fig. 2c). The focus on trees may reflect their economic importance and a bias towards research in forest systems evident in the general climate change literature (Felton et al., 2009). A small number of studies (8%) treated invasive alien species, for example to model or examine species distribution changes under climate change (Goren and Galil, 2005 and Sutherst and Bourne, 2009), measure invasion rates from intra-continental introductions (Mueller and Hellmann, 2008), or examine the relationships between invasive and native species populations under climate change (e.g., plant competitors: Bradley and Wilcove, 2009).

3.3. Knowledge transfer: social sciences and humanities literature

The topic of AM originates in the natural sciences amongst biologists concerned with how species will adapt to climate change. Nevertheless, it raises important questions for broader society and has garnered attention in the popular science literature (e.g., Appell, 2009 and Science Daily, 2008). As yet, there are few articles considering AM in the social sciences and humanities. The overwhelming majority of articles (96%) were in the natural sciences, specifically ecology and conservation biology. Only two papers focussed on the philosophical aspects of AM such as environmental ethics, theology, and the value of species (Sandler, 2010 and Southgate et al., 2008; and see Minteer and Collins, 2010), and one addressed AM in relation to urban or environmental planning (Yeang and Lehmann, 2010). While several articles treated broader socioeconomic implications (e.g., potential societal risks and benefits and methods to assess them), cross-disciplinary research is limited by the fact that most academic journals are aimed primarily at members of specific disciplines. This slow rate of knowledge transfer to the social sciences and humanities reflects a time lag and, while it is to be hoped that other disciplines become increasingly aware of the debate, the literature on science and technology transfer for commercialization purposes suggests that research takes a minimum of 10 years to be mobilized (Heher, 2006). While our study did not target the legal academic literature, a search of the TP-ALL database (all legal texts and periodicals) within Westlaw, a leading full-text legal database service, yielded 25 relevant articles on AM (November 14, 2010), indicating the saliency of the AM issue within the legal field. Future studies should be expanded to examine this important literature, since it relates directly to policy formation. The majority of papers (56/63) were not associated with any particular economic or resource sector, suggesting that AM is not yet widely applied as a policy or management tool with the possible exception of the forestry sector (6 papers). One paper addressed agricultural data (Sutherst and Bourne, 2009), but it was intended to inform scientific modeling of biological invasions and did not indicate transfer of scientific knowledge outside the academy.

3.4. The AM debate

Overall, of the 50 articles we reviewed in detail, 30 (60%) were generally supportive of AM, while 10 (20%) expressed major concerns or opposition and 10 (20%) indicated no clear position (Supplementary data, S2). The articles classified as supportive were a diverse group, some suggesting AM as one (sometimes among several) alternative for biodiversity protection in circumscribed situations (e.g., Davis and Zabinski, 1992,Marsico and Hellman, 2009, Peters and Darling, 1985, Vitt et al., 2009 and Vitt et al., 2010), others only going so far as to advocate serious consideration of AM as a possible tool to prevent species losses (Hunter et al., 2010, Sax et al., 2009 and Schwartz et al., 2009). Several argued for careful assessment of potential risks alongside benefits (e.g.,Hoegh-Guldberg et al., 2008a, Hoegh-Guldberg et al., 2008b, Hunter, 2007 and Richardson et al., 2009). Articles classified as not supportive included one presenting primary data demonstrating AM's invasion risks (Mueller and Hellmann, 2008), two questioning

AM's ability to achieve conservation objectives (Mawdsley et al., 2009 and Williams et al., 2007), and seven, mainly response letters, that were skeptical of AM being applied at all (e.g., Davidson and Simkanin, 2008, Ricciardi and Simberloff, 2009a and Ricciardi and Simberloff, 2009b) or in any but a few exceptional circumstances (e.g., Fazey and Fischer, 2009 and Sandler, 2010). These latter seven papers were all published in 2007 or later. So notwithstanding the preponderance of "supportive" articles, a vigorous debate has emerged.

3.4.1. Making sense of the debate

This becomes even clearer when we move beyond an overall snapshot to consider the range of positions and ideas identified by authors. Forty-seven of the 50 articles stated reasons for or against AM and several of these discussed the merits of both types of arguments (e.g., Hunter, 2007, McLachlan et al., 2007, Parker et al., 2010, Rahel et al., 2008 and Vitt et al., 2010). Nevertheless, most articles favored one position over the other, rather than taking a neutral stance (Section 3.4).

By categorizing arguments into a manageable number of discrete classes, indicating the amount of support for each and presenting these in a single schematic, we were able to identify the salient features of the debate and how ideas related to each other (Fig. 3). To clarify the structure of the debate, a basic distinction was made between arguments asserting the benefits or risks of AM, and other kinds of arguments. Benefits were those advantages that AM was purported to offer to species, ecosystems and society, while risks were the disadvantages AM posed to the same. Other arguments, rather than asserting benefits or risks directly, raised issues such as information needs, uncertainties, decision-making tools, implementation issues, or counter-arguments to asserted risks and benefits. This distinction was not well recognized in the literature, but it highlighted what is ultimately at stake in the AM debate, namely whether AM will be beneficial or harmful. Many arguments in favor of AM were not about its benefits per se, but rather, arguments aimed at providing rebuttal to stated risks. These included statements such as "AM will not be hazardous because we possess information sources and decision-making frameworks" and "AM is needed because it satisfies an emerging need to be proactive with community management". These sorts of counter-arguments against AM opposition cannot substitute for positive demonstrations of need. As Sandler (2010, p. 424) cautions,

That an assisted colonization is not likely to be ecologically detrimental is not a reason in favor of doing it. It is the absence of a reason not to do it …Therefore, justifying an assisted colonization requires more than demonstrating that the ecological risks of that particular translocation are relatively low…It is also necessary to justify why even relatively low risks should be taken.

Similarly, on the "con" side of the debate, concerns relating to logistics, justification and feasibility (e.g., ecological, policy and financial constraints) were classified as "other arguments". While these factors may ultimately tip decisions in one direction or another (e.g., if the feasibility of species translocation is low, the project will not be implemented), they are not fundamental reasons for designing management around AM or not. They are essentially problems of information and management.

It is currently difficult to reconcile the risks and benefits of AM. This may be one reason that the debate tends to focus on subsidiary issues indicated in our "other arguments". A larger, nuanced picture of the debate was needed (Sax et al., 2009), and it is supplied by our distinction among risks, benefits, and other arguments for and against AM. This schematic (Fig. 3) allows proponents and opponents to navigate the issues with a clearer picture of what is at stake, and provides common ground upon which both may well be happy to reside. With this in mind, we can now summarize the main positions in the debate.

3.4.2. Arguments for and against AM

Whereas AM's main stated benefits related to its potential to preserve species, its main stated risks ran in the opposite direction: the chance of invasion by the focal species and associated biological, ecosystem and socioeconomic impacts. Of these, ecological risks and benefits relating to species, ecosystems and physical environment were the focus (upper left and right, enclosed capsules, Fig. 3), while socioeconomic reasons were stated less frequently (lower left and right capsules, Fig. 3).

The main stated benefits of AM were to prevent species extinctions and protect biodiversity, particularly among species with life history traits that made them vulnerable to climate change (e.g., poor dispersal, rarity, low fecundity, long generation times; 45% of the 47 articles), or geographic distributions that would impede migration to viable habitat (e.g., confined to fragmented landscapes or high alpine or arctic areas lacking sufficient adjacent habitat; 47% of articles)

(Supplementary data, S3). The combination of climate change and land use patterns in human dominated landscapes was seen to present insurmountable difficulties for large numbers of species unless AM was attempted, with habitat restoration and connectivity not being reliable safeguards (Galatowitsch et al., 2009, Hulme, 2005 and Pearson and Dawson, 2005).

The most commonly identified risk of AM was that the introduced species would become invasive (34% of articles). This encompassed the typical suite of impacts on ecological communities and environments (see e.g. Simberloff, 2005), and the low likelihood of reversing invasions. Invasion risk was also implied in other risks identified by authors, including ecosystem impacts, genetic impacts and legitimizing unauthorized AM. Other key risks included diversion of funds away from critical biodiversity protection measures such as ecosystem restoration and reversal of fragmentation (Fazey and Fischer, 2009), and assigning less conservation value to recipient regions than to the single candidate species for translocation (Davidson and Simkanin, 2008 and Spear and Chown, 2009). Socioeconomic risks captured impacts on the economic value of target ecosystems, or of culturally, esthetically or medicinally important species as well as potential health impacts from certain introductions.

Among “other arguments against AM”, information gaps or uncertainties in predicting focal species invasion were major concerns (32% of articles), even among supportive articles. These concerns were the subject of a lively interchange of letters in two journals (Science; Trends in Ecology and Evolution). While supporters suggested ways to deal with these gaps (e.g., draw on restoration or reintroduction case histories, horticultural information and invasive species literature; employ experimental and simulation studies) and supported the use of careful planning (e.g., risk assessments, cost–benefit analysis, and frameworks for weighing competing solutions), AM skeptics argued that the invasive potential in novel environments had a high degree of unpredictability, even with good data (Ricciardi and Simberloff, 2009b). Other arguments against AM typically related to evidentiary and operational challenges, including infeasibility, constraints on management (e.g., prohibitive costs, political boundaries and species' failure to colonize) and poor justification for AM to achieve its purported goal of species preservation (e.g., low chance of single focal species benefiting recipient communities; ineffective for vast number of species in tropical biodiversity hotspots with "disappearing climates" and nowhere to relocate). Other arguments on both sides were also, frequently, responses to opposing arguments, especially those regarding the scientific bases or practical abilities to manage risks (see connections between arguments, Fig. 3). For example, the argument that planning cannot safeguard against AM risks responded to assertions that risks are manageable with appropriate decision tools. The main risks and benefits can also be seen as responses to other arguments in the sense that, for example, arguments about risks to ecosystems or society are responses to arguments in favor of adopting AM. Unlike some "other arguments," however, they stand alone as arguments in their own right, rather than just being responses to particular concerns. There may be a degree of arbitrariness in this distinction, but it is a useful heuristic tool.

3.4.3. Weighing benefits and risks: an intractable problem?

The debate revolves around a seemingly intractable conflict between AM's potential to save species from extinction, vs. its potential to cause species loss and other impacts (biological, ecosystem and socioeconomic). Given that the major risks and benefits related to the value of species in relation to potential recipient region impacts, justifying AM may require that the value of species—economic, intrinsic or otherwise—be demonstrated and shown to outweigh the risks posed by the translocated species (Sandler, 2010). An obvious limitation to exercises in species valuation is the difficulty involved in quantifying ethical, non-monetary values (Section 3.5) and this may be reflected by the fact that only one paper (Sandler, 2010) attempted such an evaluation. Some authors have asserted that the chances of a translocated species having major positive ecosystem-level benefits are rare (Davidson and Simkanin, 2008, Ricciardi and Simberloff, 2009a and Sandler, 2010), and that this is therefore not a major hinge in the debate. While this may be true for a large proportion of prospective AM species, the opposite could easily be argued for some. These include "keystone", "foundation" species, or "ecosystem engineers", such as dominant tree species that provide the major structure of forest communities along with socio-economic benefits (Ellison et al., 2005 and Jones et al., 1994). There have been previous attempts to value species for in situ biodiversity protection, typically as a response to financial constraints or competing economic interests against their preservation (e.g., Akter and Grafton, 2010, Kassar and Lasserre, 2004 and Polasky and Solow, 1995). While these studies do not capture the connection between the focal species and its potential invasion risk ex situ, they could be extrapolated to the issue of AM. We nevertheless place little faith in the potential for generalizable valuations of species and suggest that focal species benefits may need to be placed in the context of local and global stakeholder interest for particular AM proposals.

Justifying the need for translocation also requires demonstrating that the risks (primarily of invasion) are not greater than the advantages of translocation. The importance of weighing these risks and benefits was reflected in the many proposals for risk–benefit or cost–benefit assessments and decision-making frameworks containing built-in methods for evaluating risks and benefits. These strategies could also address resource allocation issues associated with the risk that funds would be diverted away from restoration of ecosystems and reversal of fragmentation, the "root causes" of biodiversity loss (Fazey and Fischer, 2009 and Davidson and Simkanin, 2008). Any assessment of AM must address these trade-offs. Nonetheless, the great difficulty of ascertaining the potential risk posed by an AM species in advance is likely to render such decision-making measures a rough guide at best.

Finally, the notion that AM pits single (focal) species against whole (recipient) communities is deeply embedded in the debate, and even more complex than implied. AM was advocated frequently for taxa whose migration would fall short of targets required to meet projected range shifts (e.g., poor dispersers, rare species; species confined to fragmented landscapes, polar or alpine species). These species collectively comprise a significant amount of biodiversity. Further, the sheer number of species threatened with stymied migration will be high even in relatively continuous, uninterrupted landscapes, if predictions of large-scale extinctions due to rapid climate change in relation to migration potentials materialize (Davis and Shaw, 2001). Assisted migration may, therefore, turn out to be the main response measure (but see Krosby et al., 2010), even if it will not be free of its own problems. In this context AM is not simply an issue of single species vs. communities, but of prioritizing among entire assemblages of species.

3.5. Barriers to consensus and proposed solutions

We identified a number of barriers to consensus (Table 1). Some represented challenges with seemingly straightforward solutions (e.g., clarify definitions, involve local communities), while others were more fundamental problems, such as the tension of choosing between AM for focal species vs. protecting recipient ecosystems, and the large uncertainties with respect to focal species responses and impacts. The association of AM with documented cases of invasive species world-wide is central to many of these stated barriers, and is one that would understandably set off alarms within the conservation community.

Table 1.
Main barriers to consensus in the assisted migration debate and suggested solutions for overcoming these that were indicated in the literature.

Barrier	Details	Solution, if suggested	References
Different definitions and emphases	Grouping AM with long-distance, translocations, those conducted for economic reasons rather than conservation, or with IAS and biological control examples	Clarify definitions and emphasis; Continue discussion on AM; Distinguish from long-range, exotic species introductions	Vitt et al., 2009 and Vitt et al., 2010
Unbalanced assessment of data	Overstating risks rather than benefits (or vice versa); Shallow evaluation of benefits; Assumption that AM will lack careful planning	Use array of decision-making and cost-/risk-/benefit analysis tools	Hoegh-Guldberg et al. (2008a), Vitt et al., 2009,Schlaepfer et al., 2009 and Sandler, 2010
Existing conservation management paradigms	Views of nature: humans set apart; intervention labelled “unnatural”, unethical; native/indigenous paradigm; Established biodiversity targets not suitable in situations of climate change	Need time for paradigm shift, idea acceptance, recognition of biophysical changes producing needs; Focus on species impacts, not ideas of “native/non-native”	Hayward, 2009 and Hagerman et al., 2010
Research/information challenges	Context, case-specific research difficult to generalize or apply in risk/ecological assessments; Uncertainty, lack of information leads to inaction, “paralysis by analysis”	Use Scenario planning (suited to situations of uncertainty, complexity); Work with existing data (e.g., reintroduction biology) and emerging insights from basic and applied research	McLachlan et al., 2007, Galatowitsch et al., 2009 and Vitt et al., 2009
The specific nature of AM	Puts conservation objectives at odds with one another: species preservation vs. integrity of recipient communities; Involves ethics, morals, values; Scientists’ area of research affects views (e.g., researchers of rare vs. invasive species)	Flexible management strategies; Consider “triage” to aid difficult decisions regarding species and case selection; Resolve conflict with “clear-goal setting”	Schwartz, 1994,McLachlan et al., 2007 and Lawler, 2009
Lack of community involvement	Lack of public involvement or guidelines for inclusion; Projects fail without local support, funding	Forums, discussions, use of local media to inform, communicate	Parker (2008)

It is not surprising, therefore, that we find the stated solutions limited in their ability to resolve these barriers to consensus. For example, furthering discussion and clarifying definitions may solve simple communication issues but is unlikely to dispel the sense that AM may prove calamitous in light of the evidence for serious impacts of intra-continental introductions (Mueller and Hellmann, 2008). Nor will it quiet concerns about the legacy of other management intervention problems including intentional introductions for horticulture and biological control (Ricciardi and Simberloff, 2009b and Simberloff, 2005). Decision making frameworks and risk analyses may bring parties closer to appreciating the benefits, risks and tradeoffs in particular projects, and scenario based planning may assist in defining benefits or uncertainties in risk prediction, but, as we express above, these are not going to solve all concerns. Time may resolve some disagreements, but if the need for action is as pressing as many suggested, time is a very limited resource.

Some articles suggested greater community involvement, such as educating and building community support, using media for communication, and bringing in potentially important interest groups to participate in decisions (Parker, 2008). While this seems promising, as we suggest in Section 3.6, it is not clear how this alone can resolve the conflicting values among these groups or the intellectual conflicts that divide the scientific community, let alone answer the key scientific questions needed to inform policy (McLachlan et al., 2007).

3.6. Recommendations for research, policy and action

The papers reviewed contained various recommendations. Given the paucity of primary biophysical research into AM processes, it was not surprising that the individual records used to construct these recommendations, as well as the arguments in the debate (Section 3.4.2), were derived mainly from ecological inductive reasoning and literature review (Fig. 4). The majority (65%) of recommendations were general principles rather than ones with sufficient detail to be considered actionable (35%). This lack of specifics may be explained by the lack of first-hand research as well as the only recent burst of attention to AM in the literature and a stalemate on policy and action posed by the intense debate. Nearly a quarter of the recommendations were information needs (24%), while 74% were action needs. Many of the papers made recommendations relating to species or site research and selection (52% of articles), planning (38%) and implementation activities (36%). Legal or regulatory needs were indicated in 16% of papers (Table 2).

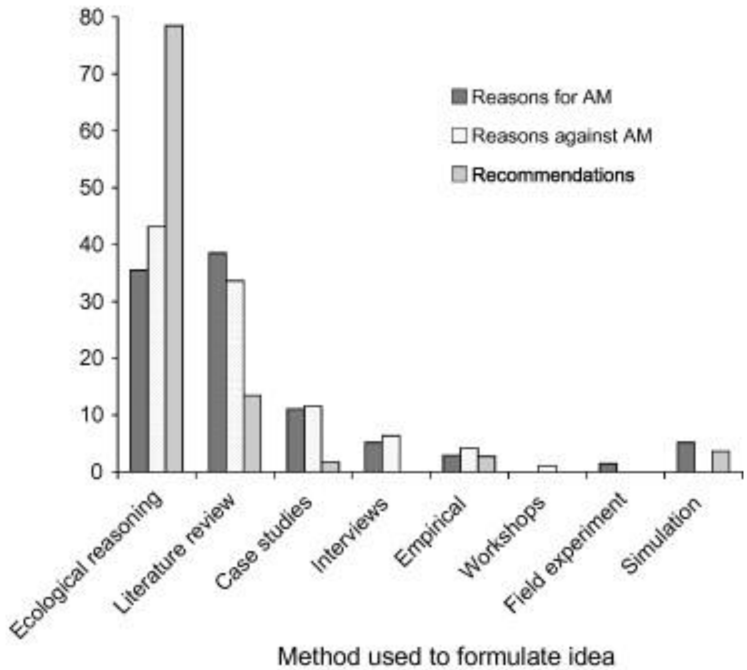


Table 2.
Summary of 65 recommendations for assisted migration organized by topic concerned.

Type Recommendation	References
Species and sites	
Tools and techniques for decisions	
Employ bioclimatic modeling, biogeographic distribution models, GIS-based habitat profiles, vulnerability or ecological assessments and analogues, triage, conservation strategy maps	Hulme, 2005, McLachlan et al., 2007, Hoegh-Guldberg et al., 2008a, Bradley and Wilcove, 2009, Carroll et al., 2009,Galatowitsch et al., 2009,Lawler, 2009, Vitt et al., 2010 and Parker et al., 2010
Research needs	
Selecting and Translocating Species: Determine species' role in ecosystem goods and services; historical presence at site; long-term viability in new range; long-distance dispersal abilities (with transmitters); ecological, economic, intrinsic "value"; need for community interactions; site's future climatic suitability; Monitor range shifts across species	Chapin et al., 2007, Hunter, 2007, McLachlan et al., 2007,Aitken et al., 2008, Bradley and Wilcove, 2009, Mueller and Hellmann, 2008, Ricciardi and Simberloff, 2009a, Carroll et al., 2009, Donaldson, 2009,Heller and Zavaleta, 2009,Schlaepfer et al., 2009,Schwartz et al., 2009, Seddon et al., 2009, Swarts and Dixon, 2009, Vitt et al., 2009, Sandler, 2010 and Vitt et al., 2010
Predicting Potential Impacts: Develop predictive	

Type Recommendation	References
understanding of focal species invasion likelihood and impacts; Employ existing databases (invasive exotics, translocation, reintroductions, restored populations, botanical gardens) and experiments (common garden, transplant); Demonstrate that value of species outweighs risks	
Selection criteria	
Prioritize: Poor dispersers; fragmented systems, isolated reserves	Davis and Zabinski, 1992,Honnay et al., 2002, Hunter, 2007, Hoegh-Guldberg et al., 2008a, Mueller and Hellmann, 2008, Bradley and Wilcove, 2009, Spear and Chown, 2009,Swarts and Dixon, 2009 and Vitt et al., 2010
Favor: Specific terrestrial plants (less invasive within-continent); species indigenous to broader biome; "non-weedy" taxa; Species, projects with good track record, practical knowledge (previous restoration), chance to improve site's conservation status; Sites with historical (paleobiological) record of taxa (but note: future climates may lack past analogues); (resilient) species-rich systems	
Avoid: natural "island" sites; aquatic (fish), "weedy" (high-risk) taxa; limit to conventional conservation measures; Do not cross boundaries of evolutionary significance	
Law or policy	
Prescription	
Regulate, centralize control; Legal, policy protection for future suitable habitat, newly transferred colonies; Revise Endangered Species Act (Sect. 3) for translocations; Develop inter-agency teams, government coordination to facilitate AM across land-ownership and political borders; Develop legal frameworks to protect AM agents, compensate recipient regions for damages; Use	McLachlan et al., 2007,Chapron and Samelius, 2008,Hoegh-Guldberg et al., 2008a,Hoegh-Guldberg et al., 2008b,Mueller and Hellmann, 2008,Lawler, 2009, Seddon et al., 2009 and Vitt et al., 2010 (and see Shirey and Lamberti (2010))

Type Recommendation	References
existing translocation guidelines, protocols, (IUCN, Reintroduction Specialty Group); Avoid designating AM populations as 'experimental' under ESA section 10(j) (weak protection)	
Planning	
Tools	
Cost–benefit, risk/benefit, feasibility analysis (socioeconomic, ecological costs, implications, feasibility); Tailored, transparent decision making tools, for systematic case assessment; Risk assessment, risk analysis, impact evaluations; Combine Scenario-based planning with Resistance/resilience/facilitation frameworks, Adaptive Management	Hunter, 2007, McLachlan et al., 2007, Hoegh-Guldberg et al., 2008a, Mueller and Hellmann, 2008, Huang, 2008,Galatowitsch et al., 2009,Heller and Zavaleta, 2009,Hayward, 2009, Lawler, 2009,Richardson et al., 2009,Schwartz et al., 2009, Spear and Chown, 2009, Schlaepfer et al., 2009, Vitt et al., 2009,Parker et al., 2010, Sandler, 2010 and Vitt et al., 2010
Specific actions	
Continue debate, AM as a policy option; Frame debate: perception of risk and confidence in ecological understanding; Integrate socioeconomic data in DMFs to capture subjective values	Hunter, 2007, McLachlan et al., 2007, Hoegh-Guldberg et al., 2008a, Mueller and Hellmann, 2008, Fazey and Fischer, 2009, Schlaepfer et al., 2009, Schwartz et al., 2009, Spear and Chown, 2009 and Vitt et al., 2009
Stakeholder inclusion	
Consider public perception; Use media to inform, raise profile, generate funding; Evaluate stakeholder positions and tailor policy approaches	Hunter, 2007, McLachlan et al., 2007, Parker, 2008,Richardson et al., 2009,Sandler, 2010 and Schlaepfer et al., 2009
Implementation	
Specific introduction techniques	
Begin in sites where species recently extinct (considering future climatic suitability); Transport seed/seedlings to northern forests; Keep pace with habitat creation (trees); Disperse in relation to bioclimatic envelopes; Introduce southern genotypes into openings within ranges; Transplant individuals from resistant and resilient	Davis and Zabinski, 1992,Honnay et al., 2002,Savolainen et al., 2004,Hulme, 2005, Hunter, 2007,McLachlan et al., 2007, Aitken et al., 2008, Carroll et al., 2009, Chen et al., 2009,Lawler, 2009, Marsico and Hellman, 2009, Swarts and Dixon, 2009 and Vitt et al., 2009

Type Recommendation	References
(coral) populations; Use wild-caught animals and acclimate; Upstream fish transport during drought, low flows; Link ex situ (botanical gardens, parks, zoos) to in situ alongside AM; Conduct paired, multi-species translocations (for obligate interactions); Change seed transfer guidelines to move seed maximum extent, milder to colder based on population response curves; Transplant entire ecosystems as climate becomes available; AM in small populations adequate	
Translocation materials	
Select for genetic variation, adaptability; Plants: use seed not transplants to filter out genotypes; Seed bank storage; Pre-adapted source populations occurring at range limits/community boundaries	Peters and Darling, 1985,Crumpacker et al., 2001,Hulme, 2005, McLachlan et al., 2007, Galatowitsch et al., 2009, Swarts and Dixon, 2009 and Vitt et al., 2010
Follow-up	
A posteriori risk management; monitor translocated populations for success	Mueller and Hellmann, 2008 and Swarts and Dixon, 2009
Approach	
Proactive	
Act if climate change pinpointed as problem, do not stall for more research; Change emphasis away from corridors towards AM; Move beyond passive, in situ, native vs. non-indigenous conservation approach to active; Emphasize impact of the species; Consider novel future assemblages (no analogs),"transformative restoration"	Pearson and Dawson, 2005,Hunter, 2007, McLachlan et al., 2007, Heller and Zavaleta, 2009, Lawler, 2009, Rahel et al., 2008, Bradley and Wilcove, 2009, Galatowitsch et al., 2009, Hayward, 2009 and Vitt et al., 2010
Traditional; in situ	
Allow species to respond naturally; Enhance traditional conservation strategies (habitat/corridor creation, restoration), first course of action	Crumpacker et al., 2001,Hunter, 2007, McLachlan et al., 2007, Hoegh-Guldberg et al., 2008a, Ricciardi and Simberloff, 2009a, Hayward, 2009, Marsico and Hellman, 2009, Vitt et al., 2009 and Vitt et al., 2010

3.6.1. Recommendations with potential to advance AM debate

To assess these recommendations, we asked which had the greatest potential to advance the debate, and how well they responded to the identified barriers to consensus and main positions in the debate. Firstly, given the central concerns around invasion and uncertainty, and the dearth of first-hand research on AM (Section 3.1), recommendations for further research on species and sites (found in 26% of the articles) are well-grounded. These included research needed to improve translocation success and anticipate migration potential, for example, in terms of long-distance dispersal abilities (McLachlan et al., 2007) as well as recommendations for techniques and data sources with which to predict impacts. It is important to note that these research needs may not be satisfied easily or quickly. Measurement of long-distance dispersal, for example, has long proved difficult (Hewitt and Kellman, 2002 and Pearson and Dawson, 2005). Furthermore, the problems with generalizing from case-specific information (Galatowitsch et al., 2009), combined with the creeping uncertainties inherent in predicting invasiveness (Ricciardi and Simberloff, 2009b), mean that this information is not likely to satisfy all needs or convince all concerned parties.

Secondly, planning tools such as decision making frameworks and risk–cost–benefit assessments, recommended in 34% of articles, provide for transparent, systematic planning and are a first step to deciding among competing biodiversity adaptations, funding priorities and concerns relating to the particular species and recipient communities (Hoegh-Guldberg et al., 2008a and Richardson et al., 2009). While these may represent the best available strategies to inform decisions, we have already noted that they may not produce decisions that satisfy all interested parties, ensure that AM projects that would have been safe and successful are implemented, or avoid projects that will have net negative impacts. Planning should also involve all relevant stakeholders within and outside the scientific and conservation communities (Parker, 2008 and Schlaepfer et al., 2009). Their inclusion acknowledges the potential impacts of AM that may be borne by the wider society and the subjective nature of weighing the merits of AM. Stakeholder engagement can contribute to the consideration of, rather than "paralysis by", uncertainty (Galatowitsch et al., 2009). As Schwartz et al. (2009, p. 474)argue,

The only way forward to confront unprecedented problems such as global anthropogenic climate change is careful risk analysis, including an honest evaluation of uncertainty and potential harm, along with broad public debate beyond the technical expertise of scientists and managers. We must engage in careful study of ethical, legal and biological issues surrounding the idea of managed relocation even if the ultimate conclusion is that it is the wrong approach to managing a difficult problem.

Thirdly, several of the suggested policy measures will be critical to removing implementation barriers and paving the way for action. For example, many prospective AM projects will require inter-governmental or inter-agency coordination to facilitate AM across land-ownership and political borders (Lawler, 2009). This coordination should be a high priority.

Fourthly, if the decision is made to proceed with AM, a flexible management approach will be needed during implementation to respond to contingencies such as failure to establish populations or remedial action to combat emerging negative impacts. A quarter (26%) of articles recommended specific implementation activities, including techniques for species introduction (e.g., focus on establishment of many small populations; conduct paired or multi-species translocations for species with interactions; Sow seed to achieve self-thinning in relation to recipient region environments). Although some were decidedly low-risk proposals (e.g., introducing southern genotypes into areas within ranges to the north; Davis and Zabinski, 1992), these specific actions seemed at odds with the frequent calls for caution and delay, reflecting the diversity of views among authors as well as the fact that some of the articles proposing these actions were published before those voicing major concerns. A flexible, adaptive approach is necessary to acknowledge these concerns and learn from the failures and negative impacts of AM implementation (McLachlan et al., 2007 and Schwartz et al., 2009). Experiences with such contingencies should inform future AM plans, with the understanding that these be halted if negative impacts become apparent across comparable cases. While this trial-and-error approach may not satisfy concerns about the irreversibility of AM impacts, it at least acknowledges the possibility of negative consequences so that these can be managed.

Finally, one point on which there should be room for agreement in the AM debate is that the urgency and scale of the climate change problem calls for a proactive and innovative, rather than reactive, approach (Heller and Zavaleta, 2009). A proactive approach can provide some common ground, however narrow, for biodiversity conservation in the face of climate change. While we distinguished between "proactive" and "traditional" approaches (Table 2), the two can be complementary. A proactive approach can encompass both traditional, risk-averse conservation strategies and unconventional, risk-tolerant ones. Aggressive in situ strategies, including habitat creation at range margins, are needed to combat the massive scale of landscape change that has occurred over the last several centuries. Without habitat creation, riskier strategies such as AM may have difficulty succeeding (and see Krosby et al., 2010 and Loss et al., 2011). On the other hand, habitat and corridor creation alone may be insufficient to preserve species or ecosystems without active strategies to control weedy or opportunistic species and ensure the dispersal of the suite of desired species (Chapin et al., 2007 and Pearson and Dawson, 2005). The complementarity of the two approaches is further illustrated by the fact that some authors proposed strategies falling under both (e.g., Hayward, 2009, Hunter, 2007 and Vitt et al., 2009).

4. Conclusions

The number of published articles on assisted migration has increased rapidly in the last several years. The fact that a majority (30/50) generally support AM as a climate change adaptation strategy worth considering should not be taken as evidence of a growing scholarly consensus. On the contrary, the debate is intensifying. All the articles that we classified as highly skeptical or positively opposed to AM were published after 2007. To help make sense of the debate, we distinguished between arguments about the direct ecological and socio-economic benefits and risks of AM, on one hand, and arguments or counter-arguments addressing such matters as information needs, uncertainties, justification, planning and implementation issues, on the other. Conceptualizing the debate in these terms helps to place the focus on what is ultimately at stake—the relative benefits and risks of AM—and may provide a common basis for both proponents and opponents to navigate the key issues. Recommendations emerging from the literature with potential to advance the debate include strategies for careful evaluation of risks, benefits and trade-offs, along with the inclusion of all stakeholders in decisions about whether to proceed with AM. If and when AM is implemented, we agree that it should be done in an experimental manner, learning from experience and adjusting policies and plans accordingly. Moreover, the lack of original research on the topic leads us to endorse the frequent calls for such research. Finally, a proactive approach may provide some common ground for supporters of both in situ and more risk-tolerant strategies, which we suggest would be complementary under this approach.

We do not suggest that any of this will resolve the debate. The potential of AM to preserve species stands in direct tension with its potential to unleash invasion by the focal species. These are not simply conflicting conservation objectives (Schwartz, 1994). They are the main perceived risks and benefits at the crux of the debate, and must somehow be weighed against each other in the face of scientific uncertainties.

This task is complicated by the moral and ethical judgments inherent in assessing AM's merits, which are essentially incommensurable.

It is possible that, as climate change becomes more apparent in its impacts, AM will follow a path similar to other policies that were initially objectionable but ultimately accepted (Hagerman et al., 2010). It could, however, follow a different trajectory, as in the case of the policy of "liming" surface waters to mitigate acid deposition. Starting in the 1960s and 1970s, Norway and Sweden added lime or other buffering minerals to thousands of lakes to reduce acidity, prevent mobilization of heavy metals, and protect fishery resources while emission controls were being implemented. In Canada and the United States liming was never pursued as a widespread policy, partly because it was seen to deflect attention from the need to reduce pollution emissions at the source (Clair and Hindar, 2005). Arguments about liming persist to this day, ranging from disagreements about its efficacy, to philosophical concerns about its creation of "unnatural" lake systems (Clair and Hindar, 2005 and Norberg et al., 2010).

As with liming 40 years ago, AM is an innovative strategy which may help solve a policy problem, but which is criticized for treating symptoms rather than causes and for challenging established conservation priorities. What some see as the leading solution remains unaccepted by others—after half a century in the case of liming. Compared with "acid rain", the problem of climate change is more widespread, complex, and less easily solved, and some of its impacts are inevitable. Assisted migration presents potentially greater challenges as a solution than liming because it poses greater risks, while the stakes of not acting are higher. It might cause ecosystem-level damage, but may also be necessary to prevent extinction of a large number of species. There is no reason to assume that AM will move from controversy to acceptance over time. At this stage it would be naïve to propose simple solutions to the AM debate. Solutions are likely to be complex, context-dependent and multi-faceted, emerging from further research, analysis, discussion and experience.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2011.04.031.

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