Who cites who in the invasion zoo: insights from an analysis of the most highly cited papers in invasion ecology

Analýza nejcitovanějších článků v invazní ekologii

Petr P y š e k[1,3], David M. R i c h a r d s o n[2] & Vojtěch J a r o š í k[3,1]

D e d i c a t e d t o M a r c e l R e j m á n e k

[1] *Institute of Botany, Academy of Sciences of the Czech Republic, CZ-252 43 Průhonice, Czech Republic, e-mail: pysek@ibot.cas.cz;* [2] *Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa, e-mail: rich@sun.ac.za;* [3]*Department of Ecology, Charles University, Viničná 7, CZ-128 02 Praha 2, Czech Republic, e-mail: jarosik@cesnet.cz*

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The citation frequency of papers on invasion ecology published between 1981 and 2003 and that had accumulated at least 30 citations on the Web of Science on 9 August 2006 was analysed. The dataset comprised 329 papers and 27,240 citations. For each paper, the total number of citations was recorded and the annual citation rate (number of citations per year) was calculated. Papers were classified into broad research fields: plant invasions, animal invasions, biological control, and general papers (reviews and syntheses). Eight papers were cited more than 300 times, five of them dealt with general topics, and the mean value of the total number of citations across the whole data set is 82.8±73.1. The mean annual citation rate is 11.5±11.3 citations per year; six studies received on average at least 50 citations each year. About a half (50.8%) of papers in the data set deal with plant invasions. General papers are significantly more cited than papers from the other categories. The annual citation rate increased with time over the analysed period (1981–2003), by 1.0 citations per year. To compare the trends in invasion ecology with those in other fields of ecology, comparable data were compiled for population ecology and dynamics, and global change. The annual citation rate for invasion ecology as a whole increased faster than that for population ecology and dynamics, but not exponentially as is the case with studies on global change. The best-cited papers on invasion ecology were distributed among most of the top ecology journals. Those published in Oikos, Journal of Ecology, Ecological Applications and BioScience are cited 3.8–5.8 times more than the average for these journals (based on the impact factor). Papers on biodiversity, community ecology, impact, invasibility, dispersal, population ecology, competition, resources, genetical issues, biological control and species invasiveness received the highest total number of citations. However, measured by the annual citation rate, the hottest current topics in invasion ecology are the effect of global change on invasions, the role of natural enemies, character of the invasion process, evolutionary aspects, invasibility of communities and ecosystem processes. Some topics are disproportionally more cited than studied and vice versa. Studies on plant and animal invasions differ in focus: the topics of invasibility, biodiversity, resources, species invasiveness and population genetics are more emphasized in botanical studies, dispersal, competition, impact and pathways in papers dealing with animal invasions. Studies of grasslands and marine environment are most frequently cited in botanical and zoological studies, respectively. Most of the highly cited papers deal with multiple species; only 14 plant species and four animal species are the primary focus of one or more of the highly-cited papers. Twenty-two authors (4.5% of the total involved in the papers analysed), each with seven or more contributions cited at least 30 times, together contributed 49.4% of the most-cited papers, and attracted 55.6% of the total number of citations.

K e y w o r d s : animal invasions, biological control, biological invasions, citation analysis, global change, impact factor, invasive species, journals, Lotka's Law, plant invasions, population ecology, research topics, temporal trends, Web of Science

Introduction

Biological invasions have emerged fairly rapidly to assume a prominent position in the suite of factors that threaten biodiversity in almost all ecosystems and at spatial scales ranging from local (plot-scale) to global (Carlton & Geller 1993, Vitousek et al. 1996, 1997, Chytrý et al. 2005, Rejmánek et al. 2005a, Sax et al. 2005). It is widely assumed that invasions rank second only to direct habitat transformation as threats to biodiversity (Soulé 1990). As such, the field of invasion ecology has attracted considerable interest among researchers, and has rapidly become one of the hottest topics in ecology.

The publication of Charles Elton's book on "The ecology of animal and plant invasions' (Elton 1958) stimulated interest in invasions, but only in the 1980s, partly as a result of the international SCOPE programme on biological invasions (Drake et al. 1989), did invasions really start their migration to centre stage in the theatre of mainstream ecology. Before this, vague concepts and terminology (see e.g. Pyšek 1995) and the lack of a facilitating framework (Shea & Chesson 2002, Richardson & Pyšek 2006) stalled the establishment of "invasion ecology" as a clearly identifiable sub-discipline of ecology. The increased interest in the formal study of invasions in the last quarter of the 20th century coincided with a general move in ecology from working only in "natural" systems (where the influences of humans could be discounted and therefore did not constitute "noise" in the study system) to the current situation where, partly driven by requirements for funding, ecologists intentionally include anthropogenic factors as crucial components in most studies (Mooney 1998).

Invasion ecology has grown at a frenetic pace in the past few decades (e.g. Lodge 1993, Williamson 1996, Ewel et al. 1999, Richardson & Pyšek 2006). This is reflected, for example, by the launching of two journals, Diversity and Distributions (in 1998) and Biological Invasions (1999) – which focus exclusively, in the case of the latter, or substantially, for the former, on biological invasions. The trend of increasing interest in invasion ecology is clearly detectable in various international programmes and numerous conferences and workshops. Every major ecological conference now has substantial sessions or symposia devoted to invasions, and most issues of the top ecology journals, and increasingly top-tier general science journals, now carry articles on aspects of invasions.

The massive increase in the number of publications dealing with aspects of invasions has clearly been driven by the rapid increase in the number of species that have become invasive over the past few decades and the corresponding increase in the types and overall magnitude of the impacts of such invasions on biodiversity and ecosystem functioning (e.g. Mack et al. 2000, Pimentel et al. 2000, Rejmánek 2000, Rejmánek et al. 2005a). Research is driven by both the need to understand invasions to manage them (to reduce the abundance and spread of invasive species and to reduce or mitigate their impacts; Rejmánek & Pitcairn 2002), as well as the need to understand invasions to gain new insights on basic issues in ecology, for example the determinants of range limits (Rejmánek 1999, Sax & Gaines 2006, Pyšek & Richardson 2006), species diversity at different temporal and spatial scales (Tilman 1999, Shea & Chesson 2002) or species invasiveness (e.g. Rejmánek 1996, Rejmánek & Richardson 1996). Several recent publications have chronicled the development of particular concepts in invasion ecology and/or have assessed progress on theoretical and practical fronts (Hulme 2003, Mooney & Hobbs 2000, Ruiz &

Carlton 2003, Rejmánek et al. 2005a, Sax et al. 2005, Pyšek & Hulme 2005, Cadotte et al. 2006, Henderson et al. 2006, Richardson & Pyšek 2006).

An analysis of publication trends in invasion ecology has the potential to shed light on important forces that are operating to structure the field. We seek insights on key drivers and trendsetters in the rapid growth of invasion ecology by studying the citation history of published work in this field. We look at the most-cited papers and consider: (1) how trends in citation have changed over time; (2) which journals are publishing the most influential (i.e., best-cited) papers; (3) the citation performance of particular research sub-fields, with special reference to main differences for studies on plant and animal invasions; (4) which topics, classified on the basis of keywords, are most frequently cited; (5) which taxa are the primary focus of most highly cited papers (for those papers that deal with one or a few taxa); and (6) which authors are over-represented in the list of 490 contributors.

Data and methods

Selection of the most cited papers in invasion ecology

To obtain the most representative and as complete a sample of papers as possible on invasion ecology that are most cited, we screened Web of Science (WoS; http://portal.isiknowledge.com; accessed on 9 August 2006) by searching for relevant terms and their combinations in the titles and keyword and recorded all papers that received at least 30 citations in total. Screening for papers dealing with invasion ecology in a database is not trivial because of the large number of terms used to describe key aspects of the field (Pyšek 1995, Richardson et al. 2000, Pyšek et al. 2004). The most commonly used terms (invasion, alien, naturalization, exotic) and their derivatives (invasive, naturalized, etc.) were searched for the main groups of taxa (plant, animal, bird, mammal, insect). In the second step, citation records of the authors of papers that appeared on the initial list were screened and their other papers on invasion ecology with more than 30 citations, not identified by the first search, added to the list. This was done partly to ensure coverage of highly cited papers that were published in journals that were not registered on WoS at the time of publication, and would thus otherwise escape detection in the main search. Only papers published between 1981 and 2003 were considered. The screening yielded 329 papers. The selection of papers was based on terms in titles, abstracts and keywords. Some relevant papers, that did not mention biological invasions explicitly in the title, abstract, or keywords, were probably missed in the search, but we believe that the search captured vast majority of relevant papers. Since the focus of our analysis was not to emphasize the citation records of individual papers, which would only have transient value due to the fast increase in the number of citations, but rather on exploring general trends, the analysed papers represent a sound background for such analysis.

For each paper, the number of citations as indicated by WoS on the day of accession was recorded. No checking was done to correct for errors in citations; we assumed that such errors would be constant throughout the dataset. For technical reasons, self-citations were not excluded; however, in this case, including self-citations is appropriate because these also contribute to the circulation of the information contained in a paper within the scientific community. Our analysis is based on a total of 27,240 citations.

To account for the different periods of time available for accumulating citations, depending on the year of publication, we calculated the number of citations per year for each paper (hereafter termed "annual citation rate" sensu Leimu & Koricheva 2005). Since the data were collated in the middle of the year 2006, the value of 0.5 was added to the number of years by which the total number of citations was divided, in order not to overestimate the annual citation rate for recently published papers. That means, for example, that the total number of citations of a paper published in 2003 was divided by 2.5 to obtain the number of citations per year.

The papers were classified into four categories (hereafter termed "research fields"): plant invasions, animal invasions, biological control, and general papers. The last category included mostly reviews and synthesis papers searching for patterns across taxa.

To compare the trends in annual citation rate in invasion ecology with that in other disciplines of ecology, we compiled data for "population ecology and dynamics" and "global change" (searching for these keywords in WoS, accessed 31 July 2006, and subsequently manually removing papers without relevance to ecology). The papers that received at least 30 citations in total were considered. These two fields were selected as examples of a traditional discipline, intensively studied for a long time, and a relatively recently emerged one, with intensive research carried out in last decades.

Analysis of research topics

For each paper dealing with invasion ecology, we recorded the original keywords (as given in the paper). These were completed by terms from the title of the paper, to account for the fact that in some journals title words are not repeated among keywords. Keywords related to invasions in general, taxa studied and geographical regions were ignored since we were interested in a general publication pattern across taxa and regions.

The keywords were grouped to rather broad categories, to avoid bias from different level of completeness adopted by the authors and/or journals. Only topics, inferred from keywords that were addressed in at least five papers were considered. This screening yielded 50 items (see Table 3 for details on grouping and the list of research topics included in the analysis).

For each keyword, we calculated (a) the number of studies in which it appeared, (b) the total number of citations received by papers in which it was included, and (c) the mean annual citation rate, based on all papers containing the respective keyword.

Statistical analysis

The total number of citations and the annual citation rate were the response variables. Because the total numbers of citations were counts, and both the response variables were right-skewed (Fig. 1), the analyses were first calculated both on untransformed and square root transformed response variables, using normal distribution of errors and identity link function, and then repeated for the total numbers of citations on Poisson distribution of errors and log-link function, which is appropriate for count data (e.g. Crawley 1993). The fitted models were compared according to their residual deviance and explained variance, and checked by plotting standardized residuals against fitted values and by normal probability plots (e.g. Crawley 2002). The fitted models on Poisson errors appeared highly over dispersed, and after the treatment of overdispersion by dividing Pearson's chi-square by

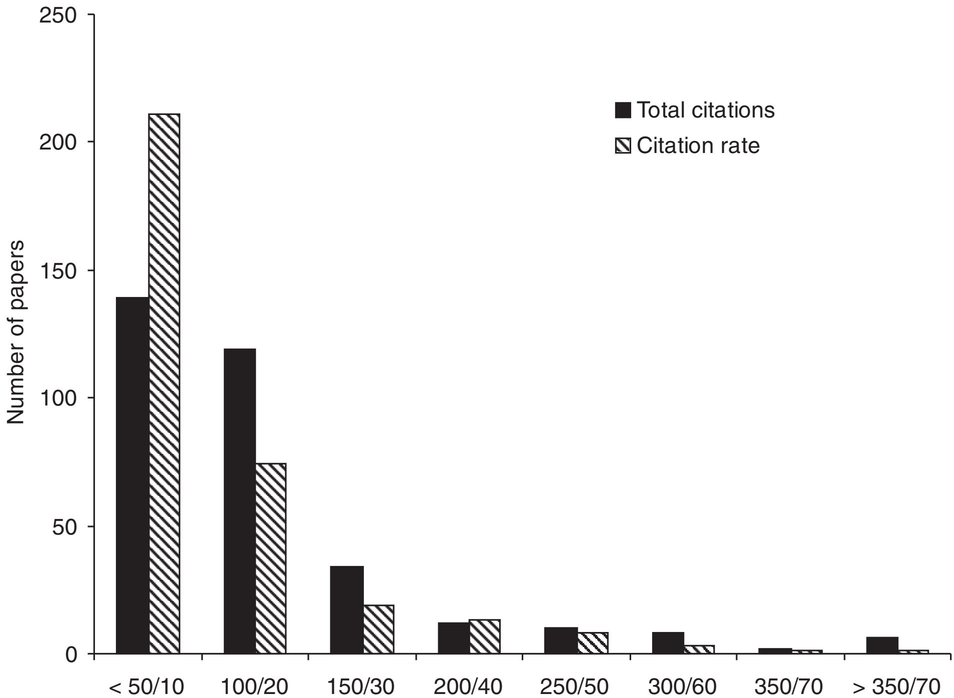

Fig. 1. – Frequency distribution of the most highly cited papers in invasion ecology (n = 329). The first number on horizontal axis indicates categories for total number of citations, the second (after the slash) for the annual citation rate, calculated as the number of citations per year.

the residual degrees of freedom (McCullagh & Nelder 1989) were insignificant, and hence unsuitable for the analyses. The models on normal errors gave smaller residual deviances and larger explanatory powers on untransformed than square-root transformed data. Therefore, the untransformed values of the response variables, normal distribution of errors and identity link functions were used in all analyses.

The a-priori hypothesis that general papers are more cited than those from the other research fields of invasion ecology, which do not differ significantly among themselves, was tested by orthogonal contrasts after one-way fixed-effect analysis of variance (e.g. Sokal & Rohlf 1995). Temporal trends in citing were compared by completed ANOVA tables with regressions, and by tests of equality of regression slopes, following Sokal & Rohlf (1995). The temporal trends that significantly deviated from linear regressions were fitted by polynomial, power, and exponential functions. The most appropriate function of those that appeared significant was chosen based on its residual deviance and explanatory power, which was calculated as the total explained variance adjusted for the number of parameters (e.g. Quinn & Keough 2002).

Results

Most cited papers in invasion ecology

The overview of most cited papers on invasion ecology is shown in Appendix 1. Eight papers were cited more than 300 times; five of these dealt with general topics, two with plants, and one with animal invasions. Twenty-six papers had more than 200 citations (12 of them on plants), and 74 papers had more than 100 citations (Appendix 1). The mean value of the total number of citations across the whole data set is 82.8±73.1 (Table 1). Only a few papers reached at least 150 citations (Parker et al. 1999, Richardson et al. 2000, Simberloff & Von Holle 1999) although the journals in which they were published, Biological Invasions and Diversity and Distributions, were not indexed on WoS when published.

Ranking the papers by the annual citation rate, six studies (four classified as general papers: Mack et al. 2000, Pimentel et al. 2000, Kolar & Lodge 2001, Sakai et al. 2001, and two on plants: Keane & Crawley 2002, Mitchell & Power 2003), received on average at least 50 citations each year, with the maximum of 89.6 (Mack et al. 2000). Twenty-six papers received more than 30 citations per year (Appendix 1). The mean value for the whole data set is 11.5±11.3 citations per year (Table 1).

The frequency distributions of the total number of citations and annual citation rate are skewed to the right, with most papers (64.9%) having on average less than 10 citations per year (Fig. 1).

The majority of papers in the data set deal with plant invasions (50.8%). Papers on animal invasions contribute 29.5%, general papers 11.9%, and biological control studies 7.9% (Table 1). General papers are significantly more cited (total citations: $F_{1, 327} = 25.62$, $P < 0.0001$; annual citation rate: $F_{1, 327} = 27.67$, $P < 0.0001$) than papers from the other fields (on average, general papers: 136.4 total citations and 20.1 citations per year, versus 73.4 and 9.8 citations, respectively, in other fields), and the other fields do not differ significantly among themselves (total citations: $F_{2, 287} = 0.98$, NS; annual citation rate: $F_{2, 287} = 2.03$, NS).

Temporal trends in citing

Annual citation rate over the analysed period of 1981–2003 followed a linear trend (Table 2) that did not differ significantly among general papers, papers on plant and animal invasions, and those on biological control (Table 3). This common trend for the four fields of invasion ecology indicated an increase by 1.0 citations per year (Fig. 2A).

The annual citation rate in invasion ecology differed significantly from those in other two disciplines of ecology: population ecology and dynamics and global change (Table 3). The increase in citations over time for population ecology and dynamics was, similar to that in invasion ecology, linear (Table 4), but nearly by a half slower (0.6 citations per year) than for invasion ecology (1.0 citations per year) (Fig. 2B). Citations on global change started at the lowest values, but increased exponentially (Fig. 2B).

Journals publishing the most cited papers

The best-cited papers in invasion ecology are distributed among most of the top ecology journals. The following journals contributed more than 10 papers to the total of 329: Ecology (36 papers), Conservation Biology (18), Biological Conservation (18), Trends in

Table 1. – Citation analysis of the fields of study within invasion ecology, based on papers that received at least 30 citations between 1981 and 2003. The mean number of citations per paper (± S.D.) is shown. Fields are ranked according to the decreasing mean annual citation rate (± S.D.). Note that the means presented in this table and elsewhere in the paper are used to compare between values obtained for the most highly cited paper as defined in this study; they are not representative for invasion ecology as a whole since papers with fewer than 30 citations were omitted.

Field	Total citations	Number of papers	Total citations per paper	Mean annual citation rate
General/reviews	5321	39	136.4±121.9	20.1±19.9
Plant invasions	13,333	167	79.8±66.4	11.3±10.5
Animal invasions	6743	97	69.5±51.8	9.2±6.6
Biological control	1843	26	70.9±48.6	8.8±6.2
Total/mean	27,240	329	82.3±73.7	11.5±11.3

Table 2. – ANOVA tables with regressions for temporal trends in annual citation rate in individual fields (general papers, plants, animals, biological control) of invasion ecology.

	General/reviews				Plant invasions				Animal invasions				Biological control			
Source of variation	df	MS	F	P	df	MS	F	P	df	MS	F	P	df	MS	F	P
Among years	14	435.64	0.68	0.7685	21	309.14	0.57	0.9345	18	85.39	0.57	0.9110	10	70.37	2.64	0.0440
Linear regression	1	2517.11	9.14	0.0098	1	3969.07	31.46	<0.00001	1	801.74	18.54	0.0005	1	589.23	46.33	0.0001
Deviations from regression	13	275.53	0.74	0.7088	20	126.15	1.60	0.0602	17	43.25	1.25	0.2481	9	12.72	0.71	0.6888
Within years	24	372.08			145	78.92			78	34.61			15	17.80		

Table 3. – Test of equality of slopes of regression lines for temporal trends in annual citation rate in invasion ecology compared to other disciplines of ecology (population ecology and dynamics, global change).

	Among fields of invasion ecology				Among disciplines of ecology			
Source of variation	df	MS	F	P	df	MS	F	P
Among fields	3	202.09	1.71	0.1738	2	660.11	4.90	0.0111
Weighted average of deviations from regression	59	117.87			54	134.80		

Table 4. Completed ANOVA tables with regressions for temporal trends in annual citation rate in selected disciplines of ecology (population ecology and dynamics, invasion ecology, global change).

	Population ecology and dynamics				Invasion ecology				Global changes				
Source of variation	df	MS	F	P	df	MS	F	P	df	SS	MS	F	P
Among years	23	204.74	0.18	1.0000	21	474.76	0.31	0.9986	13	8089.00	622.23	0.17	0.9995
Linear regression	1	3842.53	97.56	< 0.00001	1	6933.37	45.66	< 0.00001	1	4712.99	4712.99	16.75	0.0015
Deviations from regression	22	39.38	0.78	0.7538	20	151.83	1.47	0.0914	12	3376.01	281.33	2.06	0.0192
Within years	530	50.59			307	103.55			344	47032.00	136.72		

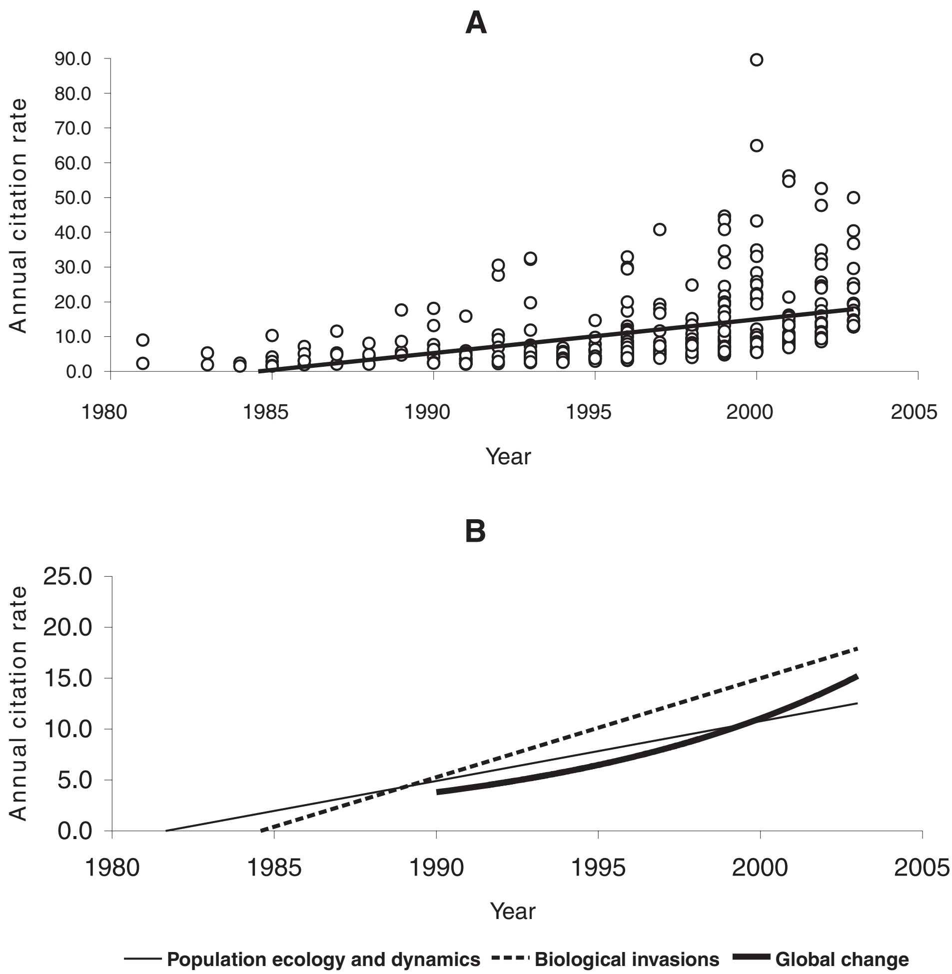

Fig. 2. – Relationship between the annual citation rate (y) and the year in which the paper was published (x). A. Observed (points) and fitted ($y = -1931 + 0.97x$, $F_{1,327} = 65.15$, $P < 0.0001$; line) relationship for the fields of invasion ecology. B. Fitted values for the fields of ecology. Population ecology and dynamics: $y = -1165 + 0.59x$, $F_{1,530} = 97.56$, $P < 0.0001$; thin line. Global change: $y = 2E\text{-}92\ e^{0.11x}$, $F_{1,356} = 103.5$, $P < 0.0001$; heavy curve. Biological invasions: see Fig. 2A for equation; medium line.

Ecology and Evolution (16), Science (15), Ecological Applications (14), American Naturalist (11), Oecologia (11) and Nature (10) (Table 5). Papers published in Annual Reviews of Ecology, Evolution and Systematics (hereafter AREES), Science, Journal of Ecology and Trends in Ecology and Evolution received on average more than 120 total citations. Papers published in AREES (26.1), Nature (23.8) and Trends in Ecology and Evolution (21.9) exceeded on average 20 citations per year (Table 5).

How papers on invasion ecology rate alongside those on other topics in a given journal can be inferred by relating their citation characteristics to the impact factor of the journal (Fig. 3). Applying this measure indicates that the top papers on invasion ecology pub-

Table 5. – Overview of journals which published most cited papers in invasion ecology. Only journals with at least five papers that received 30 or more total citations are included. Mean number of total citations per paper is shown. Annual citation rate is the mean number of citations per year, calculated for all papers published in the journal. Papers are ranked according to the decreasing total number of citations.

Journal	Number of papers	Total citations	Total citations per paper	Mean annual citation rate
Ecology	36	3795	105.4	13.1
Trends in Ecology and Evolution	16	1952	122.0	21.9
Science	15	1902	126.8	18.6
Conservation Biology	18	1635	90.8	10.0
Ecological Applications	14	1189	84.9	14.0
Biological Conservation	18	1155	64.2	7.2
Nature	10	882	88.2	23.8
Oikos	9	929	103.2	15.3
Annual Review of Ecology, Evolution and Systematics	6	919	153.2	26.1
Nature	10	882	88.2	23.8
Bioscience	9	821	91.2	13.1
American Naturalist	11	707	64.3	10.1
Oecologia	11	647	58.8	7.5
Proceedings of the National Academy of Sciences of the USA	7	627	89.6	17.7
Journal of Ecology	5	627	125.4	14.2
Canadian Journal of Fisheries and Aquatic Sciences	10	620	62.0	7.4
Journal of Applied Ecology	8	442	55.3	5.6
Ecology Letters	7	411	58.7	11.6
Journal of Biogeography	8	348	43.5	4.2
Journal of Vegetation Science	6	235	39.2	3.8

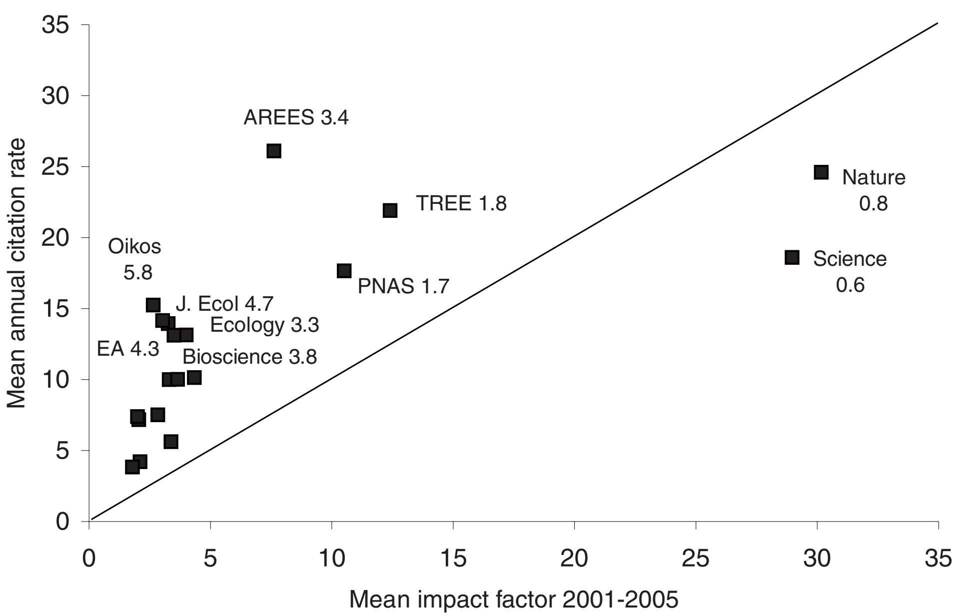

Fig. 3. – The mean annual citation rate of papers on biological invasions related to the mean impact factors of journals in which the papers were published. Numbers following the codes are ratios of both values. Papers published in journals above and below the diagonal line receive more and fewer citations than the journal's average, respectively. AREES = Anual Review of Ecology, Evolution and Systematics;, EA = Ecological Applications; J. Ecol = Journal of Ecology; PNAS = Proceedings of the National Academy of Sciences of the USA; TREE = Trends in Ecology and Evolution.

Table 6. – Citation of topics that appear most often in studies on invasion ecology, based on the analysis of keywords of the 329 most cited papers (see text for details). The number of studies that address particular topics, the total number of citations, number of citation per paper, and the mean annual citation rate per paper are shown. Keywords are ranked according to the decreasing mean annual citation rate, which is unbiased by the length of period for which the citations were being received.

Keyword/topic	Number of studies	Total citations	Mean number of citations	Mean annual citation rate
global change	8	1828	228.5	38.3
natural enemy	6	515	85.8	22.3
invasion process	19	2373	124.9	20.1
evolution	21	2271	108.1	18.1
invasibility	43	4747	110.4	17.8
ecosystem	27	3483	129.0	17.6
grassland	21	2596	123.6	17.0
extinction	12	1307	108.9	16.1
mutualism	11	1034	94.0	15.9
community	60	5223	87.1	15.1
land-use	13	1569	120.7	14.9
pathogens	10	945	94.5	14.8
native-alien relationship	10	909	90.9	14.7
biodiversity	60	5432	90.5	14.1
disturbance	25	2529	101.2	13.8
physiology	19	1947	102.5	13.7
dispersal	38	4099	107.9	13.4
impact	58	5150	88.8	13.4
management	16	1222	76.4	13.1
scale	9	733	81.4	13.0
risk assessment	8	531	66.4	12.9
competition	49	3951	80.6	12.8
resources	38	3642	95.8	12.6
genetics	40	3326	83.2	12.5
population	42	4095	97.5	12.4
experiment	9	728	80.9	12.2
islands	10	748	74.8	12.1
biological control	34	2772	81.5	11.6
prediction	25	2028	81.1	11.6
species invasiveness	34	2662	78.3	11.2
conservation	27	2515	93.1	10.7
vegetation dynamics	6	601	100.2	10.6
invasion history	11	1186	107.8	10.5
fire	8	822	102.8	10.2
animal behaviour	9	454	50.4	9.4
pathways	24	2128	88.7	9.1
climate	5	370	74.0	9.0
herbivory	29	2123	73.2	8.8
habitat	15	814	54.3	8.5
marine	29	2210	76.2	8.4
traits	32	2046	63.9	8.3
invasion dynamics	23	1579	68.7	8.3
woody plants	18	1155	64.2	8.1
model	26	1559	60.0	8.0
wetlands	21	1393	66.3	7.9
biogeography	30	1657	55.2	7.8
taxonomy	6	314	52.3	7.6
freshwater	23	1505	65.4	7.3
animal predation	10	570	57.0	6.7
fynbos	9	437	48.6	4.6

Notes on grouping of keywords used in original papers: **biodiversity** – includes species richness and diversity; **biogeography** – biogeographical patterns, species distribution ranges, biogeographical approach; **community** – species interactions, community assembly, community structure, functional groups; **competition** – coexistence, competitive effects, competitive exclusion, species replacement; **conservation** – nature reserves, national parks, endangered species; **dispersal** – incl. long-distance dispersal, dispersal of seed, propagule pressure; **ecosystem** –processes, functioning, engineering, services, stability; **genetics** – hybridization, genetic variation, bottleneck, fitness, genome size, GMO, plasticity, adaptation, polymorphism, population genetics; **herbivory** – incl. grazing, seed predation; **impact** – consequences of invasion, environmental impact, economic impact, costs, threat to biodiversity; **invasion dynamics** – rate of spread, pattern of spatial spread; **invasion history** – incl. residence time; **invasion process** – overcoming of barriers, determinants of naturalization; **land-use** – land-use change, fragmentation, habitat modification, landscape ecological aspects; **mutualism** – mycorrhizas, pollinators, positive interactions; **pathogens** – incl. parasitism and diseases; **pathways** – incl. ballast water, forestry, agriculture, transport; **physiology** – growth, productivity, photosynthesis, RGR; **population** – demography, population biology and dynamics, recruitment, mortality, population structure, metapopulation dynamics; **resources** – soil fertility, soil chemistry, nitrogen fixation, water, food habits, diet selection, resource availability and exploitation; **scale** – multiple scales, scaling artefacts; **taxonomy** – effect of taxonomic position on species invasiveness; **vegetation dynamics** – vegetation change, succession; **wetlands** – incl. salt marshes, estuaries, riparian.

lished in Oikos, Journal of Ecology, Ecological Applications and BioScience are cited 3.8–5.8 times more than average papers in these journals, expressed by their impact factors. On the other hand, papers on biological invasions in journals with the highest impact factors within the data set (Nature, Science) are cited less than average papers in these journals (Fig. 3).

Keyword analysis

Table 6 gives an overview of keywords representing the topics addressed in the most cited papers on invasion ecology. The total number of citations is a measure integrating the long-term interest of research community in particular issues. Topics that received highest numbers of citations are consistently studied over the whole period analysed and have a high annual citation rate: biodiversity, community ecology, impact, invasibility, dispersal, population ecology, competition, resources, genetical issues, biological control and species invasiveness (Fig. 4). These keywords also appear most frequently in the papers analysed (Table 6).

Nevertheless, the annual citation rate, averaged across all papers using a given keyword, provides a better picture of current hot topics in the study of invasions. For example, the eight papers addressing global change issues received on average 38.3 citations per year; other high-ranking topics are the role of natural enemies (22.3), invasion process (20.1), evolutionary aspects (18.1), invasibility of communities (17.8), ecosystem processes (17.6), invasions into grasslands (17.0), extinctions due to invasive species (16.1) and mutualistic relationships (15.9) (Table 6).

An interesting question arises whether the research effort invested in particular topics and the "recognition" (expressed by citations) of these topics is balanced. To get an insight into this, we related their mean annual citations rate to the number of studies, as recorded for the keywords (Fig. 5). The graphical presentation of topics that are disproportionally more cited than studied (appearing above the diagonal line in Fig. 5) and vice versa (falling below that line) indicates that issues such as global change, invasion process, natural ene-

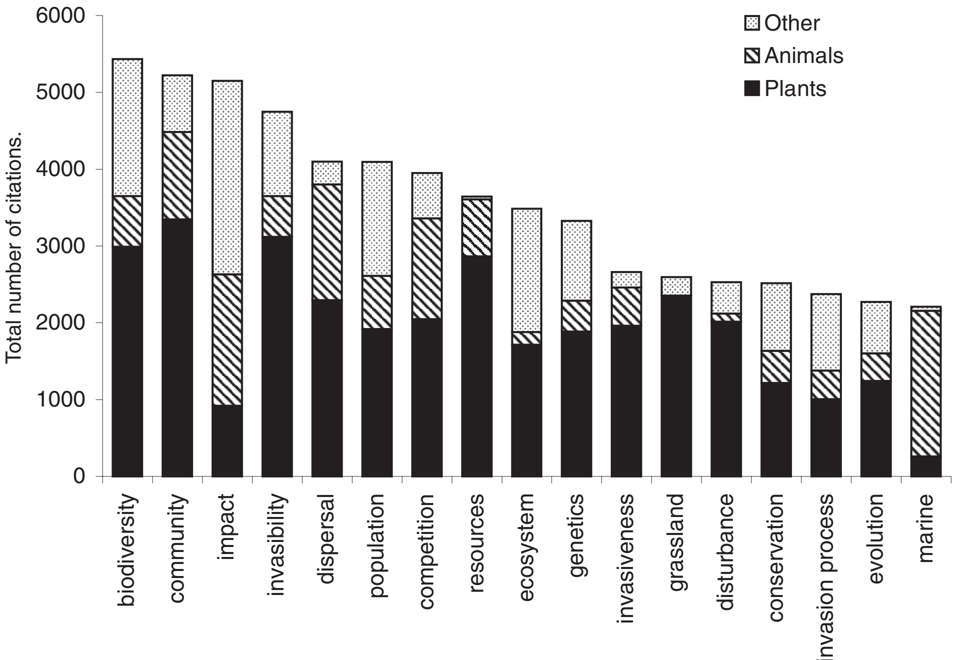

Fig. 4. – The total number of citations accumulated by papers that dealt with particular topics, as indicated by the keywords they used. Contributions of papers on plant and animal invasions are indicated (others include biological control and general papers/reviews). See Table 6 for the total numbers of citations for the complete set of keywords considered.

mies, evolution, extinction and mutualism are disproportionally little studied but highly "recognized" and cited. On the other hand, others are very often studied but receive fewer citations than expected for the research effort (biodiversity, invasibility, impact, competition, community ecology) (Fig. 5).

Differences in research topics between plant and animal invasions

Studies on plant and animal invasions contribute differently to the total number of citations received by papers indicating particular keywords (Fig. 4). The two fields are similar in terms of the number of citations attributed to studies on dispersal and competition. However, it needs to be taken in account that the total number of studies on plant invasions is higher than for animals, and so is the total number of citations (Table 1). Therefore, the contribution of the latter is generally lower. Nevertheless, some topics related to invasions are typically botanical, such as biodiversity and invasibility issues, ecosystem processes and the role of disturbance (Fig. 4).

Differences are clearly detectable by inspecting the relative contribution of particular keywords to the total number of citations received by plant and animal studies (Fig. 6). The most striking differences are in the topics of invasibility, biodiversity, resources, species invasiveness and population genetics; these facets are much more emphasized in bo-

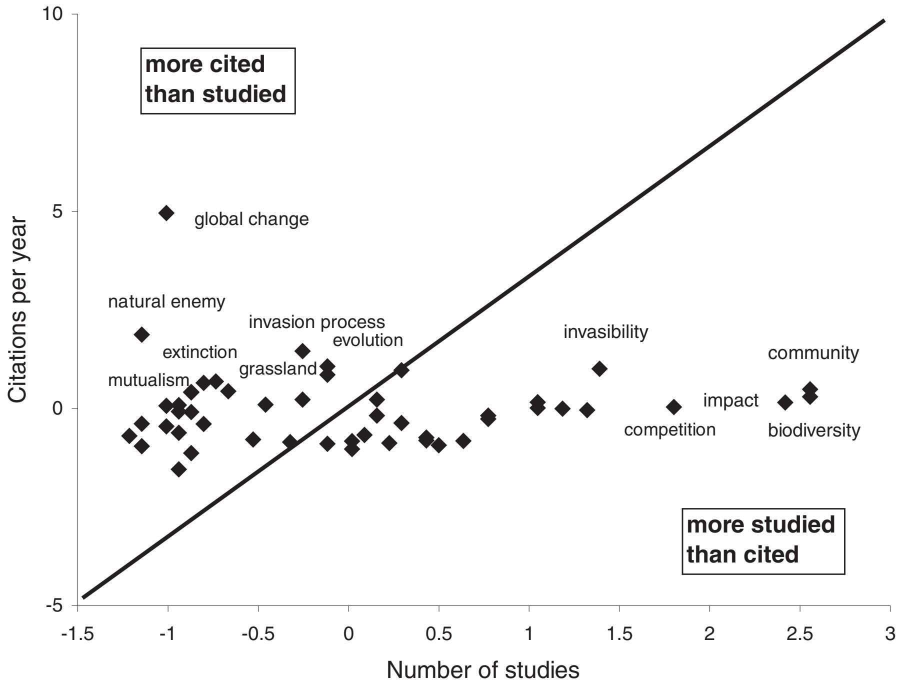

Fig. 5. – The mean annual citation rate of papers in which particular topics are addressed related to the number of studies in which they appear. Values are standardized (zero mean, variance 1) and the diagonal line (slope 1) divides the topics into those disproportionally more cited than studied and vice versa. Keywords with average number of citations per year > 15 (see Table 6) are indicated.

tanical, than in zoological, studies. On the other hand, more emphasis has been given to dispersal, competition, impact and pathways in papers dealing with animal invasions. In terms of citations, invasions of grasslands are an exclusively botanical topic, whereas marine invasions are the most frequently cited topic in zoological studies (Fig. 6).

Discussion

Caveats to the interpretation

The results of our analysis of the citation history of recent papers in invasion ecology should be considered with the caveats that have emerged from recent studies of citation patterns in ecology in general. For example, Leimu & Koricheva (2005) found that citation frequency in ecology was influenced by the direction of the study outcome with respect to the hypothesis tested (supportive versus unsupportive evidence), by article length, the number of authors, and their country and university of affiliation. Not all these factors were explored in our study. We only tested for the possible effect of the number of authors on the annual citation rate; as expected, papers with more authors attracted more citations per year, but this effect was mediated by the research field and the time since publication (results not shown here). Although factors other than scientific ones, notably the professional standing of the cited author, play a significant role in citation decisions in ecology, Leimu & Koricheva (2005) admitted that the correlative nature of their study and the complex nature of the explanatory variables they used made it difficult to interpret the causes of this pattern. Nevertheless, the temporal trends in citations and differences in attractiveness of particular research topics revealed in the present paper seem to be robust enough and are probably not seriously biased by the mediating factors identified by Leimu and Koricheva (2005), Hence, they provide a sound basis for interpretation.

The value or "effect size" (Jennions & Moller 2002), as expressed by citation frequency, of some more recent papers is almost certainly downplayed in our analysis, as many papers, like invasions themselves, have a "lag phase" – a period during which the paper may enjoy little attention/citation, with its value only to be recognized at a later stage. This aspect was not analysed in our study. The measure of annual citation rate is therefore slightly biased against most recent papers; some of them might be highly cited but do not meet the 30 total citations threshold. On the other hand, this is certainly not the case for all papers, as indicated by steadily increasing accelerating annual citation rates in all four research fields examined. Obviously, some papers have little or no "citation lag phase".

The most cited papers and citation dynamics over time

Besides effects that can be quantified (Leimu & Koricheva 2005), citation success is determined by factors related to human behaviour and psychology that cannot easily be quantified. We suggest that an important factor is whether a paper is "punchy", i.e., it has a short, gripping title, is uncomplicated and/or proposes a novel approach described by an attractive term or metaphor. This was the case of e.g., the "invasional meltdown" paper (Simberloff & Von Holle 1999; see the recent discussion: Simberloff 2006, Gurevitch 2006). Obviously, people love to relate the results of their own research to a hot topic. Every hat is looking for a good peg to hang on. Moreover, as pointed out by Leimu & Koricheva (2005), citations in ecological papers are often used as rhetorical devices to convince the readers of the validity of the study claims, rather than as simple acknowledgements of the sources of background information. Such papers, chosen as a reference to support the claims made, quickly become highly cited, especially if they cover a range of topics related to invasion ecology and highlight general patterns.

The question of whether one can equate a high "effect size" (citation rate) with the degree to which a publication is influential in a particular field is complicated. As a general rule, review papers are mostly less influential in real terms than is indicated by the simple metric of number of citations. This is because many review papers are highly cited not because they make any substantial contribution, nor because they suggest profitable new areas of research, but rather because citing such papers is an efficient way of making the point that a particular issue is, for example, widely studied, deemed important, or worthy of further study. Of course, many other reviews do stimulate fresh research avenues and are highly influential, especially when they offer critical assessments of research efforts, explore links between different schools of thought or different approaches, or propose new frameworks, hypotheses and research directions. We do not attempt to unravel such discrepancies, partly because we are too closely involved in some of the research and our views would be considered biased. Nevertheless, the point needs to be made that the rank of review papers in our assessment needs to be considered with these points in mind.

That several papers accumulated many citations (Parker et al. 1999: 203 citations, Richardson et al. 2000: 182, Simberloff & Von Holle 1999: 159) despite the fact that the journals in which they were published, were not indexed on WoS at the time of publication, suggests that the research community in invasion ecology is rather small and closely linked, and that influential papers are quickly recognized and are widely circulated even if they are not published in journals covered by WoS. The present analysis covered only papers published in journals, but there are influential chapters and books that directed the research in years following their publication and received numbers of citations comparable to, or even much higher than best cited papers – e.g. Elton 1958 (1278 citations); Williamson 1996 (613); Crosby 1986 (599) and Drake et al. 1989 (317) for books, and Baker 1965 (388), Crawley 1987 (270) and Rejmánek 1989 (168) for chapters. These figures clearly indicate that research progress is fuelled not only by publications in journals. On the other hand, there are probably many valuable contributions that have appeared in books or the grey literature that have not garnered the attention they deserved.

The increase in citation frequency over time is undoubtedly partly due to the general increase in publication and citation frequency in science. With the data at hand, we cannot conclude whether the citation frequency for papers dealing with invasion ecology has increased disproportionally. Nevertheless, some indication of trends in invasion ecology relative to other fields is provided by comparison with long-term citation dynamics in the two other ecological disciplines. Although the citation dynamics in invasion ecology as a whole are not as fast as in global change, an intensively studied fashionable issue which is multidisciplinary in nature (hence citations to papers on global change appear in a wider range of journals), they match those of a more traditional subdiscipline, namely population ecology. This is documented by comparison of the total number of citations in the sample of papers cited more than 30 times. The most cited paper in population ecology (Lebreton et al. 1992: 1095 citations) received markedly more citations than is the case for the best-cited one in invasion ecology (Mack et al. 2000: 493 citations) but on average, the total number of citations is higher for papers on invasions (82.8±73.1, n = 329) than for population ecology and dynamics (69.7±70.0, n = 554). In addition, the increase in annual citation rate over time is significantly faster for papers on invasion ecology. These results confirm that invasion ecology is among the most rapidly developing fields of ecology.

Journals

That we compared the citation rate over the whole period since publication of the paper with the journals' impact factors over the last five years does not seem to bias the observed pattern since changes in ranking of journals according to impact factor over time are not dramatic. Moreover, annual citation rate over the whole period since publication provides a reliable measure of value for an ecological paper, because the importance of many papers is recognized long after they have been published and such papers attract citations long after they appeared.

The ratio of the annual citation rate of a paper published in a journal to the journal's impact factor shows whether the best-cited papers in invasion ecology are cited more or less than average papers in that journal. A high index for the journal indicates that papers on invasion ecology are more widely recognized by the research community than most other papers published in that journal. On the other hand, papers on invasion ecology in journals with very high impact factors such as Nature and Science are cited less often than the average for these journals (based on impact factors). This is probably because the research community of, for example, molecular biologists is much larger than that of ecologists; because molecular papers are mostly cited by molecular biologists and ecological papers by ecologists, the average number of citations of ecological papers in top journals like Science and Nature must be smaller than that of molecular papers, simply because of the differences in the numbers of researchers in the two fields. Nevertheless, papers on invasion ecology published in journals such as Nature or Science rank high among the best cited in the field simply because the impact factors of these journals are so high. These journals select the "hottest" papers in all fields, which suits the two-year impact factor window perfectly. It may also be that the high prestige of these journals makes some authors think that such papers must be "the best papers to cite" on a particular topic.

It must be borne in mind that our analysis did not consider all papers on biological invasions, only the most cited. Leimu & Koricheva (2005) point out that the broad scatter of citation rates of individual articles in ecological journals with a high impact factor indicates that publication in a prestigious journal does not by itself guarantee high citation rates.

Research topics

The relation between annual citation rate expressed for particular research topics and the effort invested in the study of these topics indicates that some issues are less often studied but highly cited while others are very often studied but under-cited. Ideally one would expect a positive feedback: the most cited topics are rewarding in terms of scientometric measures (they attract more citations) so more researchers invest effort in studying them – given the publication and citation pressure in most academic and research institutions, it can be assumed that researchers tend to study topics that provide results which can be published in journals with a high impact factor and attract high number of citations. That the results presented in Fig. 3 do not support this assumption can be for several reasons:

On some topics it is more difficult to produce a paper than on others, because it takes more effort, money and time to collate the data (physiology, experimental studies in general) or good data sets are limited and less easily available (large-scale geographical studies, global warming, native-alien relationships, invasion process, etc.). These topics appear "under-studied" and are mostly located in the upper left part of Fig. 3. In contrast, on the opposite side are located traditional issues on which the data can be more easily obtained (community ecology, biodiversity, ecosystem studies), hence they are often studied (Fig. 3).

If a topic is intensively studied, there are more publications available and it is difficult for each individual paper to receive a high number of citations because researchers can choose from many papers. The probability of citation of any individual paper is thus much smaller for these papers – in contrast to relatively few papers available on e.g., the effect of global change on biological invasions that everybody cites (D'Antonio & Vitousek 1992, Vitousek et al. 1997, Mack et al. 2000).

How do plant invasions rate in the citation game?

To put plant invasions into a wider context and evaluate their position in the study of biological invasions in general, we also included papers on invasive animals in our analysis. The two fields are difficult to separate and the current trend is towards building a unified theory across taxonomic groups of invasive organisms (Dukes & Mooney 1999, Kolar & Lodge 2001, Lee 2002, Shea & Chesson 2002, Sax & Gaines 2003, Lockwood et al. 2005, Perrings et al. 2005). This trend is indicated by papers aimed at achieving this goal, classified as general in this study, being more cited than those from other research fields.

Compared to animal invasions, plants are the subjects of more studies, but the two groups do not differ in terms of the total number of citations that the best-cited papers receive. Not surprisingly, the principle difference in research focus between studies on plant and animal invasions concerns habitats. Our analysis shows that grasslands, among terrestrial environments, and marine habitats, for aquatic systems, are the main laboratories for research on invasions. This difference between plant and animal invasions reflects the distribution of primary producers – plants in terrestrial and animals in aquatic environments. Research in grasslands has contributed substantially to the current knowledge of biological invasions (Mack 1981, D'Antonio & Vitousek 1992, Tilman 1997, 1999, Huenneke et al. 1990, Stohlgren et al. 1999) and the same is true for marine habitats (e.g. Carlton & Geller 1993, Carlton 1996, Ruiz et al. 2000). However, these results do not imply that grasslands are the most heavily invaded ecosystems, or that they are disproportionally susceptible to, and/or degradation by, invasive species; some other habitats in parts of the world are invaded as much or more than grasslands (e.g. Rejmánek 1996, Richardson et al. 1997, Lonsdale 1999, Rejmánek et al. 2005b, Chytrý et al. 2005). It probably is simply a reflection of the geographical location of well-resourced researchers, mainly in North America, where temperate grasslands suffer from invasions by annual grasses of Eurasian origin (Mack 1981). As shown by Leimu & Koricheva (2005), papers by US researchers attract significantly more citations than those by authors from other regions.

Other differences in research focus between the two fields result from the differences in the subjects of study. Botanical studies are better suited to addressing questions associated with community structure, such as is vulnerability to invasion, the role of soil resources, the importance of traits, and the role of mutualisms. Common issues include community ecology in general, biodiversity, prediction of factors that determine invasiveness of species and evolutionary and conservation aspects. In contrast, hot topics in the study of animal invasions include dispersal, competition, and pathways; research on the latter two areas obviously benefits from data on the release of introduced animals – birds and fishes in particular – information which is rarely available for plants (but see Richardson 2006 for discussion regarding the special case of pines). Nevertheless, the pattern presented in Fig. 6 indicates that studies on plants and animals are to some extent complementary, and that this may contribute to the development of more general theories on biological invasions in the future.

Big issues, major themes and dominant contributors

The results presented here provide a foundation for further analysis of research trends in invasion ecology. As with any young and rapidly developing field of science, research in invasion ecology in the past few decades has been characterized by fads, controversies, parochial interests, and a non-representative selection of study subjects (in this case species and ecosystems). It is probably too early to unravel these complexities. To us, some of the most interesting and important focal areas of research on invasions over the period covered by this analysis have been (representative papers addressing these issues are listed in brackets; numbers refer to Appendix 1): the "terminology debate", including the issues of

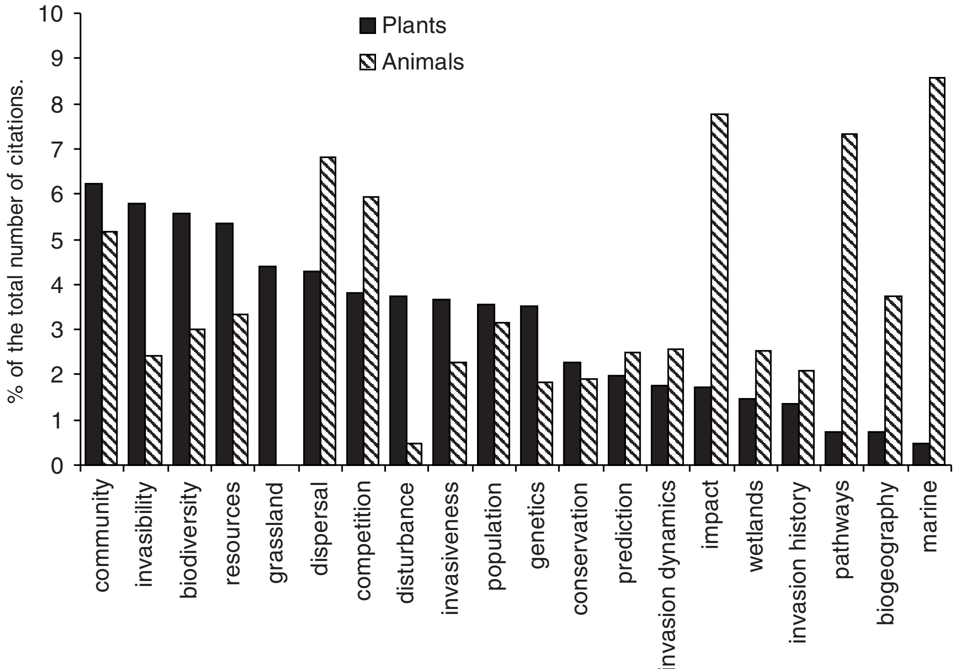

Fig. 6. – The percentage of total number of citations accumulated by papers using individual keywords, compared for plant and animal invasions. The total number of citations is the sum of all paper/keywords combinations (n = 53,706 and 22,087 for plants and animals, respectively); each keyword used by a respective paper was attributed the number of citations that the paper accumulated.

whether evidence of impact is a prerequisite for denoting invasiveness and discussion on the use of "militaristic" metaphors (31); whether prediction is possible beyond trivial generalization (e.g. 14, 16, 33, 38, 59, 90, 161); the relationship between species richness and invasibility at different spatial scales (5, 6, 10, 13, 21, 27, 49, 51, 58, 65, 69, 86, 92); deterministic vs. probabilistic approaches to understanding invasibility (11, 19, 74, 101, 117, 157, 174); detailed elucidation of processes of invasion (5, 18, 43, 41, 46, 50, 54, 55, 64, 66, 67, 70, 75, 85, 94, 95, 99, 110, 116, 119, 145, 156, 163, 165, 184), including modelling studies (45, 92, 129, 141, 153, 185, 186, 187); emerging approaches to incorporating propagule pressure as a determinant of invasions (12); increasing evidence of the major role of positive interactions as mediators of invasions, including the notion of "invasional meltdown" (2, 35, 36, 47, 61, 91, 112, 115, 150); invasions as components of global change, including studies of the combined effects of invasions and other factors (8, 34, 48, 52, 60); the search for objective means for defining impacts (26, 78, 79, 102, 138, 146); ecosystem-level determinants and effects of invasions (9, 12, 23, 25, 72, 75, 87, 113, 120, 132, 152, 160); the overwhelming role of people, including the analysis of vectors and pathways – the human dimension (3, 13, 17, 24, 40, 111, 179); applying emerging theory to improve management, including risk assessment (44, 68, 98, 90, 111, 122); the role of biological control in management – theory and practice (20, 28, 30, 42, 73, 83, 88, 105, 124, 143, 151, 176, 189), issues of transgenic plants (17, 39); and objective cataloguing of alien species (134, 168). The above mentioned topics are likely to dominate the field of invasion ecology in the immediate future. One issue that has risen to prominence since 2003 is the role of propagule pressure in driving and structuring invasions (Lockwood et al. 2005, Colautti et al. 2006). We suggest that this topic is likely to enjoy considerable research effort over the next decade.

Relatively few of the best-cited studies (with at least 50 citations; Appendix 1) focus on single species or species within a genus. Those that do deal mostly with a diverse assortment of plants: *Bromus tectorum* (22, 57, 136, 182, 190), *Carduus nutans* (169), *Carpobrotus edulis* (81), *Caulerpa taxifolia* (188, 192), *Centaurea maculosa* (91, 108), *Codium fragile* (159), *Cytisus scoparius* (143, 148), *Lythrum salicaria* (88), *Myrica faya* (9, 23, 178), *Pennisetum setaceum* (163), *Prosopis glandulosa* var. *glandulosa* (84), *Sapium sebiferum* (128), *Spartina anglica* (119) and *S. alterniflora* (183). The genus *Pinus* also received good coverage (14, 92, 127, 145). As a family, *Poaceae* is well represented (2, 22, 57, 119, 126, 136, 163, 181, 182, 183, 190). For animals, four species are dealt with in detail in the set of highly cited papers: one terrestrial insect and three marine invertebrates: the Argentine ant, *Linepithema humile* (63, 82, 99, 116, 118), the European green crab, *Carcinus maenas* (125, 160, 184), the zebra mussel, *Dreissena polymorpha* (114, 115, 140, 166, 175) and the crayfish *Orconectes rusticus* (76, 102). The taxa listed above have emerged, for various reasons, as highly informative case studies in invasion ecology.

Because science is done by people, we conclude our analysis by looking at the authors of the 329 best-cited papers in invasion ecology. In total, 490 researchers were involved, but a striking feature of the dataset is that a relatively small number of authors are dominant contributors. Only 22 authors contributed to seven papers or more in the list of most-cited contributions: B. Blossey (7 papers – plants), J. T. Carlton (20 – marine), T. J. Case (14 – insects), M. J. Crawley (7 – plants), C. C. Daehler (7 – plants), C. M. D'Antonio (12 – plants), E. D. Grosholz (7 – marine), R. J. Hobbs (8 – plants), D. A. Holway (10 – insects), D. M. Lodge (11 – freshwater fishes), W. M. Lonsdale (9 – plants), R. N. Mack (14 – plants), I. M. Parker (7 – plants), P. Pyšek (7 – plants), M. Rejmánek (7 – plants), D. M. Richardson (18 – plants), G. M. Ruiz (8 – marine), D. Simberloff (8 – biological control, theory & management), D. R. Strong (7 – plants), A. V. Suarez (9 – insects), P. M. Vitousek (12 – plants) and M. Williamson (7 – theory). These authors, individually or in partnership, contributed to 163 papers from the list; this means that 4.5% of all the authors represented were involved in 49.4% of the most-cited papers, which in turn attracted 55.6% of the total number of citations. This indicates that the group of most influential researchers in invasion ecology is rather limited, and that plant ecologists, marine and freshwater ecologists, and entomologists are the main contributors to the most influential papers. This finding, that a handful of authors produce the bulk of highly cited papers, agrees with those from other fields of science. This feature of the distribution of publication patterns was first observed in the 1920s by Lotka (1926), on whose work Price (1963) based the formulation of the principle he termed "Lotka's Law". According to this principle, publication productivity conforms to an "inverse square law", whereby the chances that a scientist would publish n publications are $1/n^2$.

There is an obvious dominant role of researchers based in the USA (23 of the 33 who contributed at least five papers to the list) and the only other well represented regions are South Africa, Australia and Europe (the UK, the Czech Republic and France; Fig. 7). The geographical pattern only partly corresponds with the degree to which invasions are per-

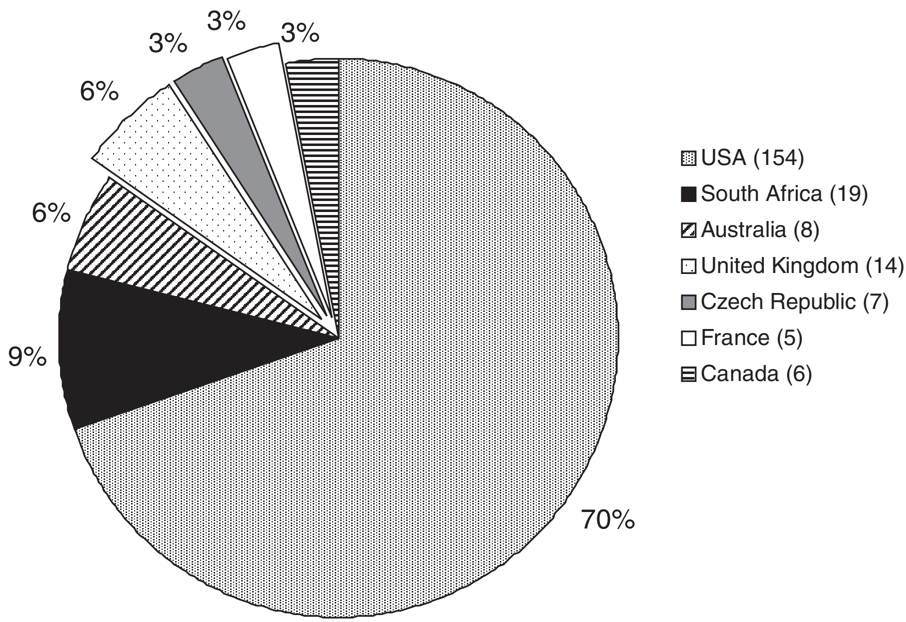

Fig. 7. – Geographical distribution of the countries of affiliation of authors of the best-cited papers in invasion ecology. Based on 33 authors who contributed with at least five papers to the 329 analysed in the present study. Numbers in brackets after the names of regions indicate the number of papers contributed by the respective researchers.

ceived as a problem in different parts of the world. It certainly reflects differences in the amount of funding allocated to research in invasion ecology as well as factors affecting citation frequency in science in general (Leimu & Koricheva 2005).

Souhrn

Práce analyzuje citovanost článků věnovaných invazní ekologii, publikovaných v letech 1981–2003, jež byly v srpnu 2006 alespoň 30× citovány na Web of Science (celkem 329 článků, které dohromady obdržely 27 240 citací). Pro každý článek byl zaznamenán celkový počet citací a roční citovanost (průměrný počet citací za rok od doby publikace). Články byly rozděleny podle tématiky na rostlinné invaze, živočišné invaze, biologickou kontrolu a obecné (review věnovaná obecným problémům invazní ekologie). Osm článků bylo citováno více než 300×, průměrně obdržel článek 82,8±73,1 citací. Průměrná roční citovanost je 11,5±11,3, šest převážně obecných článků je citováno alespoň 50× za rok. Více než polovina prací (50,8%) je věnována rostlinným invazím. Obecné články jsou průkazně více citovány než ostatní práce. Roční citovanost v čase průkazně lineárně stoupá o 1,0 citace/rok. Nárůst roční citovanosti v invazní ekologii je rychlejší než v populační ekologii a dynamice, není však exponenciální jako v pracích věnovaných globálním změnám. Nejcitovanější články v invazní ekologii jsou publikovány ve většině špičkových ekologických časopisů, v některých (Oikos, Journal of Ecology, Ecological Applications, BioScience) jsou citovány 3,8–5,8 × více, než je průměr pro dané časopisy, vyjádřený impakt faktorem. Nejvíce citací získávají články zabývající se vztahem invazí k biodiversitě, ekologii společenstev, populační ekologii, kompetici a zdrojům, dále pak genetickými tématy, invazibilitou a rozšiřováním invazních druhů. Použijeme-li však jako měřítko roční citovanost, nejatraktivnějšími tématy jsou důsledky globálních změn, evoluční aspekty, zákonitosti invazního procesu, invazibilita společenstev a vliv invazí na ekosystémové procesy. Některá témata jsou více citována, než by odpovídalo intenzitě jejich studia, a vice versa. Studium rostlinných a živočišných invazí se liší v tématech, kterým se oba obory intenzivněji věnují; invazibilita, biodiverzita, význam zdrojů,

vlastnosti invazních druhů a populační genetika jsou zdůrazňovány v botanických studiích, rozšiřování, kompetice, impakt a způsoby zavlékání v zoologických. Většina nejcitovanějších prací se zabývá druhovými soubory, pouze 14 rostlinných druhů je předmětem studia článků s více než 50 citacemi. Pouze 22 autorů (4,5 % z celkového počtu podílejících se na 329 analyzovaných článcích) je zastoupeno 7 a více alespoň 30 × citovanými články; dohromady se tito autoři spolupodíkejí na 49,4 % z celkového počtu prací, které získaly 55,6 % z celkového počtu citací.

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Appendix 1. – The most cited papers on biological invasions (those that were published up to 2003 and attracted at least 50 citations). Fields (F): a – animal invasions, c – biological control, g – general papers and reviews, p – plant invasions. Total number of citations as recorded using Web of Science (accessed 9 August 2006) and annual citation rate (number of citations per year) is shown. Papers are ranked according to the decreasing total number of citations and by the decreasing year of publications for the same number of citations. Only the first three authors are indicated in multi-authored papers.

No	F	Author	Year	Title	Total citations	Annual citation rate
1	g	Mack R.N., Simberloff D., Lonsdale W.M. et al.	2000	Biotic invasions: causes, epidemiology, global consequences, and control. Ecol. Appl. 10: 689–710.	493	89.6
2	p	D'Antonio C.M. & Vitousek P.M.	1992	Biological invasions by exotic grasses, the grass fire cycle, and global change. Ann. Rev. Ecol. Syst. 23: 63–87.	412	30.5
3	a	Carlton J.T. & Geller J.B.	1993	Ecological roulette: the global transport of nonindigenous marine organisms. Science 261: 78–82.	407	32.6
4	g	Lodge D.M.	1993	Biological invasions: lessons for ecology. Trends Ecol. Evolut. 8: 133–137.	403	32.2
5	g	Hobbs R.J. & Huenneke L.	1992	Disturbance, diversity, and invasion: implications for conservation. Conserv. Biol. 6: 324–337.	374	27.7
6	g	Pimentel D., Lach L., Zuniga R. et al.	2000	Environmental and economic costs of nonindigenous species in the United States. Bioscience 50: 53–65.	357	64.9
7	p	Tilman D.	1997	Community invasibility, recruitment limitation, and grassland biodiversity. Ecology 78: 81–92.	347	40.8
8	g	Vitousek P.M., D'Antonio C.M., Loope L.L. et al.	1996	Biological invasions as global environmental change. Amer. Scient. 84: 468–478.	313	32.9
9	p	Vitousek P.M. & Walker L.R.	1989	Biological invasion by *Myrica faya* in Hawaii: plant demography, nitrogen fixation, ecosystem effects. Ecol. Monogr. 59: 247–265.	291	17.6
10	p	Tilman D.	1999	The ecological consequences of changes in biodiversity: A search for general principles. Ecology 80: 1455–1474.	290	44.6
11	p	Burke M.J.W. & Grime J.P.	1996	An experimental study of plant community invasibility. Ecology 77: 776–790.	284	29.9
12	p	Lonsdale W.M.	1999	Global patterns of plant invasions and the concept of invasibility. Ecology 80: 1522–1536.	283	43.5
13	g	Vitousek P.M.	1990	Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. Oikos 57: 7–13.	281	18.1
14	p	Rejmánek M. & Richardson D.M.	1996	What attributes make some plant species more invasive? Ecology 77: 1655–1661.	280	29.5
15	p	Stohlgren T.J., Binkley D., Chong G.W. et al.	1999	Exotic plant species invade hot spots of native plant diversity. Ecol. Monogr. 69: 25–46.	265	40.8
16	g	Kolar C.S. & Lodge D.M.	2001	Progress in invasion biology: predicting invaders. Trends Ecol. Evolut. 16: 199–204.	253	56.2
17	a	Mills E.L., Leach J.H., Carlton J.T. et al.	1993	Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 19: 1–54.	247	19.8
18	g	Sakai A.K., Allendorf F.W., Holt J.S. et al.	2001	The population biology of invasive species. Ann. Rev. Ecol. Syst. 32: 305–332.	246	54.7
19	p	Davis M.A., Grime J.P. & Thompson K.	2000	Fluctuating resources in plant communities: a general theory of invasibility. J. Ecol. 88: 528–534.	238	43.3
20	c	Howarth F.G.	1991	Environmental impacts of classical biological control. Ann. Rev. Entomol. 36: 485–509.	230	15.9
21	g	Levine J.M. & D'Antonio C.M.	1999	Elton revisited: a review of evidence linking diversity and invasibility. Oikos 87: 15–26.	225	34.6

22	p	Mack R.N.	1981	Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agroecosystems 7: 145–165.	221	9.0
23	p	Vitousek P.M., Walker L.R., Whiteaker L.D. et al.	1987	Biological invasion by *Myrica faya* alters ecosystem development in Hawai'i. Science 238: 802–804.	214	11.6
24	a	Carlton J.T.	1985	Trans-oceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceanogr. Marine Biol. 23: 313–371.	212	10.3
25	p	Huenneke L.F., Hamburg S. P., Koide R. et al.	1990	Effects of soil resources on plant invasion and community structure in Californian serpentine grassland. Ecology 71: 478–491.	205	13.2
26	g	Parker I.M., Simberloff D., Lonsdale W.M. et al.	1999	Impact: toward a framework for understanding the ecological effects of invaders. Biol. Invas. 1:3–19.	203	31.2
27	g	Levine J.M.	2000	Species diversity and biological invasions: relating local process to community pattern. Science 288: 852–854.	192	34.9
28	c	Simberloff D. & Stiling P.	1996	How risky is biological control? Ecology 77: 1965–1974.	190	20.0
29	a	Cohen A.N. & Carlton J.T.	1998	Accelerating invasion rate in a highly invaded estuary. Science 279: 555–558.	186	24.8
30	p	Keane R.M. & Crawley M.J.	2002	Exotic plant invasions and the enemy release hypothesis. Trends Ecol. Evolut. 17: 164–170.	184	52.6
31	p	Richardson D.M., Pyšek P., Rejmánek M. et al.	2000	Naturalization and invasion of alien plants: concepts and definitions. Diversity Distrib. 6: 93–107.	182	33.1
32	g	Shea K. & Chesson P.	2002	Community ecology theory as a framework for biological invasions. Trends Ecol. Evolut. 17: 170–176.	167	47.7
33	g	Williamson M. & Fitter A.	1996	The varying success of invaders. Ecology 77: 1661–1666.	165	17.4
34	p	Vitousek P.M., D'Antonio C.M., Loope L.L. et al.	1997	Introduced species: a significant component of human-caused global change. N. Z. J. Ecol. 21: 1–16.	164	19.3
35	g	Simberloff D. & Von Holle B.	1999	Positive interactions of nonindigenous species: invasional meltdown? Biol. Invas. 1: 21–32.	159	24.5
36	p	Callaway R.M. & Aschehoug E.T.	2000	Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science 290: 521–523.	156	28.4
37	p	Blossey B. & Nötzold R.	1995	Evolution of increased competitive ability in invasive nonindigenous plants: a hypothesis. J. Ecol. 83: 887–889.	154	14.7
38	p	Reichard S.H. & Hamilton C.W.	1997	Predicting invasions of woody plants introduced into North America. Conserv. Biol. 11: 193–203.	153	18.0
39	p	Crawley M.J., Hails R.S., Rees M. et al.	1993	Ecology of transgenic oilseed rape in natural habitats. Nature 363: 620-623.	148	11.8
40	a	Carlton J.T.	1989	Man's role in changing the face of the ocean: biological invasions and implications for conservation of near-shore environments. Conserv. Biol. 3: 265–273.	143	8.7
41	p	Ellstrand N.C. & Schierenbeck K.A.	2000	Hybridization as a stimulus for the evolution of invasiveness in plants? Proc. Nat. Acad. Sci. USA 97: 7043–7050.	142	25.8
42	c	Louda S.M., Kendall D., Connor J. et al.	1997	Ecological effects of an insect introduced for the biological control of weeds. Science 277: 1088–1090.	142	16.7
43	p	Abbott R.J.	1992	Plant invasions, interspecific hybridization and the evolution of new plant taxa. Trends Ecol. Evolut. 7: 401–405.	142	10.5
44	p	Moody M.E. & Mack R.N.	1988	Controlling the spread of plant invasions: the importance of nascent foci. J. Appl. Ecol. 25: 1009–1021.	142	8.1

45	p	Higgins S.I. & Richardson D.M.	1999	Predicting plant migration rates in a changing world: the role of long-distance dispersal. Amer. Natur. 153: 464–475.	141	21.7
46	p	Crawley M.J.	1986	The population biology of invaders. Phil. Trans. R. Soc.London B 314: 711–731.	140	7.2
47	p	Richardson D.M., Allsopp N., D'Antonio C.M. et al.	2000	Plant invasions: the role of mutualisms. Biol. Rev. 75: 65–93.	137	24.9
48	p	Dukes J.S. & Mooney H.A.	1999	Does global change increase the success of biological invaders? Trends Ecol. Evolut. 14: 135–139.	130	20.0
49	p	Knops J.M.H., Tilman D., Haddad N.M. et al.	1999	Effects of plant species richness on invasion dynamics, disease outbreaks, insect abundances and diversity. Ecol. Let. 2: 286–293.	126	19.4
50	p	Mitchell C.E. & Power A.G.	2003	Release of invasive plants from fungal and viral pathogens. Nature 421: 625–627.	125	50.0
51	p	Planty-Tabacchi A., Tabacchi E., Naiman R. J. et al.	1996	Invasibility of species-rich communities in riparian zones. Conserv. Biol. 10: 598–607.	124	13.1
52	p	Brothers T.S. & Spingarn A.	1992	Forest fragmentation and alien plant invasion of Central Indiana old-growth forests. Conserv. Biol. 6: 91–100	124	9.2
53	a	Ricciardi A. & MacIsaac H.J.	2000	Recent mass invasion of the North American Great Lakes by Ponto-Caspian species. Trends Ecol. Evolut. 15: 62–65.	123	22.4
54	a	Lee C.E.	2002	Evolutionary genetics of invasive species. Trends Ecol. Evolut. 17: 386–391.	122	34.9
55	a	Tsutsui N.D., Suarez A.V., Holway D. A. & Case T.J.	2000	Reduced genetic variation and the success of an invasive species. Proc. Nat. Acad. Sci. USA 97: 5948–5953.	121	22.0
56	a	Case T.J.	1990	Invasion resistance arises in strongly interacting species-rich model competition communities. Proc. Nat. Acad. Sci. USA 87: 9610–9614.	120	7.7
57	p	Mack R.N. & Pyke D.A.	1983	The demography of *Bromus tectorum*: variation in time and space. J. Ecol. 71: 69–93.	119	5.3
58	p	Naeem S., Knops J.M.H., Tilman D. et al.	2000	Plant diversity increases resistance to invasion in the absence of covarying extrinsic factors. Oikos 91: 97–108.	116	21.1
59	p	Mack R.N.	1996	Predicting the identity and fate of plant invaders: emergent and emerging approaches. Biol. Conserv. 78: 107–121.	115	12.1
60	a	Suarez A.V., Bolger D.T. & Case T.J.	1998	Effects of fragmentation and invasion on native ant communities in coastal southern California. Ecology 79: 2041–2056.	114	15.2
61	p	Klironomos J.N.	2002	Feedback with soil biota contributes to plant rarity and invasiveness in communities. Nature 417: 67–70.	113	32.3
62	a	Williamson M.	1999	Invasions. Ecography 22: 5–12.	113	17.4
63	a	Holway D. A.	1999	Competitive mechanisms underlying the displacement of native ants by the invasive Argentine ant. Ecology 80: 238–251.	112	17.2
64	a	Moyle P.B. & Light T.	1996	Biological invasions of fresh water: empirical rules and assembly theory. Biol. Conserv. 78: 149–161.	111	11.7
65	p	Kennedy T.A., Naeem S., Howe K.M. et al.	2002	Biodiversity as a barrier to ecological invasion. Nature 417: 636–638.	108	30.9
66	a	Ruiz G.M., Fofonoff P.W., Carlton J.T. et al.	2000	Invasion of coastal marine communities in North America: Apparent patterns, processes, and biases. Ann. Rev. Ecol. Syst. 31: 481–531.	107	19.5
67	a	Carlton J.T.	1996	Pattern, process, and prediction in marine invasion ecology. Biol. Conserv. 78: 97–106.	107	11.3
68	p	Hobbs R.J. & Humphries S.E.	1995	An integrated approach to the ecology and management of plant invasions. Conserv. Biol. 9: 761–770.	103	9.8
69	a	Stachowicz J.J., Whitlatch R.B. & Osman R.W.	1999	Species diversity and invasion resistance in a marine ecosystem. Science 286: 1577–1579.	102	15.7

70	p	Rejmánek M.	1996	A theory of seed plant invasiveness: The first sketch. Biol. Conserv. 78: 171–181.	102	10.7
71	a	Torchin M.E., Lafferty K.D. Dobson A.P. et al.	2003	Introduced species and their missing parasites. Nature 421: 628–630.	101	40.4
72	p	Mack M.C. & D'Antonio C.M.	1998	Impacts of biological invasions on disturbance regimes. Trends Ecol. Evolut. 13: 195–198.	101	13.5
73	c	McFadyen R.E.C.	1998	Biological control of weeds. Ann. Rev. Entomol. 43: 369–393	100	13.3
74	p	Johnstone I.M.	1986	Classification of invasion potential plant invasion windows: a time-based classification of invasion potential. Biol. Rev. Cambridge Phil. Soc. 61: 369–394.	100	5.1
75	a	Ruiz G.M., Carlton J.T., Grosholz E.D. et al.	1997	Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. Amer. Zool. 37: 621–632.	99	11.6
76	a	Lodge D.M. & Lorman J.G.	1987	Reductions in submersed macrophyte biomass and species richness by the crayfish *Orconectes rusticus*. Can. J. Fish. Aquat. Sci. 44: 591–597.	99	5.4
77	a	Carlton J.T., Thompson J.K., Schemel L.E. et al.	1990	Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*.1. Introduction and dispersal. Marine Ecol. – Progr. Ser. 66: 81-94.	98	6.3
78	g	Mooney H.A. & Cleland E.E.	2001	The evolutionary impact of invasive species. Proc. Nat. Acad. Sci. USA 98: 5446–5451.	96	21.3
79	a	Ricciardi A. & Rasmussen J.B.	1998	Predicting the identity and impact of future biological invaders: a priority for aquatic resource management. Can. J. Fish. Aquat. Sci. 55: 1759–1765.	94	12.5
80	a	Moyle P.B. & Light T.	1996	Fish invasions in California: do abiotic factors determine success? Ecology 77: 1666–1670.	94	9.9
81	p	D'Antonio C.M.	1993	Mechanisms controlling invasion of coastal plant communities by the alien succulent *Carpobrotus edulis*. Ecology 74: 83–95.	94	7.5
82	a	Cole F.R., Medeiros A.C., Loope L.L. et al.	1992	Effects of the Argentine ant on arthropod fauna of Hawaiian high-elevation shrubland. Ecology 73: 1313–1322.	94	7.0
83	c	Hopper K.R., Roush R.T. & Powell W.	1993	Management of genetics of biological-control introductions. Ann. Rev. Entomol. 38: 27–51.	93	7.4
84	p	Brown J.R. & Archer S.	1989	Woody plant invasion of grasslands: establishment of honey mesquite (*Prosopis glandulosa* var *glandulosa*) on sites differing in herbaceous biomass and grazing history. Oecologia 80: 19–26.	93	5.6
85	p	Bais H.P., Vepachedu R., Gilroy S. et al.	2003	Allelopathy and exotic plant invasion: from molecules and genes to species interactions. Science 301: 1377–1380.	92	36.8
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87	p	Jackson R.B., Banner J.L., Jobbagy E.G. et al.	2002	Ecosystem carbon loss with woody plant invasion of grasslands. Nature 418: 623–626.	90	25.7
88	p	Malecki R.A., Blossey B., Hight S.D. et al.	1993	Biological control of purple loosestrife. Bioscience 43: 680–686.	90	7.2
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94	g	Stebbins G.L.	1985	Polyploidy, hybridization and the invasion of new habitats. Ann Missouri Bot. Garden 72: 824–832.	85	4.1
95	a	Holway D.A., Lach L., Suarez A.V. et al.	2002	The causes and consequences of ant invasions. Ann. Rev. Ecol. Syst. 33: 181–233.	84	24.0
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98	g	Ruesink J.L., Parker I.M., Groom M.J. et al.	1995	Reducing the risks of nonindigenous species introductions: guilty until proven innocent. Bioscience 45: 465–477.	82	7.8
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102	a	Olsen T.M., Lodge D.M., Capelli G.M. et al.	1991	Mechanisms of impact of an introduced crayfish (*Orconectes rusticus*) on littoral congeners, snails, and macrophytes. Can. J. Fish. Aquat. Sci. 48: 1853–1861.	77	5.3
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104	g	Usher M.B.	1988	Biological invasions of nature reserves: a search for generalizations. Biol. Conserv. 44: 119–135.	76	4.3
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106	a	Veltman C.J., Nee S. & Crawley M.J.	1996	Correlates of introduction success in exotic New Zealand birds. Amer. Natur. 147: 542–557.	75	7.9
107	c	Louda S.M., Pemberton R.W., Johnson M.T. et al.	2003	Nontarget effects: the Achilles' heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Ann. Rev. Entomol. 48: 365–396.	74	29.6
108	p	Ridenour W.M. & Callaway R.M.	2001	The relative importance of allelopathy in interference: the effects of an invasive weed on a native bunchgrass. Oecologia 126: 444–450.	73	16.2
109	c	Hopper K.R. & Roush R.T.	1993	Mate finding, dispersal, number released, and the success of biological control introductions. Ecol. Entomol. 18: 321–331.	73	5.8
110	p	Galatowitsch S.M, Anderson N.O. & Ascher P.D.	1999	Invasiveness in wetland plants in temperate North America. Wetlands 19: 733–755.	72	11.1
111	g	Chown S.L., Gremmen N.J.M. & Gaston K.J.	1998	Ecological biogeography of southern ocean islands: species-area relationships, human impacts, and conservation. Amer. Natur. 152: 562–575.	72	9.6

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122 a	Myers J.H., Simberloff D., Kuris A.M. & Carey J.R.	2000	Eradication revisited: dealing with exotic species. Trends Ecol. Evolut. 15: 316–320.	67	12.2
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138 p	Levine J.M., Vilà M., D'Antonio C.M. et al.	2003	Mechanisms underlying the impacts of exotic plant invasions. Proc. R. Soc London B 270: 775–781.	63	25.2
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158 a	Petren K. & Case T.J.	1996	An experimental demonstration of exploitation competition in an ongoing invasion. Ecology 77: 118–132.	59	6.2
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