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Progress and perspectives in the discovery of polychaete worms (Annelida) of the world

Joko Pamungkas[1,2*], Christopher J. Glasby[3], Geoffrey B. Read[4], Simon P. Wilson[5] and Mark J. Costello[1]

Abstract

Despite the availability of well-documented data, a comprehensive review of the discovery progress of polychaete worms (Annelida) has never been done. In the present study, we reviewed available data in the World Register of Marine Species, and found that 11,456 valid species of Recent polychaetes (1417 genera, 85 families) have been named by 835 first authors since 1758. Over this period, three discovery phases of the fauna were identified. That is, the initial phase (from 1758 to mid-nineteenth century) where nearly 500 species were described by few taxonomists, the second phase (from the 1850's to mid-twentieth century) where almost 5000 species were largely described by some very productive taxonomists, and the third phase (from the 1950's to modern times) in which about 6000 species were described by the most taxonomists ever. Six polychaete families with the most species were Syllidae (993 species), Polynoidae (876 species), Nereididae (687 species), Spionidae (612 species), Terebellidae (607 species) and Serpulidae (576 species). The increase in the number of first authors through time indicated greater taxonomic effort. By contrast, there was a decline in the number of polychaete species described in proportion to the number of first authors since around mid-nineteenth century. This suggested that it has been getting more difficult to find new polychaete species. According to our modelling, we predict that 5200 more species will be discovered between now and the year 2100. The total number of polychaete species of the world by the end of this century is thus anticipated to be about 16,700 species.

Keywords: Biodiversity, Echiura, Marine, Polychaeta, Pogonophora, Species discovery rate, Taxonomy, Vestimentifera

Introduction

The taxonomic work underlying species discoveries lays the foundations for all subsequent biodiversity-based research. To know how many species exist provides valuable information about progress in the rate of discovery of life on Earth [1]. Moreover, species richness—the number of different species in an area—is one of the key metrics for estimating species diversity, which is the basis for many comparative ecological, biogeographic and conservation studies.

One useful method to estimate total species richness—or the number of species that will be discovered by a particular time—is by looking at species discovery rates [2]. Using this approach, Costello et al. [3] have predicted global species richness to be around 1.8 to 2.0 million species. Appeltans et al. [4], using a statistical model of past rates of species description, field observations of undescribed species, and over one hundred expert's assessments, estimated the number of marine species to be 0.5 ± 0.2 million. Their model could not be used for polychaetes alone, but their expert-opinion estimate was that some 6320 polychaete species remained to be described, and they speculated that "a total of 25,000 to 30,000 species would not be surprising."

Polychaetes are segmented worms belonging to the phylum Annelida. They are predominantly marine with some species in fresh and terrestrial groundwaters [5, 6]. Their naming began before the formal start of taxonomy (arbitrarily deemed to be 1758, matching the 10th edition of Linnaeus's Systema Naturae). The historic developments of polychaete taxonomy, and the seminal works on each family, were reviewed by Fauchald and Rouse [7] and Rouse and Pleijel [8]. All the thousands of Polychaeta

*Correspondence: joko.pamungkas@lipi.go.id; jpamungkas_lipi@yahoo.com
[1] Institute of Marine Science, University of Auckland, Auckland 1010, New Zealand
Full list of author information is available at the end of the article

names created up to the 1960's were subsequently captured by Hartman [9, 10, 11]. Those early names, along with all the names published since, were digitized by Kristian Fauchald, and the data have been made publicly available in 2007 as part of the World Register of Marine Species (WoRMS) online database.

Despite the availability of those well-documented data, a comprehensive review of the discovery rate of polychaetes has never been done. Here, we review progress in the discovery of polychaete species and estimate the number of species that will be discovered by the end of the twenty-first century.

Methods

The present study was based on data from the World Polychaeta Database, which is part of WoRMS [12], downloaded on 10 October 2016. It included all the taxa traditionally referred to as polychaetes (assigned class rank in WoRMS) within the Annelida, plus the more recently added Pogonophora and Vestimentifera (now the siboglinids) and the echiurans, but not aeolosomatids and myzostomids (both of them are Annelida *incertae sedis*), and not the clitellates and sipunculans. Sipunculans appear to be basal annelids [13], not 'polychaetes' per se; and the clitellates, while now molecularly aligned within Sedentaria polychaetes, have been outside the scope of WoRMS to date because they are largely terrestrial, so complete data on clitellates was unavailable. WoRMS and this study do not include polychaete species that are informally named, even when these names are connected to vouchered and registered museum specimens as they are not accepted species names.

During initial analyses, we noticed issues that merited correction. These were corrected prior to data analysis to maximize the accuracy of the data used (Additional file 1: Table S1). We included only Recent species-rank names whose WoRMS-status was 'accepted'. Consequently, 499 species of fossils, 204 names not checked by a taxonomist, 424 currently accepted subspecies, and some taxonomically uncertain name categories were excluded (Additional file 1: Table S2). We included only family names currently valid in WoRMS (notably subfamilies in Terebellidae are elsewhere treated at family level by some workers). Although many other family names have been proposed, they are now synonyms or subfamilies, either for nomenclatural reasons such as priority, or more fundamental reasons such as re-classification following insights from molecular analyses (e.g., Pisionidae as part of Sigalionidae [14]).

The discovery rate of polychaetes was studied in the following ways. First, the cumulative number of species described from 1758 to 2016—for both errant and sedentary species—was plotted to see if the curve reached an asymptote. The non-homogeneous renewal process model of Wilson and Costello [15] was then run to forecast the number of species that would be described by the years 2050 and 2100 with 95% confidence limits. The equation used was:

$$\boldsymbol{t} = \frac{\boldsymbol{N}}{\mathbf{1} + \mathbf{exp}(-\boldsymbol{N}\boldsymbol{\beta}(\boldsymbol{t} - \boldsymbol{\alpha}))}$$

where $\boldsymbol{t}$ is the number of polychaete species discovered by a particular year; $\boldsymbol{N}$ is the total number of polychaete species to be discovered; $\boldsymbol{\alpha}$ is the year of the maximum rate of discovery; and $\boldsymbol{\beta}$ is the overall rate of discovery (a larger $\boldsymbol{\beta}$ implying a faster rate). In addition, the annual number of species described was plotted to see the general trend of species discovery.

As an indicator of taxonomic effort through time, the number of first authors describing polychaete species was plotted yearly. Here, we only considered unique surnames of first authors so that the presence of additional authors did not inflate the apparent effort. Thus, for example, the well-known nineteenth century pairing of Audouin and Milne Edwards was counted once. In cases where different authors have the same surname, we attempted to find the original source of descriptions to distinguish them based on their given names (e.g., F. Müller, O. F. Müller, M. Müller and M. C. Müller). When this was not possible, we counted a surname for 50 years from its first occurrence, with an assumption that any effects of different authors with the same surname within a year were negligible and/or random over time.

Next, the average number of polychaete species described per first authors per year was plotted. A least squares piecewise regression analysis was additionally performed to identify the period from where the number of species described per author began to decrease. Bouchet et al. [16] suggested that the decline in the number of species described per author in Mollusca may be caused by many citizen-scientist authors describing just one or two species, and thereby does not necessarily indicate a difficulty in finding new species. To ascertain whether any increase in first authors of new species descriptions was due to an increasing proportion of authors who only described one species, we looked at their contribution to species descriptions over decades (we used decades to minimize the occurrence of zero values). In addition, we used Pearson's skewness coefficient to compare the relative number of species described by all first authors over the decades. A change in skewness could indicate a changing proportion of highly productive authors.

Finally, we counted the number of non-polychaete species described by the top 25 most prolific first authors using the 'advanced search' feature in WoRMS to see if polychaete taxonomists are now more specialized than they were in the nineteenth century (note that some of these authors may have named non-marine species that are not in WoRMS). We counted surnames from different authors as previously explained, and only counted non-polychaete names that were accepted species.

Results

Species richness

WoRMS is constantly being updated and corrected. At the time of the data download in 2016, as many as 11,456 polychaete species (1417 genera, 85 families) had been described (Table 1)—these are the valid names remaining from the 21,104 names actually created, which include as well all of the unaccepted names (Additional file 1: Table S2). Of these species, 6033 species belong to the subclass Errantia, whereas 5085 and 158 species belong to the subclasses Sedentaria and Echiura, respectively. Additionally, 180 species were from families currently outside of, or as yet unassigned to, subclass groupings in WoRMS, and referred to as Polychaeta *incertae sedis*.

We found that six polychaete families were the most species-rich. That is, in order, Syllidae (993 species), Polynoidae (876 species), Nereididae (687 species), Spionidae (612 species), Terebellidae (607 species) and Serpulidae (576 species) (Table 1). About 38% of known polychaete species belonged to these families. By contrast, four polychaete families, i.e., Ichthyotomidae, Ikedidae, Laetmonectidae and Pontodoridae, were monotypic (having only one species) (Table 1). These four family names are hierarchy place-holders for morphologically distinctive species with as yet no obvious affinities to other families. Rouse and Pleijel [8] regarded such monotypic family group names as being redundant as they represented an 'empty taxon'.

Species discovery and authors

We identified three phases of polychaete species discovery. The initial phase, where few polychaete species had been described by few taxonomists, occurred from 1758 to the middle of the nineteenth century (Fig. 2). During this period, the cumulative number of species described increased slowly (Fig. 1), and nearly 500 species, or about 4% of the known species, had been described.

The second phase of the discovery started from about the 1850's to the middle of twentieth century, indicated by many species being described mostly by some very productive authors. For example, McIntosh [17] recorded 308 full species from the Challenger (1872–1876) expedition, of which 220 (71%) were new. The 1860's stand out as an unusually productive and dynamic time for polychaete taxonomy (Fig. 2c) due to major monographs or series by Claparède, Ehlers, Grube, Kinberg, Malmgren, Quatrefages, and Schmarda. Despite a low period of activity in the late nineteenth century (Fig. 2a) and a dip in active authors during the Second World War (Fig. 2b), almost 5000 species, or about 43% of the known species, had been named by the end of this phase.

The third phase of the discovery started after the Second World War. At this point, the annual number of species described rose significantly and reached a peak in the 1960's (Fig. 2a). It then plateaued until 1990, declined to around the turn of the century, and increased again from 2010 (Fig. 2a). Over this period, approximately 6000 species, or about 52% of the known species, had been described by the most authors ever (Fig. 2b). The trend in the cumulative number of polychaete species described was similar for both errant and sedentary polychaetes (Additional file 1: Figure S1).

Based on earlier species discoveries and at 95% probability, we forecast medians of 2600 (± 300) and 5200 (± 600) more polychaete species will be discovered by the years 2050 and 2100, respectively (Fig. 1). The cumulative numbers of polychaete species described are thus estimated to be about 14,100 and 16,700 species by the years 2050 and 2100, respectively (Fig. 1).

From 1758 to 2016, 835 taxonomists were first authors of the descriptions of the 11,456 valid polychaete species. Among them, Hartmann-Schröder, Hartman, and Grube were the top three most prolific authors describing about 1400 species or about 12% of the known species (Table 2). Thus, 25 authors have described over 5200 species, or 45% of the known species (Table 2). One-third (278) of authors have described 90% of the known species.

The number of first authors describing polychaete species per year increased slowly from 1758 to mid-nineteenth century (Fig. 2b). It then increased moderately and dropped most noticeably during the Second World War (Fig. 2b). Afterwards, many more authors described species, and the past two decades were the period with the most first authors ever (Fig. 2b). In contrast to this, the number of polychaete species described per first author per year began to decrease since around the middle of the nineteenth century (Fig. 2c, Additional file 1: Figure S2).

The majority of the 25 most prolific authors had polychaete publication lifetimes of around 30–60 years. There is no indication these are decreasing (Additional file 1: Figure S3), and three of these prolific authors are still active (Table 2). Among the 25 most prolific authors, 14 individuals also described non-polychaete species (Table 2), which were mostly published between the 1840's and 1960's (Additional file 1: Figure S4), indicating that past polychaete taxonomists were more generalistic than recent ones. There was no clear trend in the proportion of non-career first-author polychaete

Table 1 The list of valid polychaete families and their author(s), species and genera (ranked by species number per family), as well as years of first and last species descriptions and cumulative percentages of species described per half century

Family	Author(s)	Species	Genus	First name	% of species described by				Last name
					1850	1900	1950	2000	
Syllidae	Grube, 1850	993	103	1776	2	20	34	79	2016
Polynoidae	Kinberg, 1856	876	174	1758	3	31	60	95	2016
Nereididae	Blainville, 1818	687	50	1758	10	35	61	94	2016
Spionidae	Grube, 1850	612	54	1767	3	12	27	83	2016
Terebellidae	Johnston, 1846	607	73	1766	4	28	55	85	2016
Serpulidae	Rafinesque, 1815	576	77	1758	8	29	47	90	2016
Sabellidae	Latreille, 1825	493	42	1767	10	39	61	86	2016
Phyllodocidae	Örsted, 1843	448	34	1767	7	36	58	93	2015
Eunicidae	Berthold, 1827	419	14	1767	6	46	70	94	2014
Onuphidae	Kinberg, 1865	340	24	1776	2	20	40	90	2016
Ampharetidae	Malmgren, 1866	306	66	1835	1	20	46	81	2016
Lumbrineridae	Schmarda, 1861	302	22	1776	3	27	56	91	2014
Cirratulidae	Carus, 1863	291	21	1776	3	22	41	75	2016
Maldanidae	Malmgren, 1867	272	45	1780	2	33	64	96	2016
Sigalionidae	Malmgren, 1867	219	28	1830	3	29	53	91	2016
Hesionidae	Grube, 1850	214	37	1780	3	19	36	83	2015
Dorvilleidae	Chamberlin, 1919	201	37	1828	1	13	23	83	2015
Capitellidae	Grube, 1862	193	46	1780	1	13	35	83	2016
Orbiniidae	Hartman, 1942	184	25	1758	3	16	32	90	2016
Flabelligeridae	de Saint-Joseph, 1894	182	27	1776	6	30	59	80	2016
Siboglinidae	Caullery, 1914	178	32	1933	0	0	2	86	2015
Paraonidae	Cerruti, 1909	169	10	1879	0	2	10	83	2013
Opheliidae	Malmgren, 1867	155	10	1818	4	22	49	85	2015
Amphinomidae	Lamarck, 1818	152	22	1766	8	44	81	95	2012
Nephtyidae	Grube, 1850	144	6	1780	4	27	52	94	2016
Sabellariidae	Johnston, 1865	130	13	1767	5	20	46	91	2015
Aphroditidae	Malmgren, 1867	123	12	1758	9	43	77	94	2013
Sphaerodoridae	Malmgren, 1867	112	11	1843	1	5	15	80	2016
Pilargidae	de Saint-Joseph, 1899	105	13	1758	1	9	25	76	2013
Fabriciidae	Rioja, 1923	91	21	1774	1	10	22	89	2014
Oenonidae	Kinberg, 1865	90	19	1804	8	35	65	97	2015
Goniadidae	Kinberg, 1866	90	12	1833	4	27	59	94	2004
Chrysopetalidae	Ehlers, 1864	87	27	1855	0	13	23	74	2015
Glyceridae	Grube, 1850	87	3	1776	9	46	67	83	2012
Echiuridae	Quatrefages, 1847	79	7	1766	5	25	76	99	2013
Trichobranchidae	Malmgren, 1866	78	6	1758	3	21	33	77	2016
Bonelliidae	Lacaze-Duthiers, 1858	74	31	1821	1	12	34	97	2015
Chaetopteridae	Audouin & Edwards, 1833	73	5	1804	3	26	52	69	2015
Magelonidae	Cunningham & Ramage, 1888	67	2	1858	0	5	19	81	2013
Scalibregmatidae	Malmgren, 1867	66	16	1843	3	12	26	83	2015
Acoetidae	Kinberg, 1856	60	10	1817	5	30	65	97	2008
Euphrosinidae	Williams, 1852	59	4	1818	7	29	70	92	2009
Pectinariidae	Quatrefages, 1866	57	5	1766	14	40	79	88	2015
Oweniidae	Rioja, 1917	55	6	1844	2	18	29	67	2015
Tomopteridae	Grube, 1850	52	3	1825	6	34	87	100	1992
Nerillidae	Levinsen, 1883	49	14	1848	2	4	20	90	2009

Table 1 (continued)

Family	Author(s)	Species	Genus	First name	% of species described by				Last name
					1850	1900	1950	2000	
Alciopidae	Ehlers, 1864	47	10	1828	10	60	79	100	1991
Acrocirridae	Banse, 1969	44	10	1835	2	11	25	84	2012
Protodrilidae	Hatschek, 1888	39	4	1868	0	10	33	85	2015
Travisiidae	Hartmann-Schröder, 1971	34	1	1840	3	29	65	88	2006
Poecilochaetidae	Hannerz, 1956	31	1	1875	0	3	13	90	2009
Sternaspidae	Carus, 1863	29	3	1817	7	28	41	45	2015
Cossuridae	Day, 1963	26	1	1887	0	4	0	85	2015
Pholoidae	Kinberg, 1858	25	5	1776	20	24	0	88	2016
Arenicolidae	Johnston, 1835	22	5	1758	14	55	68	96	2001
Eulepethidae	Chamberlin, 1919	22	7	1875	0	18	41	86	2011
Fauveliopsidae	Hartman, 1971	22	2	1922	0	0	9	86	2014
Saccocirridae	Czerniavsky, 1881	22	1	1872	0	5	36	82	2007
Lopadorrhynchidae	Claparède, 1870	19	5	1855	0	53	84	100	1978
Typhloscolecidae	Uljanin, 1878	17	3	1851	0	53	100	0	1950
Dinophilidae	Macalister, 1876	15	3	1848	7	60	80	100	1999
Polygordiidae	Czerniavsky, 1881	15	1	1868	0	40	87	100	1999
Trochochaetidae	Pettibone, 1963	15	2	1844	13	33	60	87	2013
Histriobdellidae	Claus & Moquin-Tandon, 1884	13	3	1858	0	15	39	85	2005
Iphionidae	Kinberg, 1856	13	4	1818	8	23	0	92	2014
Lacydoniidae	Bergström, 1914	13	1	1875	0	8	15	69	2016
Spintheridae	Augener, 1913	12	1	1845	17	33	67	92	2003
Alvinellidae	Desbruyères & Laubier, 1986	11	2	1980	0	0	0	100	1993
Longosomatidae	Hartman, 1944	7	1	1874	0	14	29	86	2016
Apistobranchidae	Mesnil & Caullery, 1898	6	1	1879	0	33	0	100	1978
Psammodrilidae	Swedmark, 1952	6	1	1952	0	0	0	50	2015
Aberrantidae	Wolf, 1987	4	1	1965	0	0	0	50	2005
Iospilidae	Bergström, 1914	4	3	1879	0	75	100	0	1911
Urechidae	Monro, 1927	4	1	1852	0	75	100	0	1928
Antonbruunidae	Fauchald, 1977	3	1	1965	0	0	0	33	2015
Hartmaniellidae	Imajima, 1977	3	1	1977	0	0	0	100	1986
Uncispionidae	Green, 1982	3	2	1982	0	0	0	67	2011
Yndolaciidae	Støp-Bowitz, 1987	3	3	1987	0	0	0	33	2004
Paralacydoniidae	Pettibone, 1963	2	1	1913	0	0	100	0	1923
Parergodrilidae	Reisinger, 1925	2	2	1925	0	0	100	0	1934
Protodriloididae	Purschke & Jouin, 1988	2	1	1904	0	0	100	0	1926
Ichthyotomidae	Eisig, 1906	1	1	1906	0	0	100	0	1906
Ikedidae	Bock, 1942	1	1	1904	0	0	100	0	1904
Laetmonectidae	Buzhinskaya, 1986	1	1	1986	0	0	0	100	1986
Pontodoridae	Bergström, 1914	1	1	1879	0	100	0	0	1879
Total		11,456	1417						

taxonomists over the past centuries (Fig. 3a). This indicates that the increase in the number of authors was not due to more incidental authors. Rather, it suggests that there has been increased taxonomic effort since the 1950's, as already shown in Fig. 2b. Moreover, the positive skewness values show that over all decades most authors described few species (Fig. 3b).

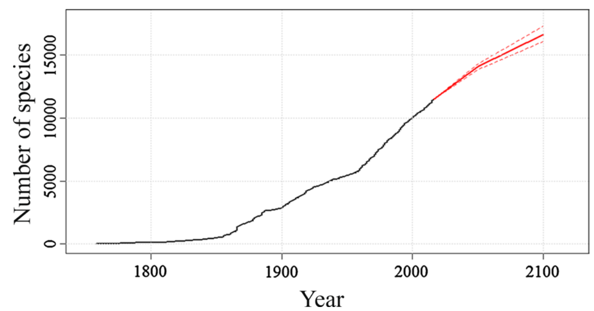

Fig. 1 Cumulative (black line) and median predicted (red line with 95% confidence limit) numbers of species described to 2100 using the model of [15]

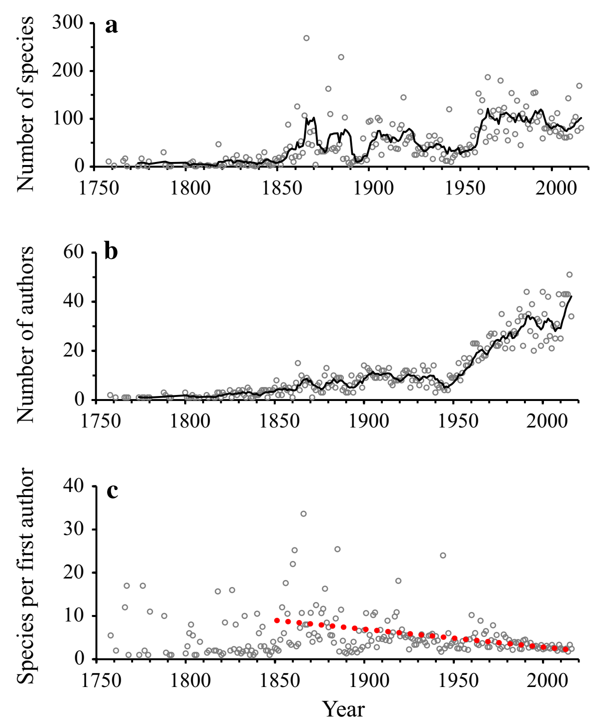

Fig. 2 **a** The number of species described per year. **b** The number of first authors per year. **c** The number of species described per first author per year. The black lines are six-year moving average. The red linear correlation line represents the best fit based on the piecewise regression analysis (Additional file 1: Figure S2), showing that there is a statistically significant trend of decreasing number of species per author since around mid-nineteenth century (prior to that, there is not enough evidence to identify a trend)

Discussion

We found that there were 11,456 validly named polychaete species at the time of the data download in 2016 (Table 1). This number is rather lower than that used by Appeltans et al. [4], i.e., 12,632 species, and coincidentally close to that used by Costello et al. [3], viz., 11,548 species. The decrease, despite well over one hundred new taxa added every year, is due to recognition of synonyms as a consequence of data revisions.

Our model based on current rates of species descriptions showed that about 5200 more polychaete species will be discovered by 2100 (Fig. 1); this number is around one-third of the total predicted number of species by then (16,700 species). In other words, as shown in Fig. 1, approximately two-thirds of the total predicted number of polychaete species by 2100 have already been described; a proportion regarded as typical for progress in marine and other taxa by some analysts [3, 18].

The high current rate of polychaete species discovery is being supported by an increasing number of people describing the animals since the 1960's (Fig. 2b). A similar trend of an all-time peak in authors in recent decades was also observed for various taxa such as fossil mammals [19], amphibians, birds, cone snails, flowering plants, mammals and spiders [20, 21], fish [22, 23], Brazilian flowering plants and land vertebrates [24], parasites [25], and amphipod crustaceans [26]. The increase in the number of authors was also the case for all taxa on Earth [3]. Our findings on the increase in first author numbers for polychaete taxonomy were thus inconsistent with the common belief that the science of taxonomy is in crisis [27], and that the number of people specializing in taxonomy is in decline [28, 29]. Recent analyses confirm earlier indications that the increase in taxonomic authors has been particularly high in South America and Asia [1, 30, 31].

In contrast to the increasing number of first authors, the number of polychaete species described per first author in a year has declined since around mid-nineteenth century and shows a continued decline since the 1960's, with noticeably reduced variation in the data since the 1990's (Fig. 2c). This is different from the accepted phenomenon of author-inflation per article. As to the latter, in the case of taxonomy one possible reason for there being more authors per individual species is likely to be partly due to there being higher-quality species descriptions (especially those including molecular data) that require a wider range of expertise [32], as well as possible changing authorship practices.

The gradual decrease in the number of species described per first author per year may be a sign of an increasing difficulty in finding new polychaete species as the more widespread and conspicuous taxa have been discovered (the remaining species may require more careful taxonomic review and scrutiny to distinguish). Yet, the greater number of first authors, new sampling methods (e.g., scuba, ROVs), more advanced technology (e.g., better microscopes, digital drawing and photography tools, molecular methods), the rapid increase in

Table 2 The top 25 most prolific first authors along with their numbers of polychaete species described, first and last discoveries, cumulative proportion of the number of polychaete species described, publication lifetime and the number of non-polychaete species described

First author	Polychaete species described	First discovery	Cumulative % of species described by				Last discovery	Publication lifetime	Non-polychaete species described
			1850	1900	1950	2000			
G. Hartmann-Schröder	517	1956	0	0	0	100	1998	43	4
O. Hartman	473	1936	0	0	26	100	1971	36	1
A. E. Grube	468	1840	5	100	100	0	1881	42	78
W. C. McIntosh	297	1868	0	82	100	0	1924	57	14
E. Ehlers	262	1864	0	53	100	0	1920	57	6
M. Imajima	239	1959	0	0	0	78	2013	55	0
J. P. Moore	223	1894	0	2	100	0	1923	30	7
H. Augener	217	1906	0	0	98	100	1970[1]	65	2
J. G. H. Kinberg	212	1855	0	100	100	0	1910[2]	56	0
J. A. Blake	206	1969	0	0	0	85	2016	48	0
P. A. Hutchings	197	1974	0	0	0	89	2015	42	0
J. H. Day	192	1934	0	0	6	100	1977	44	0
K. Fauchald	188	1965	0	0	0	100	2012	48	0
A. L. Treadwell	168	1900	0	1	100	0	1945	46	0
M. H. Pettibone	158	1948	0	0	1	100	1997	50	0
P. Fauvel	142	1900	0	1	95	100	1959	60	0
A. de Quatrefages	141	1843	9	100	0	0	1870	28	22
R. V. Chamberlin[3]	131	1918	0	0	100	0	1920	3	1652[3]
A. E. Verrill	123	1873	0	99	100	0	1901	29	730
C. C. A. Monro	121	1924	0	0	100	0	1939	16	0
R. Horst	116	1889	0	3	100	0	1924	36	1
G. San Martín	112	1982	0	0	0	45	2014	33	0
L. K. Schmarda	111	1861	0	100	0	0	1861	1	92
C. Gravier	107	1896	0	24	100	0	1936	41	47
M. Caullery	103	1896	0	11	100	0	1944	49	28
Total	5224								

Authors in italic indicate those who are still active until now

[1] Posthumous, deceased 1938

[2] Posthumous, last article in 1867

[3] Arthropod taxonomist with brief career in annelids

the number of scientific journals publishing taxonomic works and easier access to publications since the era of the Internet [1, 33] should at least balance the greater effort needed to describe species more comprehensively in recent decades [34]. If this is the case, such a pool of taxonomic workers, at some point, will no longer maintain the description rate, and a reduction in the number of species described per year will occur. This phenomenon has already occurred for various taxa such as some insects [35], scleractinian corals [36], fossil mammals [19], marine fishes [22], amphibians, birds, flowering plants, mammals, spiders [20, 21], algae [37], flowering plants [38], beetles [39], parasites [25] and amphipod crustaceans [26].

If the drop in the number of polychaete species described per first author was due to a bigger proportion of non-career taxonomists nowadays, then the increase in the number of authors since the 1960's would not reflect increased taxonomic effort. In this study, we do not know for how long recent authors (i.e., people who described species since the 1950's) will continue to publish species descriptions. Therefore, whether the working lifetime of recent authors will be similar to that of previous decades remains to be seen. Nonetheless, our analysis found no trend in the proportion of non-career polychaete taxonomists over time (Fig. 3a), which is consistent with the observation on the proportion of non-career taxonomists through time globally [30]. Thus, the

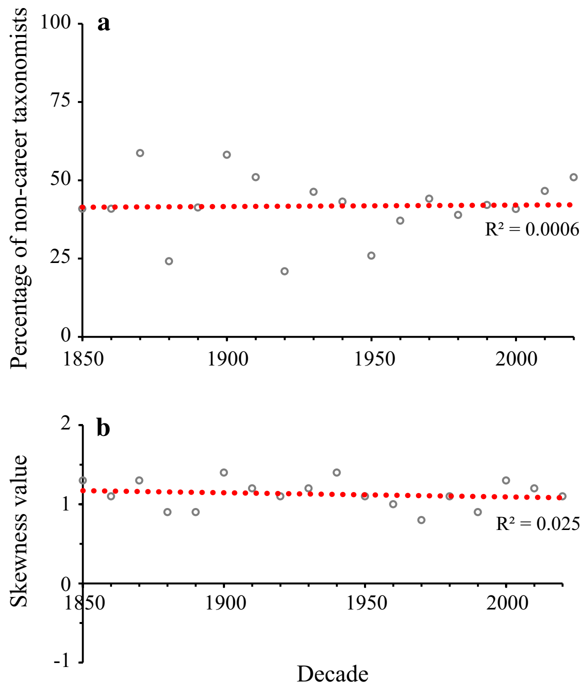

Fig. 3 a The proportion of authors describing one species only per decade (i.e., non-career taxonomists). **b** The Pearson's Skewness coefficient per decade. The red dashed lines are the linear trends

considerable increase in the number of first authors since the 1960's (Fig. 2b) appears to reflect greater scientific effort, and the drop in the number of species described per first authors (Fig. 2c)—despite the greater effort—indicates difficulty in finding new species. However, reasons for the increased difficulty in finding new polychaete species may be more complex than having discovered most of them. Perhaps, an equally likely reason is that small-sized and cryptic species are being under-sampled by commonly-employed survey sampling methods and the greater focus on more obvious collectable invertebrate species [40]. Certainly Annelida, whose members show a four orders of magnitude size variation (including meiofaunal-sizes) and an apparent abundance of cryptic species, provide a bigger challenge than many other phyla in estimating species diversity.

Conclusions

This study analysed the rate of description of polychaete worms over about 2.5 centuries, and found that 11,456 species (1417 genera, 85 families) have been formally described by 835 first authors (a species total distilled down in re-evaluations from nearly double (21,104) that number of names actually created over time). Proportionally, the 11,456 is about two-thirds of the total predicted number of polychaete species of the world by the end of the twenty-first century (16,700 species). The trend in polychaete species discovery thus seems to be following the overall global estimate of Costello et al. [3] in that about two-thirds of the total predicted number of global species by then have already been discovered.

The decline in the number of polychaete species described per author since around mid-nineteenth century, despite greater taxonomic effort and more favourable conditions for science pertaining to both species sampling and descriptions, suggests that it is now getting harder to find new polychaete species (using present sampling methods) as the more widespread and conspicuous ones may have been discovered. Despite this, approximately 5200 more polychaete species are predicted to be discovered by the end of this century. Given that the most prolific specialist taxonomic authors may describe about 100 species in their lifetime, and that the remaining species are likely to be more difficult to find and/or discriminate, this suggests that the world needs a further 50 full-time polychaete taxonomists to complete the work.

Additional files

Additional file 1: Table S1. The details of data selection conducted before analyses. **Table S2.** Data selection from WoRMS for the present analyses. **Figure S1.** Cumulative number of errant (red dots) and sedentary (black dots) polychaete species described over time. **Figure S2.** The least squares piecewise regression analysis. From the point of view of minimising the squared error between the correlation line and data (Fig. 2c), the middle of the 19th century was identified as the period from where the number of species described per author began to decrease. Prior to that period, there is not enough evidence to identify a trend. **Figure S3.** The number of polychaete (black triangles and line) and non-polychaete (red dots and line) species described by the 25 most prolific first authors during their publication lifetime. **Figure S4.** The number of non-polychaete species described by the 14 most prolific polychaete first authors over time. The red line is a three-year moving average.

Additional file 2: Table S3. The cleaned dataset of valid polychaete species names.

Authors' contributions

JP cleaned and analysed the dataset, created the figures and tables, and wrote the manuscript. CJG and GBR cleaned the dataset and were major contributors in writing the manuscript. SPW did the non-homogeneous renewal process model and least squares piecewise regression analysis. MJC wrote the manuscript and supervised JP in conducting the study. All authors have read and approved the final manuscript.

Author details

[1] Institute of Marine Science, University of Auckland, Auckland 1010, New Zealand. [2] Research Center for Deep Sea, Indonesian Institute of Sciences, Ambon 97233, Indonesia. [3] Museum and Art Gallery of the Northern Territory, Darwin, NT 0801, Australia. [4] National Institute of Water and Atmospheric Research (NIWA), Wellington 6021, New Zealand. [5] Trinity College Dublin, Dublin 2, Ireland.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The dataset analysed during the current study is available as Supplementary Material (Additional file 2: Table S3) and at Figshare (https://figshare.com/s/f4a1de71020d66a9fe6c).

Consent for publication
Not applicable.

Ethics approval and consent to participate
Not applicable.

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