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Characterizing a scientific elite (B): publication and citation patterns of the most highly cited scientists in environmental science and ecology

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Abstract Science is principally driven by the efforts of a vanishingly small fraction of researchers publishing the majority of scientific research and garnering the majority of citations. Despite this well-established trend, knowledge of exactly how many articles these researchers publish, how highly they are cited, and how they achieved their distinctive accomplishments is meager. This article examines the publication and citation patterns of the world's most highly cited environmental scientists and ecologists, inquiring into their levels of scientific productivity and visibility, examining relationships between scientific productivity and quality within their research programs, and considering how different publication strategies contribute to these distinctive successes. Generally speaking, highly cited researchers are also highly productive, publishing on average well over 100 articles each. Furthermore, articles published by this group are more highly cited on average than articles published in premier generalist journal like *Nature* and *Science*, and their citation to publication ratios are more equitably distributed than is typical. Research specialization and primacy of authorship are important determinants of citation frequency, while geographic differences and collaborative propensity matter less. The article closes with a set of suggestions for those wishing to increase the use of their research by the scientific community.

Keywords Citations · Scientific elite · Scientific productivity · Collaboration · Ecology · Environmental science · Specialization

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Introduction

Background

Bibliometricians have long appreciated the vast inequalities characteristic of the professional production of scientific knowledge. Formative attempts to uncover the structure of the scientific community vis-à-vis its publications revealed massive discontinuities in both scientific productivity and the allocation of scientific recognition via referenced citations (Lotka 1926; Dennis 1955; Price 1963). The conformation of scientific productivity and recognition to such power-law distributions remains among the best tested findings in science studies—a consistent reminder that science is principally driven by the efforts of a vanishingly small fraction of researchers. Despite this established trend, our knowledge of these researchers and how they attain their productivity and visibility is scant. We recently addressed this lacuna to some extent by analyzing the social characteristics of the world's most highly cited environmental scientists and ecologists (Parker et al. 2010a). Here, we turn our attention to their publication practices, asking the following questions: (1) How productive and highly cited are these researchers? (2) What is the relationship between scientific productivity and quality within their research programs? (3) How do different research strategies and publication practices contribute to these distinctive scientific accomplishments? Examining these questions enhances our understanding of the social mechanisms structuring stratification in scientific communities, the publication practices which result in highly cited research, and where we as individual researchers stand within the overarching edifice of science.

Garfield's (1981) seminal study was the first attempt to systematically examine the world's most highly cited scientists, but in the interim between that work and today research on this topic has been rare. Citations are imperfect indicators of scientific quality (MacRoberts and MacRoberts 1986, 1996; Warner 2000) but are among the most used metrics of scientific impact, correlating positively with other forms of scientific recognition (Cole and Cole 1973; Garfield 1973, 1984, 1992). Moreover, though citations are allocated for reasons other than quality this is unlikely to be the case for citation elites. Comprising the 0.1 % highly cited researchers in their fields, their impact on their disciplines is immense irrespective of the quality of any particular publication. Highly cited scientists tend be male, middle aged, from North American and Western Europe (Garfield 1981; Batty 2003; Basu 2006; Trifunac 2006). Little else is known beyond these gross generalizations. The first detailed, field-specific study found that the most highly cited environmental scientists and ecologists globally share this general demographic profile (Parker et al. 2010a). They also tend to have high average funding levels and large laboratories, work about the same number of hours as their less-cited colleagues, spend slightly more time on service as compared to research, fare well in peer-review, drink more alcohol than does the average American, and are split in their opinion regarding whether citations accurately reflect publication quality (*ibid*). Here, we turn our attention to an as yet unexplored aspect of highly cited researchers—their publication practices, citation patterns, their interrelationships and the social attributes with which they are associated. The following section employs findings from research on highly cited researchers, collaboration and scientific productivity to develop predictions about the publication practices and citation patterns of highly cited researchers. The second section outlines our data and methods. Our results follow. The article closes with a discussion of our findings and their implications in light of the current state of research.

Predictions

Productivity and citedness

Overall productivity and citedness Highly cited scientists also tend to be highly productive (Basu 2006). These individuals should thus be both highly productive and well-cited. Given the kurtosis of science in general, however, both productivity and citedness should also be highly variable within this population (Price 1963; Cole and Cole 1973, Seglen 1992). *Citations per paper* Beyond sheer productivity and citedness, what relationship exists between publication quantity and quality? We expect large differences in their citations per paper, but also that their research receives numbers of citations on par with articles published in leading journals. *Eureka!* Is highly cited status achieved by producing a few 'break out' publications or by consistently producing highly cited research? Citations are skewed within disciplines, journals, and individual research programs, and tend to approximate the '20/80' phenomenon, wherein 20 % of articles account for 80 % of citations (Seglen 1992; Nicolaisen and Hjørland 2007; Garfield 2006). Highly cited researchers, however, often remain so for extended periods.[1] We anticipate that the ratio of citations to publications will be less extreme than typical.

Journal character and specialization

Premier journals In biology, highest order accomplishments are often published in premier journals such as *Nature* and *Science*. Publication in such venues garners more attention and hence more citations (Callaham et al. 2002; Leimu and Koricheva 2005a; Fu and Aliferis 2008). Given this relationship, we expect these scientists to have published in these venues, and their *Nature* and *Science* articles are more highly cited than are their average publication. *Specialization* Citations are based in part on productivity, and productivity in part on pursuing specialized research programs (Leahey 2006, 2007; Leahey et al. 2008). Using the relative breadth of journals in which these authors publish as a proxy measure of specialization, we assume that specialists (those publishing in a relatively narrow suite of journals) will be significantly more highly cited than generalists. *Best fit* Applying the same reasoning, we expect most authors have a 'best fit' journal—a preferentially favored journal publishing a disproportional number of their articles. We further expect that articles published in this journal will be more highly cited than average.

Authorship effects

Collaboration Team research is a characteristic aspect of the life sciences (Parker et al. 2010b). Consequently, we assume most articles produced by these researchers will be multi-authored. Multi-authored publications tend to receive more citations (Asknes 2003; Nemeth and Goncalo 2005; Walters 2006; Kostoff 2007; Lokker et al. 2008; Hyett and Parker 2009)—a relationship confirmed for ecology (Leimu and Korcheva 2005a, b; Borsuk et al. 2009; Padial et al. 2010). We therefore expect their collaborative papers to receive more citations than their single authored. Furthermore, we expect a significant, positive relationship between each researcher's total number of unique collaborators, and their total publications and total citations. *Matthew effect* Scientific reputations develop as

[1] Every one of the top ten most highly cited environmental scientists and ecologist from 1997 to 2007 was also one of the most highly cited scientists in these fields from 1981 to 1999 (Thompson Reutars 2009).

an accumulative social process wherein initial recognition yields increasing recognition over time (Merton 1968). Given the prestige of first-authorship in the environmental sciences and ecology, we suppose these researchers' first-authored papers will be cited more often than average.

Demographic effects

Age The only analysis of the age at which highly cited researchers produce their most highly cited work suggests such accomplishments occur before fifty (Garfield 1981). Scientists also tend to be most productive in early to middle career stages (Lehman 1953; Pelz and Andrews 1966; Cole 1979; Levin and Stephan 1991). This suggests that these authors will produce their most highly cited research between 10 and 20 years after beginning their research career.[2] *Geography* There are also reasons to expect geographic differences in citation patterns. Basu (2006) found substantial differences between nations when examining national scientific productivity relative to each country's total number of highly cited scientists. Based on that analysis and the geographic distribution of highly cited environmental scientists and ecologists (Parker et al. 2010a), we predict that highly cited researchers North America will accrue the most citations, followed by Western Europe, and all other nations.

In sum, we expect that these authors: (1) are both highly productive and highly cited, and that while variable their publication and citation patterns will be less extremely distributed than typical; (2) publish in top venues and these publications are cited more often, that specialists will be cited more often, and that papers published in 'best fit' journals will be cited more often; (3) that these authors collaborate on most articles, and that collaborative articles first-authored articles will be cited more often; (4) produce their highest-cited research in mid-career, and that North Americans and Western Europeans will be cited more often than scholars in other regions.

Data and methods

We identified the world's most 0.1 % most highly cited environmental scientists and ecologists using those researchers listed in the field of 'environmental science and ecology' at *Thompson Scientific's* ISIHighlyCited.com. *Thompson Scientific* identifies highly cited researchers by first considering all articles in their database in rolling, 20 year time intervals. Three periods have been analyzed (1981–1999; 1983–2002; 1984–2003). Each article in the dataset (all three periods) is then assigned to one of the 21 broad disciplinary categories. Individual records are then created for all authors on each article. An article with n number of authors will thus have n number of individually indexed names developed for it. Citations to each article from any other article in *Thompson Scientifics'* citation databases are then counted, and each author credited with the total number of citations. Thus, in the case of an article with three authors receiving 50 citations, each author will be credited 50 citations. Each author's citations are then summed across all articles in the research area, and individual researchers are ranked according to their total number of

[2] The age at which researchers receive their PhDs, enter the scientific work force and receive research funding has increased substantially in the past few decades (Goulden et al. 2009; Collins 2010). We therefore use 'academic age' (time since first publication) as an attempt to develop a general metric applicable across time.

citations. Beginning with the most highly cited researchers, *Thompson Scientific* editors use a variety of methods to confirm the publication and citation pattern for each highly cited author. Editors then work to contact each highly cited researcher and ask them to provide a copy of her/his *curriculum vitae* and related information for inclusion in ISIHighlyCited.com's database.

To collect data on the citation and publication patterns, we searched the *Scopus* database for the 350 Highly Cited® scientists in the area of environmental sciences and ecology as listed in ISIHighlyCited.com. *Scopus* was used because it facilitates more accurate searches by allowing authors to be identified by their full names rather than first initials and last name, allowing us to better avoid including homographs. We performed 350 searches using given names and surnames. In case of common names, we also made use of the institution provided by the Highly Cited database. For each author, we collected all the records reported in *Scopus*, together with the number of times each publication has been cited. The data was collected on May 7–8, 2009. Our search found all the authors for a grand total of 51,905 articles. We then assessed data quality and accuracy. First, we checked the source titles for all the publications: there were almost 4,000 source titles (journal names, proceedings etc.). Of these, some were clearly not pertinent to ecology and environmental sciences (e.g. journals of psychiatry, thorax surgery, children development etc.) and therefore probably wrongly attributed to the authors. Others were not international journals, but rather proceedings, conference papers and technical reports. These are sources that are typically difficult to access and therefore will be cited less than articles in journals. In order to eliminate the spurious data, we compiled a list of 1,692 titles of journals that were pertinent to ecology and environmental sciences. We then filtered out all the records for which the journal was not contained in this list of journals. This left 42,093 records (note that we removed more than 60 % of titles, but this led to the removal of <20 % of the records). We then removed all the authors with fewer than 25 publications (20 authors for whom the search was probably not successful) and those who published more than 15 articles a year (3 authors with common last names, probably representing multiple authors with the same name). This left 327 authors and 40,510 articles. All analyses subsequently reported used this processed subset of data.

Results

Productivity and citedness

Overall productivity and citedness Collectively, these 327 authors published 40,510 articles accruing almost 1.6 million citations from 1981 to 2003. Individual productivity and citedness varied considerably. Total publications per author ranged from 26 to 430, and total citations from 290 to 20,280 (Fig. 1a, b). Each author averaged 124 articles, but distributions were widely disbursed (1st quartile: 75, 3rd: 152). The same was true of citations, with individuals averaging 4,241 citations each, but with wide ranging values (1st quartile: 2,934, 3rd: 5,898). *Citations per article* Mean number of citations per article varied by author from 3.6 to 224. The group average is exceptionally high (43.8 citations/article), on par with articles published in top tier environmental science and ecology journals and substantially higher than prestigious generalist journals such as *Proceedings of the National Academy of Sciences* and *American Naturalist* (Thompson Reutars 2009). At the extreme, some authors receive double the citations per article than do articles published in *Nature* and *Science* (*Ibid.*) *Eureka!* We computed the proportion of each

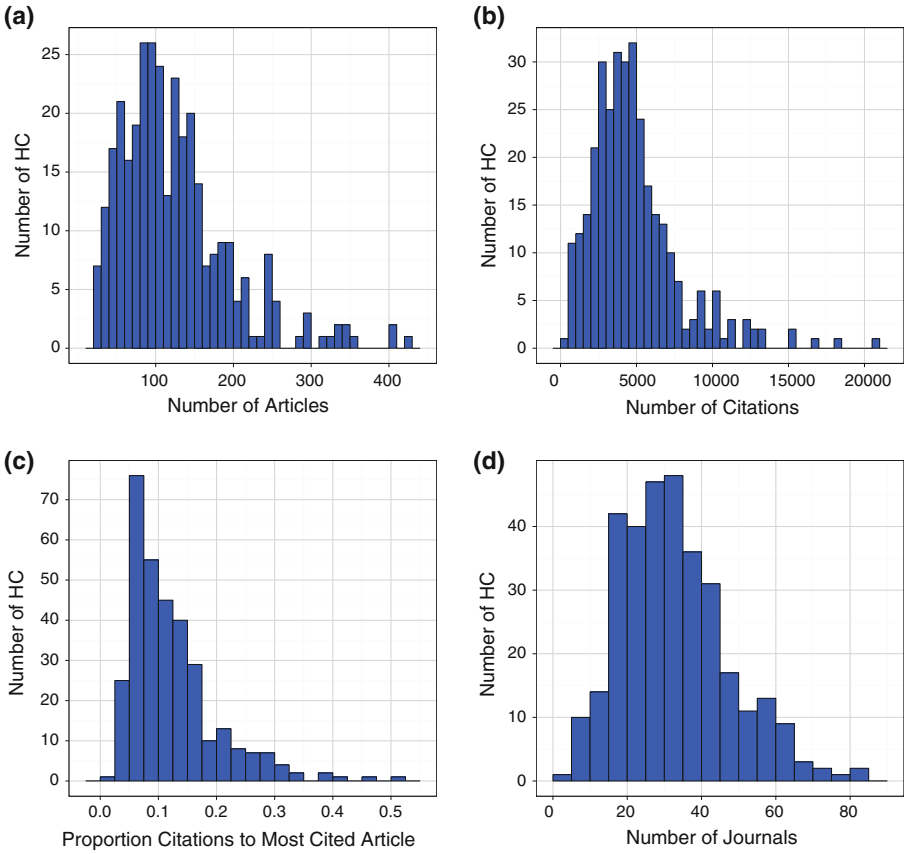

Fig. 1 Scientific productivity and citedness

author's citations accrued by their most cited article, and did the same for their top five and top ten most cited papers. On average, their most highly cited article received 559 citations (with a low of 56 and a high of 3,521). The average proportion of total citations accounted for by this article is 12.3 %, but ranges from 1.8 to 50.2 % (1st quartile: 6.6 %, 3rd: 15.2 %; Fig. 1c). On average, these author's five most highly cited articles account for more than a third of their total citations; their top ten account for almost half. The average ratio of citations to publications, however, was less extreme than typical—their top 20 % most cited articles account for 65 % of their citations.

Journal characteristics and specialization

Premier journals Every researcher published at least once in either *Nature* or *Science*; 94 published at least one item in each. The median number of publications was 3, the average 6.76, and the maximum 204. The difference between mean and median suggests that most authors publish a few papers in these journals, while a few publish many. This is exactly right: while the majority published 1–3 articles in these journals, the top ten authors account for more than 25 % of all *Nature* and *Science* articles published by this group; the top two *alone* account for 13 %. We next considered whether *Nature* and *Science* articles

accrued a disproportional number of citations relative to less prestigious venues by contrasting the proportion of papers each author published in these journals with the proportion of their total citations. For 46.1 % of authors, the proportion of citations is higher than the proportion of papers: the *Nature* and *Science* articles are cited more than the other articles by the same author. For twelve authors the ratio is 4 or more, meaning that their *Nature* and *Science* articles have been cited 4 (or more) times than expected at random. Surprisingly, for more than half of authors (53.9 %) their *Nature* and *Science* articles receive fewer citations than do their articles on average. *Best Fit* The average proportion of papers published in "favorite" journals (i.e. the one in which they have published most) was 24.4 % (1st quartile: 14.3 %, 3rd, 30.4 %. For most authors (59.6 %) papers published in this journal accrue more citations than expected at random (i.e., the average number of citations for articles published in this journal is higher than the author's average number of citations).[3] *Specialization* We measured specialization using as a proxy the number of journals in which each author published. The distribution of journals has a strong central tendency (mean 33.4), though a few publish in relatively low (<10, 6 authors) or high (>70, 5 authors) number of journals (Fig. 1d). The ratio number of articles/number of journals gives an idea of the publication diversity of each author, ranging from 1.45 to 12.59, with most authors included in the interval between 2.76 and 4.45 (median: 3.33, mean: 4.45). To test the effects of specialization on citedness, we regressed each author's total citations on their total number of journals. A significant, positive relationship exists between these variables ($R^2 = 0.263$; $p < 0.0001$). This is unsurprising given that publishing in more venues generates more potential citable items. We controlled for this by using a general linear model to compare authors with the highest and lowest levels of specialization.[4] Specialists accrue on average 27 % more citations per paper than non-specialists (GLM, Chi-square = 1,278, $p < 0.0001$).

Authorship effects

Collaboration Within this population, 91.2 % of articles were multi-authored. For most authors the proportion of sole-authored papers ranges between 2 % (1st quartile) and 12.2 % (3rd quartile; Fig. 2a), though four were sole-authors on more than half of their papers (maximum: 67.6 %). 11.7 % had no sole-authored papers. Sole-authored papers tend to be cited slightly more than expected at random (ratio proportion citation/proportion papers: median: 0.88, mean: 1.19; Fig. 2b), though this result is driven by a few researchers whose sole-authored papers are cited proportionally much more than their multi authored papers (maximum ratio: 12.34). In fact, differences in average citations between collaborative and sole-authored papers appear to be negligible. Significant positive relationships exist between total number of unique authors and (1) total number of articles ($R^2 = 0.55$; $p < 0.0001$), and (2) total citations ($R^2 = 0.41$; $p < 0.0001$). *Matthew effect* For most authors between 14.53 % (1st quartile) and 36.24 % (3rd quartile) of their articles are first-authored (mean 26.72 %; Fig. 2c). Two authors have no first-authored papers. At the opposite extreme, twenty-eight researchers have been listed as first-author on more than

[3] The set of 'best fit' journals comprises 84 titles, the most popular being *Environmental Science and Technology* (38 authors), *Ecology* (34) and *Oecologia* (25).

[4] i.e. those below and above the first and third quartiles in terms of numbers of journals in which they publish.

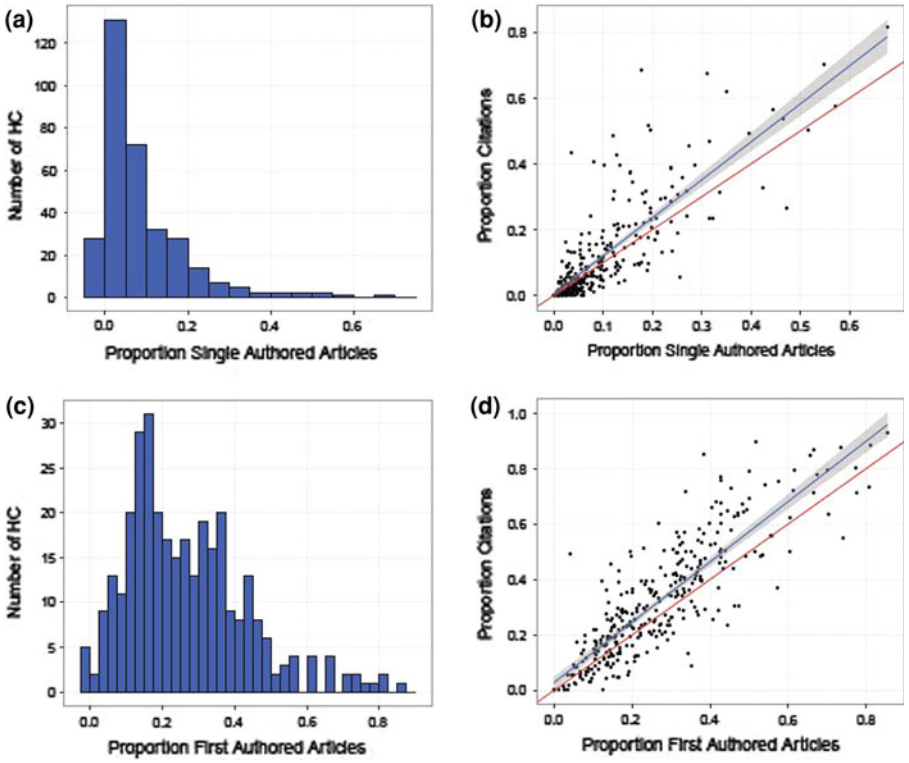

Fig. 2 Authorship patterns and citedness

50 % of their publications; one researcher exceeds 85 %. Contrasting the proportion of first-authored papers with the proportion of citations these papers received, for most researchers (66.45 %) first-authored papers were more highly cited than average (Fig. 2d). The ratio of proportion citations/proportion papers reached values of more than 1.4 (45 % more citations than expected at random) for one researcher in four.

Demographic effects

Age Scientific age (# years between first and most recent publication) spanned 15–55 years, with a mean of 32.53 (1st quartile: 28, 3rd: 36). The average scientific age at which a highly cited author published their most highly cited work is 16.93 years (1st quartile: 1, 3rd quartile 22), though this age ranges from 1 to 42 years. *Geography* Using a general linear model, determined that total citations did not differ significantly between North American, Western Europe and the rest of the world—neither did overall productivity. Western Europeans published significantly more papers per year than the other two regions (mean = 4.7 compared to 3.7 (N. America) and 3.5 (Other nations) $F = 4.3$; $p = > 0.014$). Those from other nations had a significantly higher proportion of first authored papers (0.38 compared to 0.27 (N. America) and 0.24 (W. Europe) $F = 6.5$; $p = > 0.0017$).

Discussion

This study examined the citation patterns and publication practices of the world's 0.01 % most highly cited environmental scientists and ecologists, testing several critical predictions derived from our most common assumptions about this scientific elite. It is the first study to quantify how many citations highly cited scientists accrue, relationships between scientific productivity and scientific quality, and how various research strategies and publication practices contribute to these outcomes. In brief, we found that this group is both highly productive and highly cited, and their citation to publication ratios are more equitably distributed than is typical. Research specialization contributes more to becoming highly cited than does publishing in premiere venues, while primacy in authorship order appears to matter more than collaboration. Highly cited researchers publish their most cited work mid-career, and geographic differences had little direct effect on citation patterns. Taken together, these findings have important implications for understanding social stratification in science and the social structure of the scientific community.

Given the lack of reliable information on the citation patterns generally, well-known inequities in their distribution across scientific populations, and the fact that few researchers publish most articles, it is difficult to say just how much more highly cited these researchers are than the average researcher in their field. Suffice it to say that even those highly cited researchers with values around the lower end of this distribution (i.e. 1st Quartile: 2,934 citations) have at least twenty times the average for an active researcher in this field, and probably more—this is obviously even more so the case in relation to the group average (i.e. 4,241). The same is true of their citations per article, the average value of which eclipses articles published in premier journals (Thompson Reutars 2009). Clearly, these researchers are very highly cited. They also tend to be highly productive, publishing large average numbers of papers. Still, some became highly cited by virtue of relatively few papers, indicating that in rare instances a few 'breakout' papers can allow entree into the ranks of the highly cited. The distribution of citations to papers was, however, less extreme than typical. Citation elites also tend to do a better job of balancing productivity and quality in their research programs.

Our findings were mixed regarding journal characteristics and specialization. As expected, every one of these authors published at least once in their discipline's premier journals; some have published dozens and even hundreds of times in these venues. Surprisingly, and contra our prediction and existing research (e.g. Leimu and Koricheva 2005a), items published in these venues did not receive appreciably more citations than did these authors' papers on average. The well-documented relationship between journal prestige and citations is not apparent within this population's research profile. More research is needed to determine if this is the case generally. Research specialization appears to be a more important determinant of citations. Authors did favor one or a few 'best fit journals' in which they publish a disproportional number of articles, and for most authors the articles published in these journals received more citations than average. Moreover, those publishing within a narrower suite of journals tend to accrue significantly more citations than those publishing more broadly. Taken together, these findings suggest the importance of publishing in germane rather than elite venues for having others use one's research. As relates to research visibility, it appears better to be a master of one or a few trades rather than jack of all, a finding supported by recent research in the sociology of science (Leahey 2006, 2007; Leahey et al. 2008).

Most articles published by this group are collaborative. Still, findings regarding collaboration were mixed. Collaborative papers did not receive appreciably more citations

than did sole-authored. This contravenes expectations and findings from a substantial body of research indicating that collaborative research tends to be more highly cited (e.g., Kostoff 2007; Lokker et al. 2008; Hyett and Parker 2009). At the same time, the predicted positive relationship between number of unique collaborators, total publications and total citations was supported. It may be that for this talented group including additional authors does not add significantly to the quality of the scientific work, and so does not garner more citations. Alternately, the positive relationships between collaborators, publications and citations may simply reflect greater numbers of publications and citable items. More work is required to parse apart these findings. In keeping with our predictions and models of scientific prestige as an accumulative process (e.g. Merton 1968), first-authored papers were more highly cited than average for the majority of authors. This complements and extends research indicating that articles including high profile authors tend to be more highly cited (Leimu et al. 2008).

Relationships between demographic characteristics and citation patterns were also surprising. We anticipated that these researchers would publish their more highly cited article between 10 and 20 years after their first publication. This was the case: on average, this group published their most highly cited papers between 10 and 20 years after their first publication. Though scientists now enter the research community at older ages, it appears to take about the same amount of time before they publish their most highly cited article. We found no significant geographic differences in terms of total citations or total productivity, but it is interesting to note that highly cited researchers outside of North American and Western Europe tend to first-author a greater proportion of their papers. This is likely due to the fact that these researchers are often nationally renowned scientists in countries with relatively small research communities, making it all the more likely that they will take leadership rolls on scientific research. Combined with our finding that first-authored papers tend to be more highly cited, this suggests that scientific cumulative advantage may accrue more rapidly among elite researchers working in smaller research communities.

Findings presented in this article also suggest some important principles for those wishing to improve the visibility and usage of their research. First, of all the factors analyzed in this paper variables related to research specialization were the best predictors of citations. As in other fields (Leahey 2006, 2007), a focused research program appears to be a more visible and highly cited research program. Second, collaboration may not matter as much as previously thought; the visibility associated first-authorship position may be more important for increasing the use of one's research by others. Third, the substantial time and effort required publish in high-profile venues may not be worth the effort in terms of how many people will use one's research. Authors would do better to focus on producing consistently high-quality research and publishing it in journals most salient to its subject matter. Finally, we would suggest that these findings be used with the aim of making one's research more readily available rather than for citations per se. Ultimately, researchers should focus on improving the state of knowledge in their fields rather than becoming highly cited.

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