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The law of limited excellence: publication productivity of Israel Prize laureates in the life and exact sciences

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Abstract The present paper extends Lotka's theorem—which we rename as "the law of limited excellence"—while empirically modelling the scientific productivity of 46 Israel Prize laureates in the life and exact sciences—a group best described as 'Star Scientists'. By focusing on this highly selective group we expose unequal scientific productivity even amongst Israel's most prolific scientists. Specifically, we test the invariance of Lotka's law by focusing attention on the extreme tail of publication distributions while empirically exploring the non-linearity of its seemingly "flat" tail. By exposing the rarity of excellence even in this extreme end of publication productivity we extend the generality of Lotka's theorem and expose that—like a fractal—the tail of excellence behaves as the entire distribution. We end this empirical contribution by suggesting a few implications for research and policy.

Keywords Scientific excellence · Israel Prize · Inequality in science · Lotka curve · Publication productivity

For whoever has will be given more, and they will have an abundance.
–Matthew 25:29

Lotka and the distribution of scientific productivity

In 1929 Alfred Lotka established a Pareto power law, explaining that scientists' productivity is spread unequally, with a minority of scientists responsible for the majority of scientific publications (Lotka 1929). His theorem described an inverse relationship

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between the number of scientists and the number of their publications. Lotka's curve appears in Fig. 1, indicating that in any group of scientists there is a minority of highly productive authors. For example, in a group of one hundred scientists the majority would have published one paper, compared with only one scientist publishing one hundred papers. Using a Darwinian logic, Lotka explained that scientific productivity—measured by the number of publications—resembles the fight for survival in nature. The scientific system, he said, is a tough competitive system with strict selection procedures. Consequently, only very few scientists make it to the top by publishing a large number of publications. Most young scientists are hence expected to publish one paper and disappear into non-recognition; while only few will publish a significant number of scientific papers and win exceptional scientific prizes for their outstanding productivity.

In this paper we refer to Lotka's theorem as "the law of limited excellence" while empirically modelling the scientific productivity of 46 Israel Prize laureates in the life and exact sciences—a group best described by Abramo's title of 'Star Scientists' (Abramo et al. 2009). By focusing on this highly selective group we extend the theorem of limited excellence and expose unequal scientific productivity even amongst Israel's most prolific scientists. Specifically, we test the invariance of Lotka's law by focusing attention on the extreme tail of Fig. 1 while empirically modelling its seemingly "flat" tail. By exposing the rarity of excellence even in this extreme end of publication productivity we extend the generality of Lotka's theorem and expose that—like a fractal—the tail of excellence behaves as the entire distribution.

The rarity of extreme productivity is often thought of in terms of statistical outliers (Gladwell 2008). The present study shows that even when sampling a group of outliers—i.e., Israel Prize Laureates—we still discern outliers amongst the outliers. Publication productivity even of Israeli star scientists follows Lotka's theorem, with very few scientists exhibiting truly exceptional levels of productivity. In discussing the substantive implications of this empirical demonstration we further contribute to discussions of the Matthew effect and intellectual innovation in the sociology of science and raise initial questions about funding policies for supporting excellence.

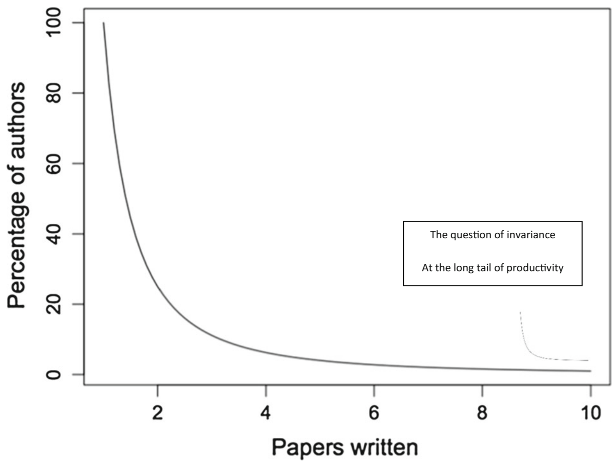

Fig. 1 Lotka's Theorem—invariance at the tail?

The law of limited excellence: bibliometric measures and sociological insights

Lotka's theorem about the rarity of extreme productivity was applied extensively. Specifically, a mathematician named Zipf argued that Lotka's law is also valid in linguistics (Zipf 1949). He showed that a small number of words appear in the literature at a high frequency, while a very large number of words appear at a low frequency. Similarly, Bradford claimed that the distribution of significant articles follows a nonlinear function too (Black 2004). Thus, if journal articles are arranged by a descending order of significance, their distribution is such that the most important articles are concentrated in a relatively small number of journals. Using Bradford's model, it was possible to identify a "core" of journals, which encompassed most of the significant articles in a given discipline.

Eugene Garfield (Garfield 1970, 1972, 2006, 2009), founder of the field of bibliometry and known for initiating the Web of Science, developed Bradford's insights further. Since the 1970s he analyzed citation patterns of thousands of journals, and determined that while there are approximately 10,000 journals—only 500 of them serve as the core of science. Specifically, most highly cited articles are published in a small number of leading journals; and only 15% of a journal's articles collate 50% of the its overall citations (Seglen 1992). On this basis, scholars developed tools for assessing the impact of scientific publications and extended the applicability of Lotka's insights.

As a rule, Lotka's, Zipf's, and Brandford's laws belong to the family of Pareto distributions—which are often described as the 20/80 approach—whereby 20% of scientists publish 80% of all journal articles (see review in Garfield 2009); or 20% of the journals holding 80% of the citations. Indeed, this family of measures received considerable applications in the study of science (Barabasi 2002). Derek de Sola Price provided a summary conclusion in his well-known book "Little Science, Big Science" (Price 1963), contending that there is a "natural law" of inequality in academia whereby highly prolific scientists are rare. He concluded that every scientific field is led by a small scientific elite, trailed by many researchers who publish few and infrequently cited papers (see further review of developments in this field in Haustein and Larivière 2015).

Sociologists of science Robert Merton and Jonathan Cole described a similar law they entitled the "Matthew Effect" (Merton 1968, 1973). Merton borrowed this metaphor from Christianity—stressing that one who was blessed once will be blessed again. According to their theory, young scientists which were awarded with their first scholarship or prize were thus signified to be bearers of exceptional talents—evolving in a self-fulfilling prophecy that ends up by widening minor initial gaps in publication productivity. In fact, mechanisms of prestige building lead to reduced competition in science, such that most of the resources are dedicated to a gradually diminishing few (Cole and Cole 1967, 1973; Cole and Singer 1991; Zuckerman 1991). This school has shown that small differences in productivity in the first stages of a scientific career are gradually widened as careers develop, since those marked as excelling at the beginning receive more scholarships, research grants, and invitations to serve as visiting scholars. This academic plenitude accelerates career trajectories of those marked early as excelling, while the rest of the scientists—who initially had almost similar productivity—begin to trail behind and even drop out of the competitive academic race. Merton and Cole's sociological theory supports Lotka's theorem while suggesting several mediating mechanisms for the inequitable distribution of scientific productivity (for early proof and explanation see Merton 1988; Price

1976). This theory of 'cumulative advantage' is often used to explain social inequality in science (see examples in Abramo et al. 2009; Yair 2008) and provides a theoretical answer for how small initial differences at the start of scientific careers end up with wide gaps as they culminate (Cole and Singer 1991; Keith et al. 2002).

Lotka's theorem and the Matthew Effect were corroborated by various investigations of scientific productivity on both an institutional and national level (Bentley and Kyvik 2013; Egghe 2005; Kwiek 2015; Kyvik 1989). For example, Mark Kwiek (2015) has recently shown that the law of limited excellence is valid with regard to the scientific productivity of European scientists. His study of 17,211 researchers working at research institutes and universities indicates that the most productive 10% published about 50% of all publications. According to Kwiek, the rarity of scientific productivity is true of most EU countries. In fact, the law of limited excellence is true of elite European institutions and for leading countries alike. In other words, star scientists are responsible for most publications while the majority of researchers generate a minority of this corpus. Science, concludes Kwiek, is an elitist affair across disciplines, institutes, and countries.

Further examinations of this database showed that differences in productivity are slightly reduced when the language of publication is taken into account (Bentley 2015). In countries with a market for non-English publications, such as the German publishing market, the differences between researchers diminish, as a significant part of the publications are in languages other than English. In a study published by Bentley and Kyvik two years earlier they even found that a significant predictor of the number of publications is researchers' motivation and the time they are willing to devote to research (Bentley and Kyvik 2013).

The more developed the study of Scientometrics becomes—Lotka's classical theorem remains bona fide, suggesting, indeed, that extreme productivity is rare, and that there are limits to scientific excellence. In the current study we provide an original test for the validity of the law of limited excellence. Instead of inspecting a general group of scientists, expected to contain within it a small group of more productive scientists, we analyze the productivity of the most celebrated group of Israel's scientists. We refer to 46 scientists who had been awarded the Israel Prize in the life and exact sciences. By analyzing their publication productivity we further validate the law of limited excellence while showing that even amongst the most outstanding scientists, it is possible to find productivity distributions that follow on Lotka's theorem. In other words, even at the far end of publication productivity—when selecting the very best star scientists—we empirically discern Lotka's curve, thereby providing further proof for its substantive invariance.

Context and method

Prior evidence indeed suggests that scientific excellence is a limited matter (Murray 2003). In most countries, the rewards granted to scientists are distinguished mainly on the basis of prestige, as scientists' salary is relatively equitable (Cole and Cole 1967, 1973). Scientific excellence is often awarded by important scientific prizes (Zheng and Liu 2015). The most prestigious ones are the *Nobel Prize* (Zuckerman 1996), the *Fields Medal* in mathematics, the *Balzan Prize*, and the *Holberg Prize*, awarded for academic achievements in the social sciences, as well as the *Kyoto Prize* and the *Wolf Prize*.

Similar to those international prizes, countries often award their star scientists with national awards. In Israel, the most prestigious is the *Israel Prize*, awarded annually as of

1953 in the fields of Jewish studies, social sciences and the humanities, life and exact sciences, culture and arts, and lifelong enterprise. The prize committee usually awards the prize for life's work. This is evident in the average age at time of awarding, namely 72 years. The prestige of the Israel Prize derives from its rarity and symbolic value, reflecting Israel's recognition of science as a worthy endeavor. During the six decades from 1953, the Ministry of Education has awarded 708 prizes.

Laureates are commonly believed to be a fairly homogeneous group. Some believe that while they outperform the vast majority of their less productive peers—they have similar, though rare, publication output. In order to study the publication productivity of Israel Prize recipients we focused on the fields in which publication lists are available and cover most scholarly publications. Specifically, we accessed the publication lists of 46 researchers in the life and exact sciences. This group of scientists is comprised by 14% women and 86% men, all particularly productive and outstanding researchers. After cleaning the data we imported the publications into CoolCite, a portal developed by the first author for managing academic information. We were thus able to assess several dimensions of the data, first and foremost scientific productivity.

In what follows we test the law of limited excellence in the extreme end of the distribution of publication productivity. Our analyses show that even in this select and seemingly homogeneous group of laureates it is still possible to differentiate between a group of four exceptionally productive scientists and the rest of the awardees, who published significantly less. Following Lotka's tradition, we conclude that even when selecting the very end of the distribution of publication productivity we can still point at a small group of laureates who publish outstanding numbers of publications, while the majority of Israel Prize recipients contribute less. Excellence—even when selecting the excellent—is rare.

Findings

Data for all prize categories—limited to university scholars—shows that researchers from the Hebrew University of Jerusalem comprised 48% of all prize recipients (Shanghai Rank 2016 = 87), followed by researchers from Tel Aviv University, who comprised 26% of the recipients (rank = 151–200). Researchers from the Weizmann Institute of Science received 9% of the Israel Prize awards (101–150), while researchers from Bar-Ilan University received 8% (not ranked). Finally, researchers from the Technion and Haifa University comprised 4% of the sample each (rank 69 and non-ranked respectively). At the bottom of the list are researchers from the youngest institution, Ben Gurion University, who received only 1% of the awards (401–500). Moreover, the Hebrew University of Jerusalem also leads the other institutes when limiting the sample of laureates to the exact and life sciences with 35% of the awardees, followed by the Weizmann institute with 28%.

Furthermore, inspection of awardees' Alma Mater shows that 81% of the laureates who got their PhD in Israel completed their studies at the Hebrew University of Jerusalem (77 out of 93). The Technion (6.5% of those who earned their PhD in Israel), Weizmann Institute of Science (6.5%), Tel Aviv University (5%), and Bar Ilan University (1%) follow at a large distance. Moreover, 58% of the researchers who received the Israel Prize earned their PhD in Israel, while 25% earned their PhD in the US. Researchers trained in the UK (9%), France (6%), and other countries (2%) are the minority. Figure 2 shows the prominence of researchers from the Hebrew University of Jerusalem among recipients of

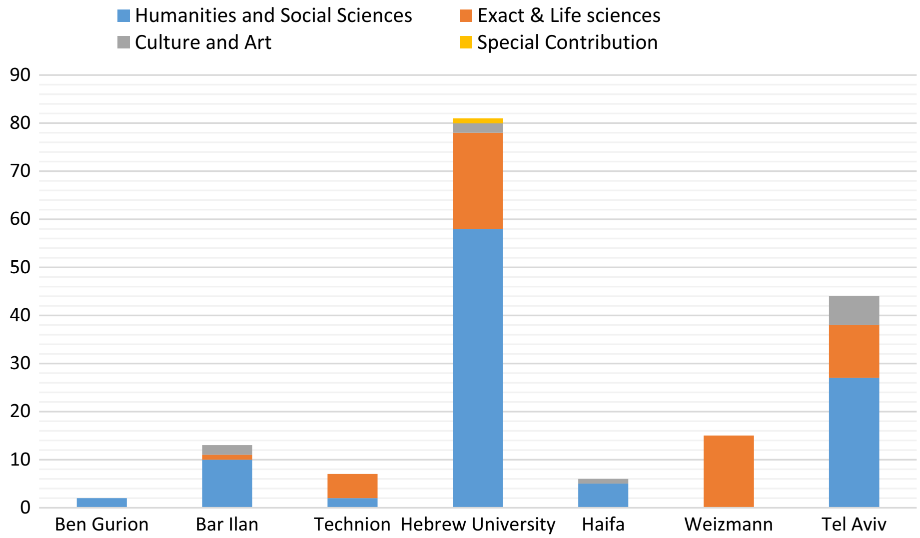

Fig. 2 Distribution of Israel Prize laureates by discipline and institution

the Israel Prize, even in the field of life and exact sciences. These findings reflect the concentration of scientific talent in elite universities in Israel (Yogev 2000).

As stated, the current study focuses on Israel Prize recipients in the life and exact sciences. The 46 prizes awarded in this field are divided among several disciplines. Medicine received most prizes, with ten recipients, followed by physics and chemistry with five recipients each, biology and engineering with four recipients, and mathematics, life sciences, computer sciences, and earth sciences with three recipients each. The combined discipline of physics and chemistry adds another two recipients, as well as the combined mathematics-computers discipline. Finally, one recipient from the field of statistics was awarded the prize. (For technical reasons we did not include agriculture in this study, although it belongs to this category and although seven researchers in this discipline were awarded the prize). It should be emphasized that three Israel Prize laureates later won the Nobel Prize. Others served as presidents of research institutes and the National Academy of Science. By any standard, indeed, they are truly the top Israeli scientists.

This is proved by the sheer magnitude of their productivity. The recipients published 6400 journal articles and chapters in some 600 journals and books, in addition to 126 books (with Springer as leading publisher) and 23 patents. The meaning of those figures is that each researcher published, on average, close to 140 articles and chapters, as well as three books and half a patent—an impressive number that meets all standards of academic excellence. It should be noted, though, that 78% of all publications were published with co-authors—as is typical for the exact and life sciences. This practice is said to support overall scientific productivity (Ductor 2015).

Table 1 presents the list of journals in which the group published the largest number of papers. It is evident that Israeli scientists who received the Israel Prize are "closely linked" to US academia, as nine of the ten journals they often publish in are in English. Only one journal, *Harefuah* (Medicine), is published in Hebrew. Moreover, the list shows that prize recipients manage to publish in top general scientific journals, i.e., *Nature, Science*, and the *Proceedings of the National Academy of Sciences of the United States of America* side by

Table 1 Most popular journal outlets of Israel Prize laureates

Name of journal	Number of papers	Number of laureates
Proceedings of the National Academy of Sciences of the United States of America	139	17
Journal of Symbolic Logic	138	1
Journal of the American Chemical Society	92	5
Physical Review B (Condensed Matter and Materials Physics)	91	4
Physical Review Letters	88	7
Nature	82	19
Annals of Pure and Applied Logic	81	2
Water Resources Research	73	1
Harefuah	55	5
Journal of Medical Sciences	50	2
Science	44	15

side with leading discipline-specific journals in mathematics, physics, and chemistry. As mentioned, 10 Prize recipients engage with medical research. Consequently, the list also includes many publications in leading journals on cancer research, such as *Cell* (four authors with 21 papers), *Cancer* (three authors with 20 papers) and *Blood* (four authors with 20 papers).

Moreover, examination of the average citation impact of the journals (by means of SCImago Journal Rank, SJR) indicates that the expected average annual number of citations is close to four citations per publication. This too shows the collective academic prowess of the group.

Figure 3 indicates that the number of annual publications rises with the years, and that co-authorship proportions remain more or less stable across the years, with only 20% of the publications published as single authors. This finding reflects two factors: The growing size of the awardee group, and the laureates' continued productive work even after retirement. Figure 3 also shows that in the last decade the overall annual number of publications by members of the group was over 200, averaging between four and five publications per researcher per year. Hence, however the data are inspected it seems that Israel Prize laureates in the life and exact sciences are indeed extraordinarily productive, publishing frequently and regularly throughout their lengthy career—mostly with peers and graduate students. If anyone had any doubts whether the Israel Prize was given to "dead wood"—those findings dispel them.

Before examining the law of limited excellence in our select group of Israel Prize laureates we first sought to test Lotka's theorem amongst five ordinary academic departments. Two departments were from Israeli academia (business administration and a program for outstanding scholars in the humanities), three from American universities ranked among the top ten institutions worldwide (sociology, economics and earth sciences). We included a variety of disciplines in order to examine the invariance of the law of limited excellence within different disciplines and institutions. These preliminary analyses have indeed shown that the distributions of scientific productivity were congruent with the law of limited excellence: In all five departments, a small group of researchers was found to

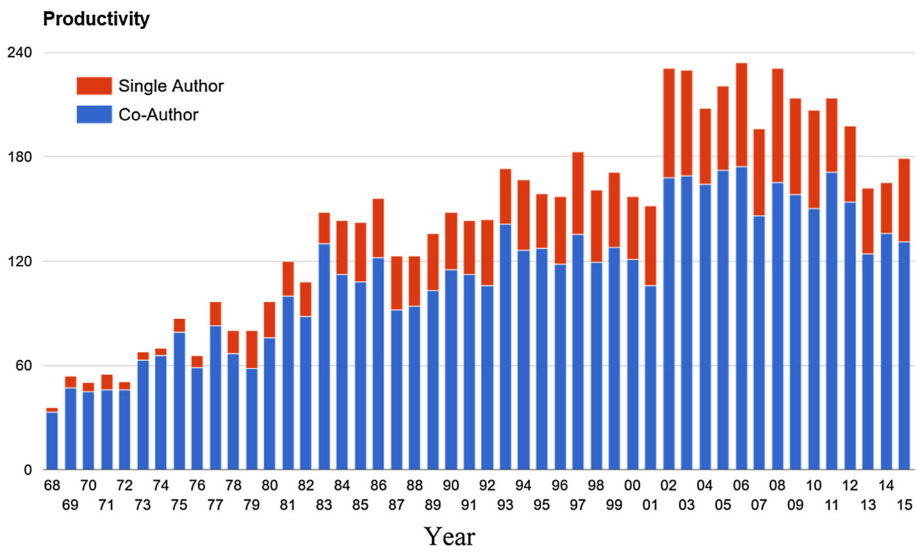

Fig. 3 Annual number of publications of Israel Prize recipients in the natural sciences and life sciences in the past fifty years

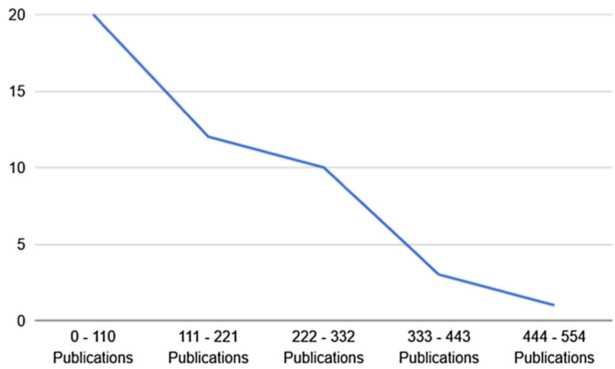

Fig. 4 Lotka's distribution of lifelong publication productivity of 46 Israel Prize laureates in the life and exact sciences

publish a high number of publications, while most members published significantly smaller quantities. Incidentally, the findings also showed that there are no large discrepancies between the five departments despite disciplinary differences. In all of them the number of publications ranged from less than ten per researcher to a large number of 100–200 publications per researcher. In this respect, those preliminary analyses showed that "regular" groups of researchers are indeed characterized by the law of limited excellence and that discipline makes little difference. Hence, Lotka's theorem is once more proved invariant, meaning that excellence is limited—in any institution, irrespective of discipline.

Notably, a comparison of the findings in Fig. 4 to the distributions in the five departments that served in the preliminary analyses shows that Israel Prize laureates indeed comprise an extraordinary exceptional group. While in the five departments the median number of publications of the less productive researchers was 10, in the case of Israel Prize laureates the median number of publications was 55, more than five times that of ordinary academics.

When examining the publication curve of the 46 Israel Prize laureates in the life and exact sciences we sought to examine whether Lotka's theorem remains invariant even when focusing on the academic "crème de la crème," namely those at the extreme end of publication productivity. As we have seen, this is undoubtedly an exceptionally productive group of researchers who were strictly selected, recommended, inspected, and received the unambiguous support of a prize committee. As we shall see, we found the law of limited excellence to be valid even in this limited cadre as well. In other words, even among this closely culled group—of whom all members are outstanding—a small number of individuals are found to outdo the rest of the outstanding researchers. Figures 4 and 5 provide various renditions for this conclusion, suggesting the distribution of excellence at the very top of Israeli science follows the same pattern as for a regular group of scientists, suggesting that a fractal description best fits this pattern (Abbott 2001; Gleick 1987).

Specifically, Fig. 4 presents the distribution of the group's overall number of publications over the years, while Fig. 5 presents four different time periods: the last decade, the last two decades, and the last three and four decades, respectively. Figures 4 and 5 are presented such that the Y axis describes the number of researchers in each productivity group, and the X axis portrays the average number of publications by that group. The figure makes it possible to empirically model the data with Lotka's theoretical curve (presented in Fig. 1) as a benchmark.

The findings presented in Fig. 4 show that the law of limited excellence is valid even within the homogeneous context of Israel Prize recipients. Those 46 star scientists are unequally productive in terms of number of publications—split into four subcategories. Figure 4 depicts two categories with four researchers whose publications are impressively

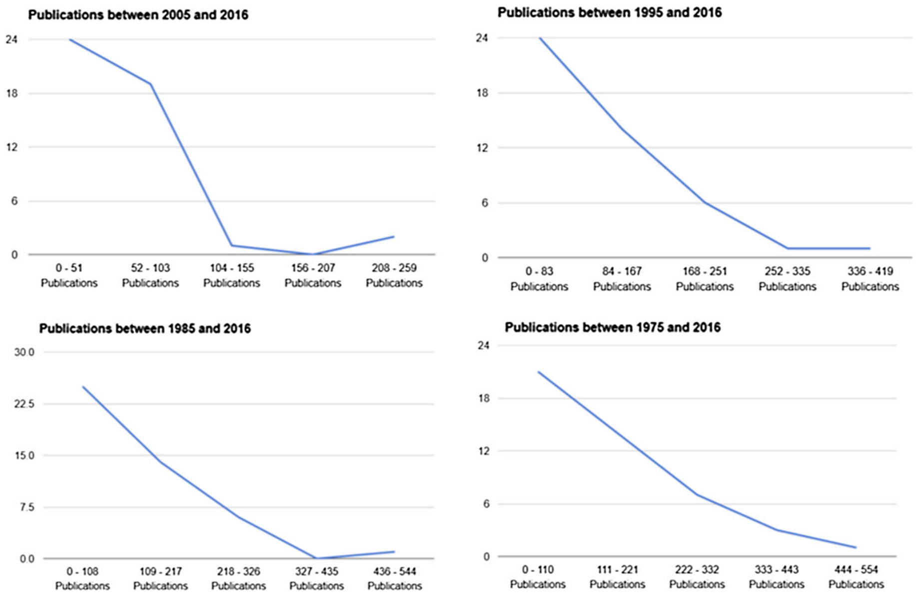

Fig. 5 Lotka's distribution of scientific productivity of the 46 recipients of the Israel Prize in the life sciences and exact sciences—divided by period

greater than those of other prize recipients. This tiny group consists of less than 10% of all prize recipients. These four researchers published a radical number of publications, up to five hundred each. Furthermore, even among those four laureates it is possible to discern a top and bottom: There is one top researcher with extreme levels of publication productivity, followed by a second category with three scholars. Thus, Fig. 4 confirms the theorem of limited excellence and shows that the productivity pyramid is topped by very few star scientists who out-publish their peers in the sample of Israel prize laureates in the life and exact sciences.

In any case, Fig. 4 shows that the Israeli academic world too is based on a power law of unequal excellence, or as we have designated it—the law of limited excellence. Although Israel Prize committees “handpick” the most outstanding researchers in the life and exact sciences, analysis of their achievements reveals an unequal distribution even in this “homogeneous” group, whereby the major part of the group is significantly less productive than a few star scientists. This supports Lotka’s theorem, namely that scientific excellence is unequally distributed. Only few scientists exhibit productivity levels that seem inhuman; and those few lead an outstanding elite, with the remaining academic masses, with a much more limited level of productivity, lingering far behind.

Finally, Fig. 5 shows that whatever period the analysis refers to—whether the last decade or the last four decades—Lotka’s curve of productivity distribution is maintained. The specific details change—i.e., the size of the group and the number of publications in each category—but the shape of the distribution is more or less invariant. The distribution of inequality in scientific productivity is maintained across time and group membership. The empirical data presented here provide a clear conclusion: Excellence—measured as publication productivity—is indeed limited.

Discussion: mechanisms and implications

The following discussion draws three short conclusions. It first advances the Matthew Effect and Cumulative Advantage theories by following on Lotka’s original Darwinian insight. Secondly, it puts a mirror in front of most scientists who accept institutional prerogatives for productivity (‘write two papers a year’) as an infrastructure underlying false perceptions of equal productivity. Lastly, building on the former argument, we shall question current funding schemes for supporting excellence in science.

First, in order to understand the rarity of excellence it is necessary to understand the competitive mechanisms which motivate productivity in science. It is here where the Matthew Effect has Darwinian rationale: The more publications authors publish—the more they have to surpass objections by reviewers and respond to critiques, necessitating creativity, integration, and analyses that might lead to innovative new research (Boyer 1990). According to Randall Collins, for example, every scientific or philosophical work is the product of intellectual struggles. Hence, the number of struggles should serve as a proxy for or a precursor to scientific excellence (Collins 1998; Kurzman and Owens 2002). Every published paper, implies Collins, energizes scholars to rise to the next challenge; coping with criticisms leads to further innovations. Therefore, the more researchers publish, the more criticism and competing ideas they must contend with.

We acknowledge that there are other variables associated with publication productivity (Aaltojarvi et al. 2008; Abramo and D’Angelo 2010; Burris 2004; Ductor 2015; Keith and Babchuk 1998; Lee and Bozeman 2005; Stack 2004; Toutkoushian et al. 2003; Yair 2008), and admit that our sample is limited—but we nonetheless seek to follow on Collins' theory of intellectual innovation and suggest that the findings above indicate that the large number of publications by Israeli star scientists had necessarily confronted them with a large number of challenges that required them to increasingly refine their ideas and publish more papers. By virtue of those academic struggles they turned their initial quantitative advantage into a growing gap of productivity—eventually becoming the rare beacons of excellence who merit national and international prizes. It is not that the rich become richer, as suggested by Merton, but rather that productive scientists grow ever more productive.

Secondly, the findings reported above raise doubts about productivity norms amongst the rank and file of academia. Specifically, many Israeli scientists assume that productivity norms are equal and—since budgets are allocated based on productivity—that everyone contributes equally to institutional budgets. Since equality is a major value in Israel, institutions rarely celebrate hierarchies of honor, nor do they glorify star scientists. Hence, faculty members feel that their productivity levels are relatively equal. Furthermore, lack of transparency prevents them from knowing how productive—or nonproductive—their colleagues are. The findings presented above contradict the common 'egalitarian' assumption by exposing the non-linear rarity of excellence. Hence, the contradiction between the law of limited excellence and the culture of egalitarianism challenges decision-makers to raise questions about transparency of publication productivity. Indeed, egalitarianism and lack of transparency allow many researchers to feel comfortable in Israeli academia, but it appears that this comfortable fraternity hides the real differences which separate scientists—even at the very top.

Finally, the law of limited excellence has significant implications for funding and pay policies too. The Ministry of Finance and the Planning and Budgeting Committee (PBC) allocate funding using a competitive scheme, with budgets provided in direct ratio to the number of papers published by faculty members (and to the sum grants they win, as well as the number of students in various degrees). Nevertheless, Israeli universities—under pressure of their faculty—adopt an egalitarian pay policy for all scientists, based on rank only. Hence, while the government utilizes a rule of limited excellence on an institutional level, the institutions block this policy by their internal practices. The law of limited excellence—and the empirical results supporting it—might provide scaffolds for new discussions of extant funding practices—raising questions about merit pay and meritocracy more generally (Yair 2007).

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