The progress of interdisciplinarity in invasion science

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Abstract: Interdisciplinarity is needed to gain knowledge of the ecology of invasive species and invaded ecosystems, and of the human dimensions of biological invasions. We combine a quantitative literature review with a qualitative historical narrative to document the progress of interdisciplinarity in invasion science since 1950. Our review shows that 92.4% of interdisciplinary publications (out of 9192) focus on ecological questions, 4.4% on social ones, and 3.2% on social–ecological ones. The emergence of invasion science out of ecology might explain why interdisciplinarity has remained mostly within the natural sciences. Nevertheless, invasion science is attracting social–ecological collaborations to understand ecological challenges, and to develop novel approaches to address new ideas, concepts, and invasion-related questions between scholars and stakeholders. We discuss ways to reframe invasion science as a field centred on interlinked social– ecological dynamics to bring science, governance and society together in a common effort to deal with invasions.

Keywords: Biological invasions Interdisciplinarity Non-native species Scientometrics Social–ecological research

INTRODUCTION

Humans influence processes that drive biological invasions by introducing species to new areas, facilitating their establishment and changing ecosystems in ways that enable the spread of these species (Kueffer and Hirsch Hadorn 2008; Richardson et al. 2011; Kueffer 2013; Hui and Richardson 2017). Increasing globalisation has promoted the establishment and expansion of non-native species across the world (Hulme 2009; Humair et al. 2015). Many introduced species are useful in new geographic areas, e.g. to provide resources or improve ecosystem services (Kull et al. 2011; Tassin and Kull 2015; Vaz et al. 2017). However, a small proportion of non-native species becomes invasive (sensu Richardson et al. 2011), i.e. they spread, often becoming abundant, and in many cases have impacts on the environment or society. Some invasions contribute to major social–ecological changes—i.e. shifts in the state of ecosystems and coupled social systems—with positive or negative consequences for human values and welfare, such as those related to culture, health, and economy (Simberloff et al. 2013; Schindler et al. 2015; Kueffer and Kull 2017; Vaz et al. 2017).

The social–ecological challenges arising from biological invasions have led to calls for insights from multiple disciplines (Kueffer and Hirsch Hadorn 2008; Richardson 2011a; Rotherham and Lambert 2011; Kueffer 2013; Matzek et al. 2013). Specifically, interdisciplinarity at the interface of ecological and social sciences is needed for understanding and managing invasions as an inherent social–ecological phenomenon (‘‘the human dimension’’

sensu McNeely 2001). Such interdisciplinarity has been advocated to do the following: (1) understand the multiple ecological and social drivers of invasions (Kueffer 2013); (2) clarify social conflicts, interests, values, perceptions, and attitudes associated with non-native and invasive species (Larson 2005; Este´vez et al. 2014; Humair et al. 2014a; Kueffer and Kull 2017); and (3) improve tools and strategies for management and policy (Kueffer and Hirsch Hadorn 2008; Matzek et al. 2013; Head et al. 2015; Essl et al. 2017).

Invasion science, here understood as ‘‘the study of the causes and consequences of the introduction of organisms to the areas outside their native ranges’’ (Richardson and Ricciardi 2011, p. 1461), intrinsically merges interests from multiple disciplines to focus on, e.g. species transportation, establishment and spread, biological interactions, and invasion costs and benefits to human systems (Richardson 2011a; Essl et al. 2017). The pivotal role of (interdisciplinary) social–ecological approaches in invasion science has already been recognised (Kueffer and Hirsch Hadorn 2008; Richardson 2011a; Estévez et al. 2014; Head et al. 2015; Courchamp et al. 2017), specifically by economists, geographers, historians, philosophers, politicians, and sociologists (e.g. Larson 2005; Carruthers et al. 2011; Hattingh 2011; Kull et al. 2011; Rotherham and Lambert 2011; Head and Atchison 2015). Contributions from these scholars call for the elucidation of feedbacks between ecological and social drivers (Kueffer 2013; Matzek et al. 2013), and the valuation of invasion effects which are co-produced by society, scientific facts, and cultural norms (McNeely 2001; Hattingh 2011; Kull et al. 2011; Estévez et al. 2014; Jeschke et al. 2014; Tassin and Kull 2015; Essl et al. 2017; Kueffer and Kull 2017). Other scholars have also focused on the role of societal beliefs, perceptions, memory, and cultural aspects related to non-native and invasive species that shape human attitudes, and therefore decisions relating to these species management (e.g. Carruthers et al. 2011; Estévez et al. 2014). Consequently, issues such as what constitutes a native or non-native species, whether a species is considered good or bad, and subsequent conservation and management positions (e.g. Rotherham and Lambert 2011) are still debated amongst experts from different disciplinary back- grounds (Larson 2007; Carruthers et al. 2011; Brunel et al. 2013; Humair et al. 2014a).

Given the growing appeal of interdisciplinarity, experts have called for a reframing of invasion science as a problem-oriented and multidisciplinary science, rather than a purely ecological science (Kueffer and Hirsch Hadorn 2008; Kueffer 2013; Estévez et al. 2014; Head et al. 2015; Essl et al. 2017). As in the case of other environmental challenges (Liu et al. 2007; Larson 2011; Tengo et al. 2014; Rissman and Gillon 2016; Bennett et al. 2017), a social– ecological lens can help to reframe invasion science (e.g. Larson 2007; Kueffer 2013; Matzek et al. 2013; Tassin and Kull 2015) by better accounting for social–ecological feedbacks that mediate the dynamics and valuation of bio- logical invasions (Kueffer 2013; Kull et al. 2013; Head et al. 2015). A social–ecological perspective is particularly expected to improve the effectiveness of invasion science for management (e.g. McNeely 2001; Kueffer and Hirsch Hadorn 2008; Matzek et al. 2013; Tassin and Kull 2015; Woodford et al. 2016; Hui and Richardson 2017). Among other things, it is hoped that more robust social–ecological perspectives will help informing options for management at different stages of invasions (Kueffer and Hirsch Hadorn 2008; N’Guyen et al. 2016; Essl et al. 2017). Human perception, culture,

attitudes, ethics, actions, and adaptive learning-based approaches in invasion management can differ depending on the invasion stage, for example introduction versus spread phases (Rotherham and Lambert 2011; Heger et al. 2013; Simberloff et al. 2013; Tassin and Kull 2015; Chaffin et al. 2016).

Despite the recognition of a need for more cross-cutting collaborations, an overview of the extent of interdisciplinarity in invasion science is lacking. The first requirement to achieve such an overview is a thorough review of the state of interdisciplinarity in the field, based on published literature. Previous studies have reviewed the eco- logical literature (e.g. Davis et al. 2001; Davis 2011), as well as the social and interdisciplinary literature in invasion science (McNeely 2001; Kueffer and Hirsch Hadorn 2008; Richardson 2011a; Kueffer 2013; Estévez et al. 2014; Kueffer and Kull 2017). However, a broader quantitative assessment is still missing.

This paper examines the extent to which interdisciplinarity has featured in research addressing biological invasions over the last half-century. We begin with a quantitative analysis of interdisciplinary research in invasion literature, focussing on the integration of ecological and social sciences. Concurrently, we present a qualitative narrative of documented milestones of the progress of invasion science. We analyse how social–ecological approaches in invasion science have been conceptualising: (1) how the causal influences between the social system and the invasion process and vice versa are described; (2) how impacts are characterised (anthropocentric vs. ecocentric); and (3) whether research is focused on understanding causal relationships, valuation, or management support. We further investigate which stages of the invasion process and management strategies have been addressed from a social–eco- logical perspective. Finally, based on our quantitative review and temporal narrative of invasion science, we suggest avenues for fostering progress and adjusting the course of invasion research by reframing research questions through an explicit interdisciplinary and social–ecological approach.

A QUANTITATIVE REVIEW OF INTERDISCIPLINARY IN INVASION LITERATURE

Literature search

Following Richardson et al. (2011), we consider non-native species as those that were introduced (accidentally or intentionally) by humans to new geographic areas, and invasive species as non-native species that spread, some- times becoming abundant and leading to major impacts on the environment or society. A literature search on non- native/invasive species was conducted using the ‘‘ISI Web of Science’’ core collection (ISI WOS; http:// webofknowledge.com/). Since we were interested in all relevant research related to biological invasions, we com- piled a list of terms related to the main keyword ‘‘biological invasions’’ (Table S1). The time span of our search was 1950–2014, corresponding to the period when the systematic study of invasive species began, after the publication of Elton’s (1958) book (Richardson and Pyšek 2008; Hui and Richardson 2017). Searches were conducted between February and September 2015. The records retrieved by the search (total number, n = 23 640) were subjected to inclusion/exclusion criteria to eliminate irrelevant information (e.g. topics such as invaders from outer space; see Table S2). These criteria were applied individually by checking the title and keywords of each record.

Records classification and analytical framework

A four-step analytical framework was then applied to the final dataset (n = 23 390), the aim being to classify the records according to their disciplinary and social–ecological scope (Fig. 1).

In the first step, we classified each record based on the number of different ‘‘Research Areas’’ (hereafter RAs) according to ISI WOS, as either interdisciplinary (attributed to at least two RAs) or monodisciplinary (Rafols et al. 2010; Stock and Burton 2011). A total of 110 RAs were retrieved. The full list of RAs is shown in Table S3. The RAs considered here correspond to the scientific disciplines attributed to each individual record by ISI WOS. These categories are widely applied in scientometrics for the evaluation of interdisciplinarity research (Porter and Rafols 2009; Rafols et al. 2010; Wagner et al. 2011). We are aware that pre-existing categorisations have limitations for measuring interdisciplinarity (e.g. due to a lack of consensus regarding the accuracy of the classification, or because one RA is nested within another RA). However, the system is well- established, improving our ability to compare classification across large areas of science and with thousands of studies (Rafols et al. 2010). We are also aware that when disciplines join forces to solve a common problem, other terms are used (including cross-, multi-, inter-, trans-, supra-disciplinarity) which also have slightly different meanings. Since it was beyond the scope of our study to explore differences among disciplinarity concepts, we adopted ‘‘interdisciplinarity’’ in the bibliometric portion of this study as a lowest common denominator umbrella term for designating a research publication that draws on, or involves, more than one discipline (see e.g. Stock and Burton 2011).

In the second step, we grouped RAs into nine broader research fields. The classification into research fields was conducted by our interdisciplinary team, supported by the description of RAs provided by ISI WOS and following the works of Leydesdorff and Rafols (2009), Porter and Rafols (2009), Rafols et al. (2010), and Wagner et al. (2011). We are confident that this classification represents the most intuitive combinations of RAs in the biological invasion literature, while it facilitates the disclosure of the set of RAs retrieved by our search. (This is the reason why the fields of ecology, environment, biology, and (other) natural sciences were considered as separated research fields, whereas the broad research fields of social sciences and humanities were not subdivided; see Table S3 for details on research fields and categorisation.)

In the third step, we grouped the RAs into two broad categories: ecological/environmental, and social/human. For the ecological/environmental category, we combined Ecology & Evolution with Environmental Sciences. For the social/human category, we combined Social Sciences and Humanities. The remaining scientific fields were not considered, since our focus was on ecological, social, or social–ecological records. We then classified each record as purely ecological (i.e. records that only comprise RAs categorised as ecological/environmental), purely social (i.e. records that only comprise RAs categorised as social/ human), or social–ecological (i.e. records which comprise RAs from both ecological/environmental and social/human categories). In the final step, we analysed all records that were classified as social–ecological (n = 293 out of 23 390). Each record was reviewed to confirm its social–ecological scope by screening the title, keywords, and abstract. After removing

unsuitable articles, the full text of the final set of records (n = 283) was analysed to answer the set of focal questions related to our objectives (Table 1).

Interdisciplinarity analysis

The level of interdisciplinarity in our dataset was first illustrated through network plots (Butts et al. 2015), and then measured based on the declining rate of zeta diversity (Hui and McGeoch 2014).

First, interdisciplinarity was visualised using network plots for each individual year (Rafols et al. 2010; Wagner et al. 2011). For each network produced, a given RA is represented by a node (or circle), and the relationship between a given combination of two RAs is represented by a connecting line. The thickness of the line in the network represents the number of records which are classified under both RAs (Rafols et al. 2010). Network plots were constructed using the network package (Butts et al. 2015) implemented in R (R Core Team 2014).

Next, the level of interdisciplinarity was quantified using metrics of the declining rate of zeta diversity, which expresses the number of RAs shared by multiple records (Hui and McGeoch 2014). Specifically, zeta diversity of order 1 depicts the average number of RAs per paper; zeta diversity of order 2 depicts the average number of RAs shared by two papers; zeta diversity of order n depicts the average number of RAs shared by n papers. Because RAs shared by n papers will also be shared by n - 1 papers, zeta diversity declines monotonically with its order, either exponentially or following a power law depending on whether the RAs are randomly assigned to each paper or inherently different among papers. Since all our cases followed a power-law zeta diversity decline, we chose to use the absolute exponent of the power law as a metric of interdisciplinarity, calculated based on non-linear regression for zeta diversity of order 1–5 for a focal year. A low absolute exponent represents a higher number of RAs shared by a large number of papers (and thus higher interdisciplinarity), and a lower number of RAs exclusive to selected papers especially those with fewer RAs. The

rate of zeta diversity was calculated for the whole dataset (Step 1) and for each category of records classified as social, ecological, or social–ecological at an annual pace (Step 3). In Step 3, due to the small number of records found before 1990, the rate of zeta diversity was computed by pooling the entire research during the period 1950–1990, and then at an annual pace until 2014. Computations were implemented in the package zetadiv (Latombe et al. 2015) available in R software (R Core Team 2014). Results are presented as line or column plots.

AN HISTORICAL OVERVIEW OF INVASION RESEARCH

The history of invasion science has been discussed previously (Davis et al. 2001; Davis 2006; Kueffer and Hirsch Hadorn 2008; Richardson and Pyšek 2008; Chew and Hamilton 2011; Hobbs and Richardson 2011; Simberloff 2011; Hui and Richardson 2017). We provide quantitative data on this historical overview (Fig. 2), suggesting that the invasion literature showed an exponential increase since the 1980s, with the steepest slope after 1990 (Fig. 2a).

We recognise that there has been occasional interest in non-native species and their effects on ecosystems since at least the 1700s (e.g. Curtis 1783; Watson 1847). However, the book by Elton (1958) on The Ecology of Invasions by Animals and Plants is generally considered as the beginning of

the systematic scientific study of biological invasions (Richardson and Pyšek 2008; Richardson 2011b). Elton's book brought together subjects, including ecology, evolution, biogeography, biological conservation, and social sciences, thereby envisioning an interdisciplinary scope for invasion science (Richardson and Pyšek 2007). Despite this milestone, few publications on invasions

appeared before the 1970s (see also Davis 2006; Lockwood et al. 2007; Richardson and Pyšek 2008; Estévez et al. 2014; Hui and Richardson 2017). This apparent lack of interest contrasts with the considerable advances made in ecology in general during this period, including the development of ideas and work in community ecology that were inspired by Elton's book. An explanation for this time lag may be that invasions were not yet widely considered a major global threat and therefore did not receive much attention (Richardson and Pyšek 2007, 2008; Richardson 2011b; Hui and Richardson 2017). Conservation and environmental problems were increasingly recognised in the 1970s and 1980s as topics within ecology. Population biologists applied their new concepts to the spread of non- native diseases and pests in ''natural ecosystems'' (e.g. Krebs 1972), and more generally in biodiversity conservation (Stork and Astrin 2014). The field of restoration ecology (Zhang et al. 2010), and research relating to global environmental change (Li et al. 2011) has also grown rapidly since 1980.

The rapid, tenfold acceleration of publications on invasions in the 1990s (Fig. 2a) can, however, not be explained by this general trend alone. Rather, this increase might reflect the growing interest of academics in biological invasions (e.g. the Third International Conference on Mediterranean Ecosystems in Stellenbosch, South Africa, in 1980; Richardson 2011b) and the impact of a major international SCOPE research program on biological invasions in the late 1980s (Drake et al. 1989; see also Richardson and Pyšek 2008; Richardson 2011b; Simberloff 2011; Hui and Richardson 2017). As biological invasions constituted a new topic for research assessment and publication (namely on islands; Vitousek 1988; Lovei 1997), rapid institutionalisation took place both in science (e.g. through the launching of specialised journals like Diversity and Distributions and Biological Invasions, in 1998 and 1999, respectively), policy (e.g. through legislation like the Convention on Biological Diversity, the Bern Convention, US executive orders, EU regulations), and in publicly funded programs (e.g. DAISIE, GISP; Davis 2006; Kueffer and Hirsch Hadorn 2008; Brunel et al. 2013; Hui and Richardson 2017). Thus, feedbacks between funding of scientific consortia and scientific and public interest might have maintained the further growth of the field with increasing publication and citation rates. The increased prominence of issues relating to invasions also ensured the integration of invasion science in wider interdisciplinarity perspectives (e.g. through the Millennium Ecosystem Assessment and the Intergovernmental Science-Policy

Platform on Biodiversity and Ecosystem Services; Matzek et al. 2013), including recognition of human-mediated introductions (Lovei 1997). Additionally, invasions remained a topic of interest for both basic (Sax et al. 2007) and applied research, for instance in restoration ecology (Hobbs and Richardson 2011).

The growth of invasion science can thus be seen as a paradigmatic case of the adoption of a new issue in environmental research. Within 60 years, an issue that was not widely recognised as such has become one

of the most prominent topics in environmental research and conservation policies. Decisive moments that explain the trajectory include the following: (1) the novel and broad conceptualisation by Charles Elton; (2) growing scientific and societal appreciation of conservation issues starting in the 1980s; (3) targeted funding of large international research consortia, especially the SCOPE program in the 1980s, which led to a rapid growth and internationalisation of the issue; (4) positive feedback between growing scientific and policy interests focusing on the negative values attributed to invasive species, leading to increasing institutional support for invasions; and (5) the solid grounding of the research in ecology that ensured an ongoing and growing interest of basic research in the field.

THE PROGRESS OF INTERDISCIPLINARITY IN INVASION RESEARCH

Despite the interdisciplinary scope of the field, and an oft-stated belief that interdisciplinarity is essential for addressing global, social–ecological challenges, especially in invasion science (Lockwood et al. 2007; Kueffer and Hirsch Hadorn 2008; Kueffer 2013; Estévez et al. 2014), our results suggest that the rise of interdisciplinarity only weakly followed the growth of the field (Fig. 2b). In fact, our quantitative review shows that more than half of cur- rent invasion literature (ca. 51.0% out of 23 390 publications) comprises monodisciplinary records. The remaining 49.0% of records that are classified as interdisciplinary include two (78.0%), three (19.0%), four (2.0%), or more (1.0%) RAs. Monodisciplinary records cover 60.0% of journals retrieved by our search (out of 1737 journals). Interdisciplinary records with two RAs cover 31.0% of journals; records with three or more RAs concern 8.0 and 1.0% of journals, respectively.

Our quantitative review shows that between 1970 and 1990s, interdisciplinary collaborations were largely con- fined to interactions between disciplines within the natural sciences, and more specifically within the fields of ecology and environmental sciences (Fig. 3; see also Supplementary video and Fig. S1). Such work typically focused on issues pertaining to forestry, agricultural pests, fish and game management, livestock diseases, and threats to wildlife (Davis 2006; Lockwood et al. 2007). An example found in our literature search is the study by Mann (1979) which reviewed the deliberate introduction of non-native shellfish, mentioning the introduced species and the consequences of those introductions for mariculture.

Starting in the late 1980s, and accelerating during the 1990s, interdisciplinarity in invasion research expanded to include ecosystem restoration and management, in so doing incorporating limited social insights. The beginnings are exemplified by contributions from the SCOPE program and the first conference of the Society for Ecological Restoration in 1989 (Hobbs and Richardson 2011). A typical example from our literature search discusses the spread, management, and governance of non-native species (Groves and Burdon 1986). However, the number of disciplines involved in this apparent growth phase of interdisciplinarity during the 1980s and 1990s remained relatively stable. The interdisciplinary publications of that period tended to include only disciplines closely related to ecology and environmental sciences, namely biology, geo- sciences, and other natural sciences (Fig. 3; Supplementary video and Fig. S1). Engineering and technology, as well as social sciences and humanities were represented sporadically in the 1990s. This

trend was followed by a consistent presence and steady diversification of research areas since the 2000s (Fig. 3; Supplementary video and Fig. S1), during which the time invasion science also seems to have converged towards a broader, social–ecological endeavour.

THE ADVENT OF SOCIAL AND SOCIAL– ECOLOGICAL PERSPECTIVES

Our review shows that 92.4% of ecological or social interdisciplinary publications (out of 9192) correspond to records classified as purely ecological, 4.4% correspond to purely social records, and 3.2% (293 records) are classified as social–ecological (Fig. 1). The 1990s and 2000s were characterised by the advent of purely social (1990s) and then coupled social–ecological research (2000s; Fig. 4).

The slow uptake of the human dimensions in invasion research until the 2000s might indicate that until then there was a belief that problems associated with invasive species could be solved through technological solutions, building mostly on knowledge about the ecology of invasive species (McNeely 2001; Simberloff 2001). Our results show that there was a growing interest in complex mathematical models for elucidating aspects of invasion dynamics during this period (e.g. species distribution models; Guisan and Zimmermann 2000; Thuiller et al. 2005; Fig.3; Supplementary video and Fig. S1). Yet, despite available technological solutions, management interventions were often considered as unsuccessful, possibly due to the lack of an explicit recognition of the role of the human dimension (e.g. McNeely 2001; Simberloff 2001; Chaffin et al. 2016). A second reason might be that biodiversity conservation was, until the emergence of the ecosystem services concept in the 2000s (Millennium Ecosystem Assessment 2005), virtually independent of human valuation and social insight. In contrast, research on environmental hazards and natural disasters, which were always considered as immediate threats to human life and welfare, gave explicit attention to social dimensions earlier (e.g. Dahlberg et al. 2016). A third reason could be that social– oriented publications were considered for indexing later than those from other disciplines; this may have resulted in a delayed coverage by ISI (Leydesdorff and Rafols 2009; Rafols et al. 2010).

The human dimension of invasions gained wider attention after 2000 (Figs. 4, 5). One reason was the Global Invasive Species Programme (GISP) fostered close interactions between ecologists, economists, social scientists, and especially policy makers (Kueffer and Hirsch Hadorn 2008; Davis 2011; Hui and Richardson 2017). Another reason might be the emergence of the ecosystem services concept, which provided new research directions relating to invasions - as expressed in our retrieved publications such as Zavaleta (2000), Van Wilgen et al. (2008), and Simberloff et al. (2013).

Social science and humanities perspectives are apparent in publications on the history of the field (e.g. Davis et al. 2001; Davis 2006) and on the metaphors it mobilises (e.g. Larson 2005, 2007), and in reports such as The Great Reshuffling (McNeely 2001), a special journal issue on Australian acacias (Richardson et al. 2011), or the book Fifty years of invasion ecology (Richardson 2011b). The maturation of such perspectives is also reflected in the emergence of stand-alone collections of social science or humanities publications on the topic (e.g. Rotherham and Lambert 2011; Frawley and

McCalman 2014). The recent interest of social scientists in invasions appears to be largely focused on three subjects: (1) the role of the human influence on the invasion process (McNeely 2001; Rotherham and Lambert 2011; Humair et al. 2015) with 44.0% (out of 283) of the records from our dataset

conceptualising human activities as drivers of the invasion process (S -> I; Fig. 5a); (2) direct or indirect impacts of species establishment on humans (Simberloff et al. 2013; Schindler et al. 2015), with 75.0% (out of 283) of the records (Anthropocentric; Fig.5b); and (3) practical aspects of management (Matzek et al. 2013; Head and Atchison 2015; Fig. 6 and Table S4).

Nonetheless, contributions from the social sciences and humanities still comprise a minor proportion of the invasion literature, making up less than 5.0% of the canon (Figs. 4, 5; see also Fig. S1). This is likely because the focal topic (biological invasions) was framed, defined, and elaborated foremost as an ecological phenomenon, and most of the key questions that feature prominently in research agendas still draw most interest from ecologists. The volume of basic and applied ecological, environmental, and management publications on invasions (with 75.1% of the 11465 interdisciplinary publications on invasions, corresponding to 8 496 records; Fig.1) is unsurprisingly larger than that of social science or the humanities on these themes; work in the social realm has largely emerged in reaction to ecological ideas and management actions. Most social research relating to invasions has critiqued management activities, or has addressed the philosophical, ethical, or conceptual underpinnings of the field (Carruthers et al. 2011; Estévez et al. 2014; Frawley and McCalman 2014).

However, our results must be interpreted with caution, as differences in publication culture between ecological/ environmental sciences and social science and humanities may have limited the representation of the latter in the literature covered by ISI. Social sciences and the humanities show different citation behaviour, publish more in books and journals that may not be catalogued as comprehensively by ISI, thus potentially resulting in an under- representation of contributions in our treatment (Leydesdorff and Rafols 2009; Rafols et al. 2010).

THE CURRENT DEFICIT OF SOCIAL–ECOLOGICAL APPROACHES IN INVASION RESEARCH

Biological invasions are increasingly recognised as a social–ecological phenomenon (McNeely 2001; Kueffer and Hirsch Hadorn 2008; Kueffer 2013; Estévez et al. 2014; Head et al. 2015; Hui and Richardson 2017). However, our literature survey shows that neither social–ecological research, nor explicit interdisciplinarity and integration of feedbacks between the social and the ecological systems are easily found in invasion studies (Figs. 3, 4, 5).

The 283 social–ecological studies found are relatively equally distributed across the different invasion stages, management strategies, and knowledge dimensions (Fig. 6). For all invasion stages and management strategies, studies analyse the drivers of invasions (systems knowledge; corresponding to 32.0% of social–ecological records), their valuation (target knowledge; 28.0%) and solutions to target them (transformation knowledge; 40.0%) from a social–ecological perspective.

Specifically, the set of social–ecological studies on systems knowledge, which we

found are focused on how humans shape the context for invasion, and thereby facilitate or hinder aspects of the invasion process. Specific papers from our search explore, for instance, how diverse social factors (such as government programs, peoples' beliefs, and socioeconomic status) relate with the conversion of non-invaded to invaded habitats (Brenner 2010), and how the social system affects invasion processes at different levels, through e.g. ineffective control of immigration borders or illegal trade (Rodríguez-Labajos et al. 2009). Likewise, social–ecological studies focused on valuation (target knowledge), examine how people perceive invasive species, highlighting the need to account for cultural influences and normative issues (Rotherham and Lambert 2011; Tassin and Kull 2015; Essl et al. 2017; Kueffer and Kull 2017). Examples from our search include xenophobic standpoints regarding cohabitation with non- native species (Larson 2005; Estévez et al. 2014), or aspects of valuation implicit in metaphors used in scientific writing (Larson 2005, 2013; Kueffer and Larson 2014). These examples comprise research on people's thoughts, emotions, and representations, as well as cultural and knowledge differences regarding meanings and intentions towards invasive species (Larson 2005; Hall 2009; Buijs et al. 2012; Heger et al. 2013). Finally, social–ecological studies focused on more effective management solutions (transformation knowledge) include integrative solutions regarding conflicts of interest, work capacity, efficiency, and legitimacy of individuals and groups that manage (or use) invader species or invaded areas, as well as their articulation with social institutions, frameworks, and rules (Kull et al. 2011; Matzek et al. 2013; Simberloff et al. 2013; Estévez et al. 2014; Essl et al. 2017). Examples from our search include the evaluation of enforcement and inspection regimes in firms for reducing invasion risk, both in terms of resource allocation and effectiveness of policies (Ameden et al. 2009); participatory processes with stake- holders such as the horticulture industry (Humair et al. 2014b); and approaches focused on how public advertising can increase society outreach and influence behaviour towards managing invasions (Shaw et al. 2014).

BRINGING SOCIAL–ECOLOGICAL APPROACHES TO THE CENTRE OF INVASION RESEARCH

Despite progress, achieving interdisciplinarity seems to still constitute a challenge to invasion science. To reduce the ecological-environmental focus of invasion science and pave the way for higher cross-fertilisation with the social sciences and humanities, we suggest that framing problems, methods, and applications in invasion research needs to be rethought (also following Larson 2007; Kueffer and Hirsch Hadorn 2008; Hattingh 2011). The examples dis- cussed above provide a range of entry points for initiating the reframing research questions in invasion science as a social–ecological challenge with the aim of overcoming the rooting of the field in a purely ecological perspective. Further entry points are necessary to help unlock the potential for more interdisciplinary, social–ecological thinking (also Liu et al. 2007; Hui and Richardson 2017). The starting point for research might then not simply be ''the introduction/invasion of species X in ecosystem Y'', but instead the ''interlinked social–ecological changes in region Z''. This would still permit focused ecological research on X and Y, but would also pave the way for broader perspectives and invite interdisciplinary collabo- ration (and publication) from the perspective of, and

with collaborators from, the social sciences and humanities (Larson 2007, 2011). This could also overcome the monodisciplinary nature of invasion science and allow a more genuine integration of disparate disciplines, each of which would bring their own key issues and research cultures, and identify joint research questions and linking methods (after Kueffer and Hirsch Hadorn 2008; Rissman and Gillon 2016). It would be beneficial, for instance, to promote debates that target the social construction of invasive species based on scientific facts or cultural norms (Hattingh 2011; Larson 2011; Este´vez et al. 2014; Tassin and Kull 2015; Kueffer and Kull 2017), and to welcome stakeholders besides academics. Thus, practitioners, scholars from ecology, and social scientists could be called upon not only to address pre-defined topics arising from ecological studies or resource management challenges (and vice versa; Davis 2011; Tengo et al. 2014; N'Guyen et al. 2016), but also to shape new ideas, concepts, and research questions, and to apply new approaches and methodologies for addressing these questions and to participate in communicating results to multiple stakeholders (Kueffer and Hirsch Hadorn 2008; Hattingh 2011; Richardson et al. 2011; Heger et al. 2013; Courchamp et al. 2017).

Repackaging invasion science as a field explicitly oriented towards a variety of questions centred on interlinked social–ecological dynamics would open more opportunities for merging insights from science, policy management and society to understand, deliberate, mitigate, manage, and adapt to biological invasions (Courchamp et al. 2017). Such a reframing could build on recent work on invasion management (Head and Atchison 2015; N'Guyen et al. 2016; Woodford et al. 2016), on the social, political, and economic context (Carruthers et al. 2011; Kull et al. 2011), and on the communication with the broader public (Kueffer and Hirsch Hadorn 2008; Heger et al. 2013; Estévez et al. 2014; Kueffer and Larson 2014; Tassin and Kull 2015; Courchamp et al. 2017). Lastly, invasion science could benefit from the recent developments in social–ecological systems theory or resilience thinking (Liu et al. 2007; Cote and Nightingale 2012; Frawley and McCalman 2014). These promising approaches include a human perspective on invasions, which goes beyond the unsatisfactory ''threat to native species'' or ''good versus bad'' dichotomy (Larson 2007), and thus pave the way for ''governing invasive species in a more integrated and cost-efficient manner given a renewed focus on under- standing and managing ecosystem dynamics as opposed to single species'' (Chaffin et al. 2016, p. 405).

The integration of real human-environment interactions could provide important opportunities for deliberating and forging solutions based on multiple (actor) interests and uncertainties, not only when dealing with invasions (Kueffer and Hirsch Hadorn 2008; Kull et al. 2011; Matzek et al. 2013; Head et al. 2015), but also with other social–ecological phenomena (see e.g. Tengo et al. 2014; Bennett et al. 2017). Framing invasions from a more balanced social–ecological perspective would help to, among other things, clarify distinct viewpoints relating to perceptions of risks and opportunities, and would help in decision-making by applying collaborative and participatory approaches that could not be achieved through traditional approaches (Kueffer and Hirsch Hadorn 2008; Heger et al. 2013; Kueffer 2013; Estévez et al. 2014; Tassin and Kull 2015; Chaffin et al. 2016; Courchamp et al. 2017).

CONCLUSIONS

We documented the growth of invasion science that has been rooted in ecology and has targeted an environmental problem. We provided explicit quantitative data on the invasion literature since 1950. Although interdisciplinarity has become more prominent as the field has grown, collaborations between disciplines remain largely confined within subdisciplines of ecology and the environmental sciences. The social sciences and humanities have taken an increasing interest in invasions in the last decade, but collaborations between social scientists and ecologists, and truly integrative social–ecological studies remain difficult to capture in quantitative literature searches. This is despite many calls for such studies given the social–ecological nature of invasions, their valuation, and management (following Larson 2007; Kueffer and Hirsch Hadorn 2008; Kueffer 2013; Head et al. 2015; Tassin and Kull 2015; Chaffin et al. 2016, among others). The distinct culture of social sciences and humanities concerning publication and citation approaches could have influenced the limited illustration of social and social–ecological records in our search. Nevertheless, the few social–ecological studies that we found indicate the high potential for diverse social– ecological research to address the increasingly complex dimensions of invasion science and management.

Invasion science has been punctuated by several key events over its short history. We suggest that the time is ripe for invasion science to adjust its course to the following: (1) form research teams comprising a balanced pool of social scientists (including scholars from the humanities) and ecologists (and other natural scientists) with common strategies for science disclosure; (2) establish long-term and reciprocal relationships with multiple stakeholders addressing conceptual questions, research problems, and collaborative management approaches (also N'Guyen et al. 2016); (3) encourage workshops and other forms of interaction to design novel and integrative conceptual frameworks that explicitly challenge and extend existing frameworks, methodologies, theories, and problem-framings in invasion science (also Heger et al. 2013); and (4) create arenas for social–ecological systems thinking that move beyond the classical dichotomy of invasions as beneficial (ecosystem service providers) or harmful (drivers of ecosystem disservices) to society (also Larson 2007; Vaz et al. 2017).

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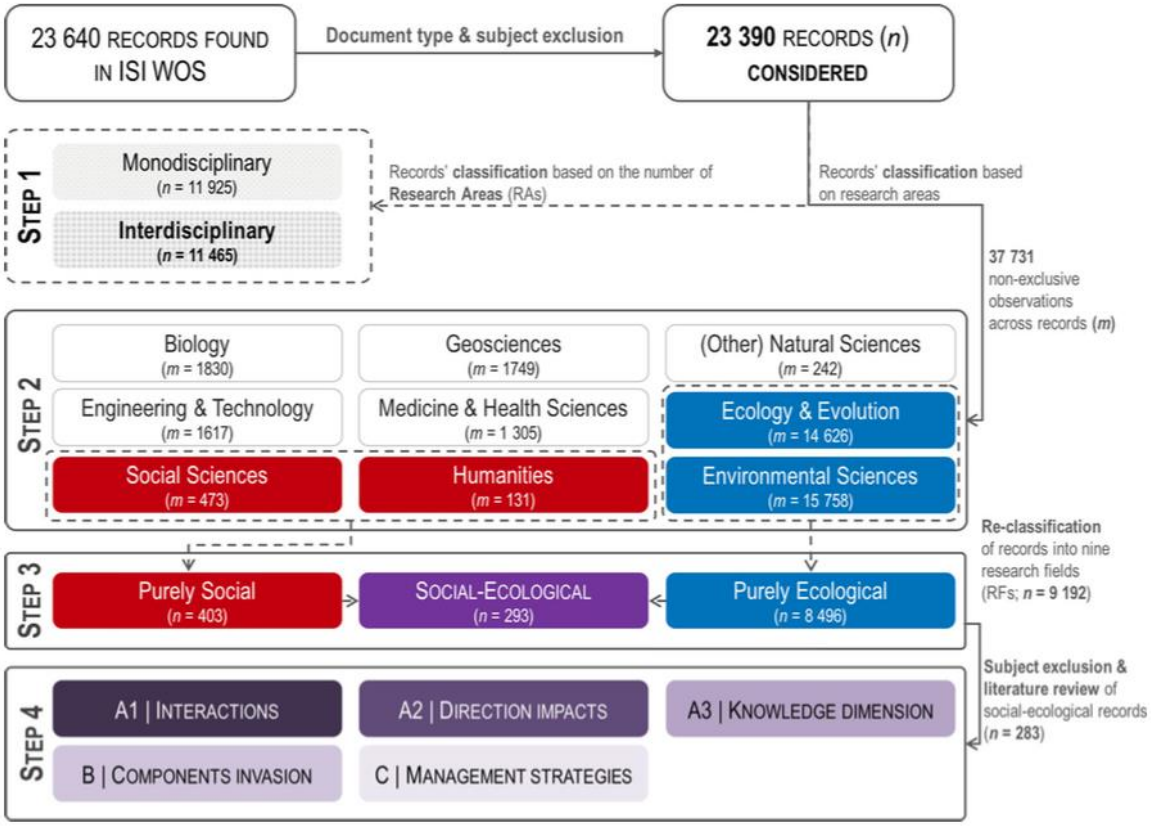

Fig. 1 Analytical framework adopted to determine the occurrence of interdisciplinary and social–ecological research in the literature of biological invasions. Search engine: ISI Web of Science (WOS), time span of the search: 1950–2014. The framework included four steps: in Step 1, we classified each of the 23 390 records as either inter- or monodisciplinary based on the number of research areas (RAs) assigned to each record by WOS; in Step 2, we classified each RA and its respective records into one of nine broader research fields (RFs); in Step 3, we aggregated the categories determined in Step 2 and classified each record as either social, ecological, or social–ecological; in Step 4, we analysed all records that were classified as social–ecological in more detail considering several focal questions (see Table 1 for more information).

Table 1 Focal questions and categories considered in Step 4 of the framework, with a detailed description and references.

Table 1 Focal questions and categories considered in Step 4 of the framework, with a detailed description and references

Codes	Description
Step 4A Social–ecological approaches	
A1 What is the main direction of influence between the social system (S) and the invasion (I) process? (adapted from Binder et al. 2013)	
Social → Invasion (S → I)	The social system drives the invasion process
Invasion → Social (I → S)	The invasion process influences the social system
Invasion ↔ Social (S ↔ I)	There is reciprocity between the two systems
A2 What is the main direction of impacts provoked by the invasion process? (adapted from Binder et al. 2013)	
Anthropocentric	The invasion process provokes impacts (partially/totally) on the social system
Ecocentric	The invasion process provokes impacts exclusively on the ecosystem
A3 Which knowledge dimension does the study produce? (Kueffer and Hirsch Hadorn 2008)	
Systems knowledge ('causes')	Oriented towards analysing and improving the causal understanding of the invasion process
Target knowledge ('valuation')	Oriented towards clarifying conflicts of interests and values, including peoples' perceptions, valuations and conceptualisations
Transformation knowledge ('solutions')	Oriented towards improving or avoiding a particular situation related to the invasion process
Step 4B Invasion process	
B. Which stages of the invasion process are studied? (adapted from Van Wilgen et al. 2014)	
Introduction	Focuses on the pathways of species introduction from one geographical region to another
Establishment	Focuses on the determinants of success of species establishment
Expansion	Focuses on the patterns and mechanisms of species expansion
Dominance	Focuses on patterns and processes related to invaders that have become dominant in an invaded area, including impacts and management
Stage independent	Studies that do not specify the stage of the invasion process, mostly because they address the invasion process as a whole
Step 4C Management type	
C. Which strategies of invasion management are considered by the study? (Van Wilgen et al. 2014)	
Prevention	Focuses on preventing the introduction of new invasive species (including risk assessments of source areas, spread pathways, and species characteristics)
Monitoring	Focuses on mapping, assessing, and monitoring the distribution and impacts of invasive species
Mitigation	Focuses on reducing the (likelihood) of impacts of an invasive species, including containment of further spread and eradication
Adaptation	Focuses on dealing with, and tolerating impacts (including tolerating species or using them, e.g. for timber, medicinal, or ornamental purposes)
No management	There is no focus on the management of invasive species
Unspecified	The study does not specify the management type

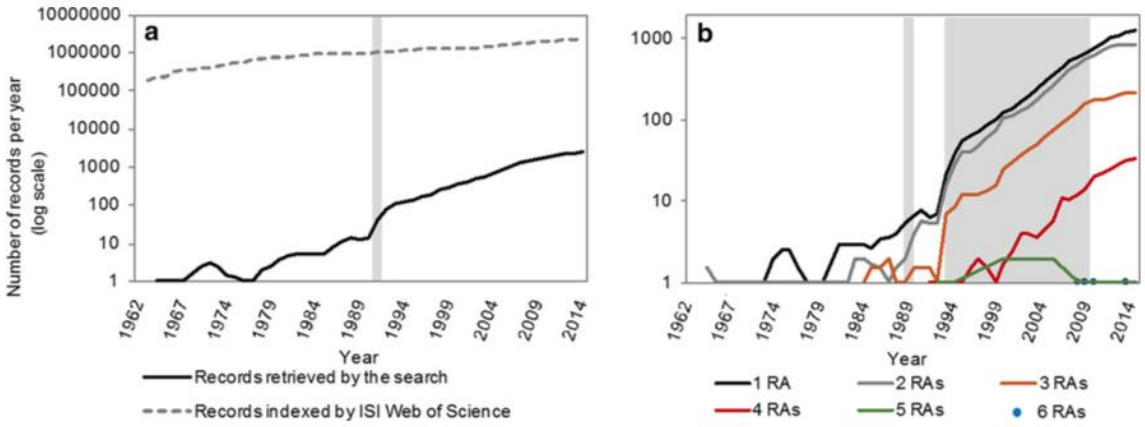

Fig. 2 The number of records retrieved by the search for invasion literature in ISI Web of Science (WOS) from 1950 to 2014 (smoothing curves showing averages for 3-year time periods), with the total number of records covered in WOS shown for comparison (a), and the number of different research areas (RAs) attributed to each individual record (b). Time periods discussed in detail along the text are highlighted with a light grey colour. Values in the y-axis are expressed in a logarithmic scale.

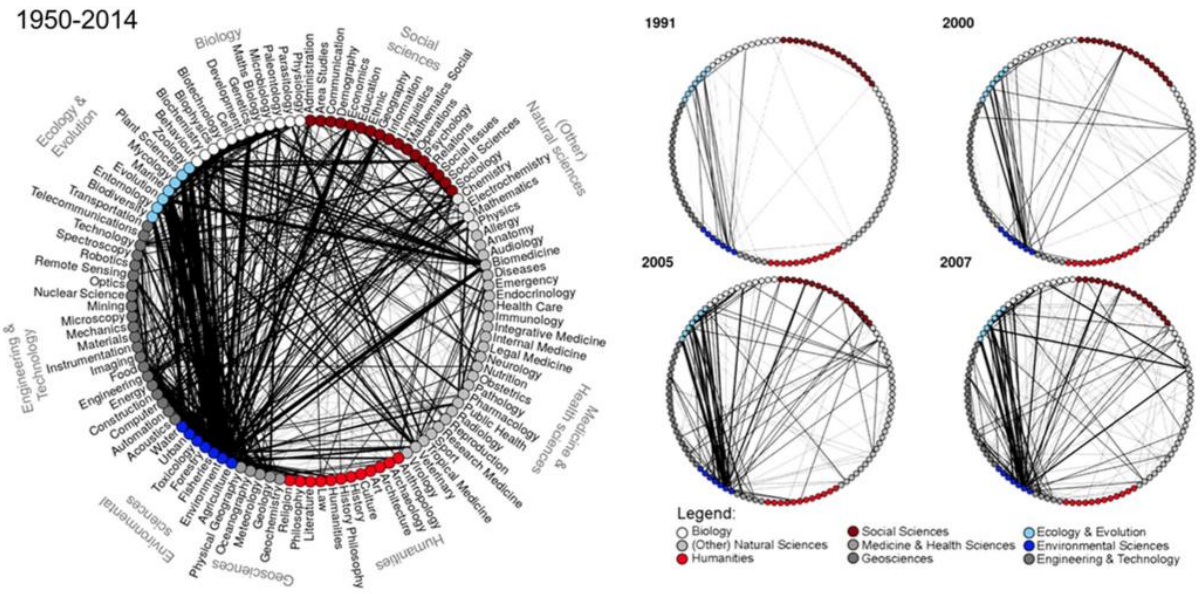

Fig. 3 Network plots showing interdisciplinarity in invasion research for the period 1950–2014, and for the years 1991, 2000, 2005, and 2007, representative for the main transitions between the 1990s and 2000s (i.e. an increase in complexity of the combination of research areas, RAs, during the 1990s, and the emergence of Social Sciences and Humanities during the 2000s). Each circle in the network represents a RA. The labels of each RA on the left network correspond to the circles of the networks on the right. The thickness of the lines in the networks is proportional to the number of records that involves two RAs that are linked by the line. The full list of RAs is shown in Table S3. The set of network plots for all years is presented in Supplementary video.

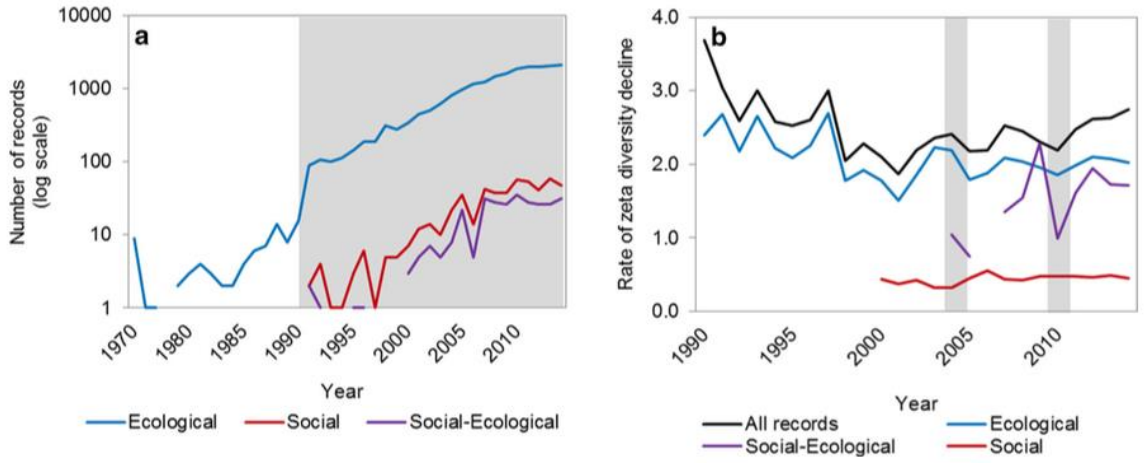

Fig. 4 The number of records attributed to ecological, social, and social-ecological RAs in a logarithmic scale (a), and the rates of zeta diversity decline calculated considering the whole set of records, and only ecological, social, or social–ecological records (b). Low rates of zeta diversity decline indicate high interdisciplinarity, expressing a higher number of RAs shared by many records, and a fewer number of RAs exclusive to selected records, especially those with fewer RAs. Due to the low number of records and RAs observed during 1950–1990, zeta diversity decline was computed for 1950–1990 as whole, and then for each subsequent year separately. Time periods discussed in detail in the text are shown in light grey.

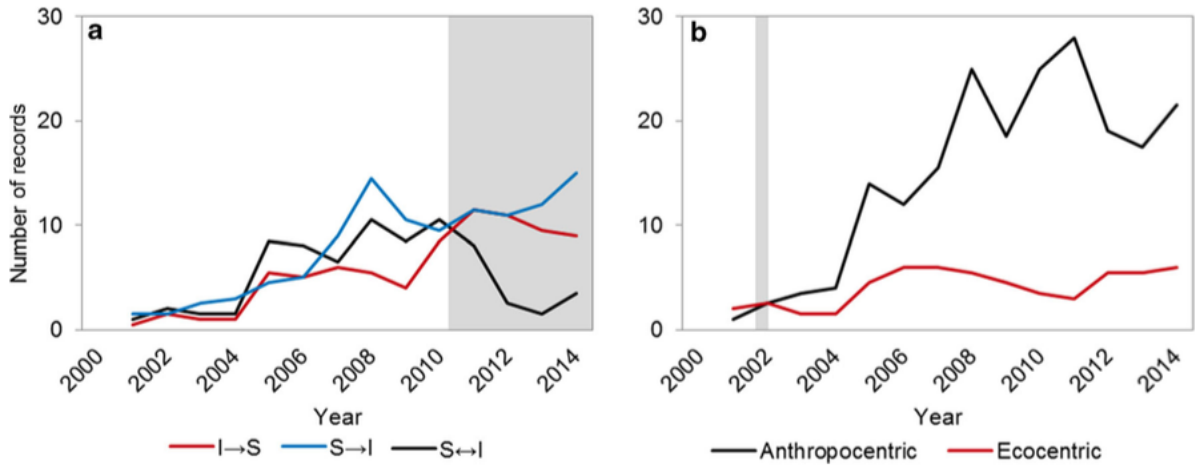

Fig. 5 The number of social–ecological records for each year (smoothing curves showing averages for 2-year periods), attributed to a specific category regarding: the direction of influence between the social system and the invasion process (a), and the main direction of impacts provoked by the invasion process (b; see Table 1 for further explanations). Time periods discussed in detail along the text are shown in light grey.

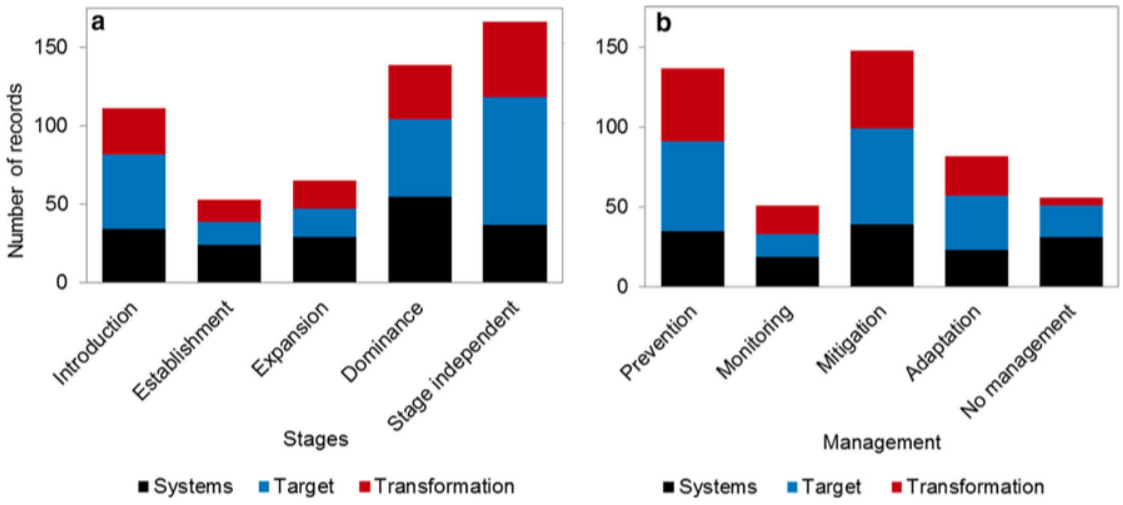

Fig. 6 The number of social–ecological records for the time-period of 2000–2014, attributed to a specific stage of the invasion process (a), and type of management strategy addressed (b; see Table 1 for further explanations). The figure also shows the distribution of knowledge dimensions (systems, target, and transformation knowledge) across the invasion stages and management strategies.