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Running title: FEWER SPECIES BEING DISCOVERED PER TAXONOMIST

More taxonomists describing significantly fewer species per unit effort may indicate that most species have been discovered

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Recent studies show that there are more taxonomists describing species in recent decades than before. However, whether the rate of increase in number of taxonomists is greater than the rate of new species description has been questioned. We found a statistically significant decline in the proportion of species being described per number of taxonomists (i.e. authors of recent species descriptions) during the past century for (a) families of insects that had been stated not to show this trend, and (b) a sample of over 0.5 million marine, terrestrial and freshwater species. We suggest that this decreased 'catch' of species per taxonomic effort, despite scientists' greater ability to explore and sample habitats, means it is getting harder to discover new species, and supports recent studies suggesting that two-thirds of all species have been named.

Some scientists consider that describing all remaining species is fruitless when so few have been described, there are insufficient taxonomists, and so many species are or soon will be extinct (Thomas 1997, Benton 2008). Such statements discourage taxonomy if further investment appears futile (Swaisgood and Sheppard 2010, Costello et al. 2013). However, recent analyses indicate that we may already have named one to two-thirds of all species (Costello et al. 2012, Appeltans et al. 2012, De Clerck et al. 2012), that there have been high rates of discovery of new species in well-studied geographic regions (Costello and Wilson 2011, Fontaine et al. 2012), and that there are more taxonomists describing species than ever before (e.g. Joppa et al. 2011a, Costello et al. 2012, Lohrmann et al. 2012, De Clerck et al. 2012, Tancoigne and Dubois 2013). However, whether an observed trend of a decreasing number of species being described per number of taxonomists (i.e. authors of recent species descriptions) is true has been more controversial (Bacher 2012). Does increased taxonomic effort explain the continued high rates of species discovery rather than the ease with which new species may be found? Is the trend of fewer species being discovered per taxonomist true? Here, we review evidence that suggests there have never been so many people describing new species; which can be considered a minimal number of taxonomists. We then provide the first statistical tests of the long-term trends in the number of species described per taxonomist for the past 240 years, and calculate the tipping-point year, when a trend for more species per taxonomist switched to one of fewer species per taxonomist.

TAXONOMISTS HAVE NEVER BEEN SO NUMEROUS AND PRODUCTIVE

Contrary to widespread belief, there have never been so many taxonomists, and age-profiles do not suggest most are near retirement in Europe, UK and Canada (Costello et al. 2006, Lovejoy et al. 2010, Boxshall and Self 2012, Costello et al. 2013). The numbers of publications describing new species has increased in all geographic regions over the past three decades, and proportionally more in Asia and South America (Lohrmann et al. 2012, Costello et al. 2013). Studies indicate that there has been a 2.5 fold increase in the proportion of animal taxonomists in South America and the Asia-Pacific region compared to Europe and North America from the 1980's (Gaston and May 1992) to the 2000's (Zhang 2010), reflecting the increasing number of scientists as their economies develop.

The increasing number of taxonomists is likely to contribute to a growth in taxonomic publications per year. Indeed, the number of taxonomic publications increased over eight-fold from 1969 to 1996 (Winston and Metzger 1998), although this may be a decreasing proportion of all the biological literature (Simon 1982). Despite the demise of some monograph series, the number of authoritative identification guides to marine species in Europe has been generally increasing since 1945 (Costello et al. 2006). On average for the past decade, the largest taxonomic journal (with over 1,500 papers published in 2010) has been publishing an additional 3,000 pages per year, including one monograph (i.e. a paper with > 60 pages) per week since 2006 and increasing (Zhang 2011). The number of publications describing new species increased each decade from 1980 to 2010 in all continents but the proportion increased relatively more in Asia and Latin America than in North America (Lohrmann et al. 2012, Costello et al. 2013). That publication rates are increasing even faster than the increase in number of authors of taxonomic papers, argues against any decrease in taxonomic productivity.

From 2000-2009, one study found over 8,600 people described 30,484 species (Costello et al. 2012), and another reported that a total of 166,000 species were named (Wheeler and Pennak 2012). Although some of the 8,600 authors will have described species not included in the 30,484, additional people may be involved whose names were not known due to their names being only listed as 'et al.' in the databases, and many people who are considered to be taxonomists may describe few to no species (e.g. when their taxa or study area are well-described) (Costello et al. 2006, Lovejoy et al. 2010, Boxshall and Self 2012). This indicates that there are at least 47,000 active taxonomists. A portion of these people may not call themselves taxonomists, but an additional number who may not have named a species in recent years may do so. Haas and Hauser (2000 estimated there were 30,000-40,000 taxonomists globally. However, perhaps the relative productivity of taxonomists has changed over time, with fewer specialists and more authors describing only a few species? Thus, we report here the trend in the proportion of authors who described only one species per decade for both the marine and non-marine datasets used in Costello et al. (2012).

SPECIES CATCH PER UNIT EFFORT

In addition to the increased taxonomic effort and number of publications describing species new to science, the modern efficiencies in access to remote locations, sampling, specimen preparation, use of traditional and molecular characters, photography and publication, suggest increasing efficiency in taxonomic discovery (Eschmeyer et al. 2010). Evidently, taxonomy has never been so productive. Thus, recent reports of a decline in the number of species described per taxonomist were surprising (Joppa et al. 2011a, Costello et al. 2012, Bacher 2012, Tancoigne and Dubois 2013). Joppa et al. (2011a) questioned whether the decline they found in the number of species per taxonomist was representative of wider biodiversity. This prompted Bacher (2012) to plot the number of species per author for two families of parasitic wasps. He concluded that there was "no sign of a decline" in species per taxonomist since 1940, and Joppa et al. (2012) did not dispute his conclusion. However, we did find a decline for a dataset of over 0.5 million marine, terrestrial and freshwater species, and also suggested it reflected an increasing difficulty in finding new species (Costello et al. 2012). Samyn and De Clerck (2012) misquoted this as confirmation of the decreasing number of species per author being peculiar to particular taxa. Tancoigne and Dubois (2013) found the same trend of decreasing species per author since 1978 for all animal species in the Index of Organism Names (Thomson Reuters 2009). However, these studies did not statistically test the trends.

METHODS

We used the data previously plotted in papers by Costello et al. (2012) for 141,000 marine and 370,000 terrestrial (including freshwater) species, and by Bacher (2012) for two families of insects, Chalcidoidea and Ichneumonoidea. These comprise the number of species being described in five year time periods, and the number of authors naming species in that period. Most species are described by one or two people, but there has been a trend of more than two authors describing a species since the 1980's (Joppa et al. 2011b, Costello et al. 2012). The Costello et al. (2012) data only contained the name of the first of such 'et al.' authors and thus may underestimate the total number of authors in a time period. These data are provided as Supplementary Material in Dryad doi:10.5061/dryad.k5268. In addition, details of the regression results are archived there.

Fitting a standard linear regression to the entire data series would not be appropriate as such a model requires assumptions of homoscedasticity and independence in the residuals. In essence, the residuals from the model fit should appear random and have no discernible pattern. However, when the entire dataset is considered there is a discernible pattern where early and late residuals lie below the fitted curve, whilst middle residuals all tend to lie above the curve. We thus fitted a linear regression line to the data for every year since 1758 (Appendix), and used Muggeo's (2003, 2008) method to detect when a break point occurred in the time-series.

RESULTS

Here we reject the hypothesis that time has not affected the number of species described per author (Figure 1). The break points in the time-series were 1838 and 1843 for Chalcidoidea and Ichneumonoidea respectively wasps; and from 1766 and 1911 for marine and non-marine species. The trends were highly significant since the latter two dates for the marine and non-marine data ($P < 0.0001$, R^2 0.17 and R^2 0.87 respectively), but not prior to that. Both the rising and falling regressions lines (Figure 1) were significant: (a) $P = 0.037$ (R^2 0.026) and $P = 0.014$ (R^2 0.173) respectively for Chalcidoidea, and (b) $P = 0.004$ (R^2 0.42) and $P = 0.001$ (R^2 0.28) for Ichneumonoidea.

It may be argued that the above trend was because there had been an increase in part-time taxonomists, such as people who only describe one species. We found that the proportion of people who only described one species per decade since 1900 has ranged from 38% to 44% for marine, and 38% to 42% for non-marine, species (Figure 2).

DISCUSSION

We show significant long-term trends in fewer species being discovered per author across all marine taxa, many terrestrial and freshwater taxa, and two insect families. Joppa et al. (2011a) showed a similar trend for flowering plants, spiders, amphibians, birds and mammals; and De Clerck et al. (2012) for algae, a polyphyletic group including seaweeds and microscopic species in land and aquatic environments that was not included in previous studies. All together these taxa cover over 0.5 million species which is about one-third of all named species (Costello et al. 2012, 2013). In addition, Tancoigne and Dubois (2013) found the same trend for a database of over 1.2 million animal species and sub-species (Thomson Reuters 2009). It remains possible that some other taxa do not show these trends, and they may not apply within some geographic areas. However, such exceptions seem unlikely to alter the global patterns found in the studies reviewed here.

Our analysis found that the proportion of full and part-time taxonomists had not shown any trend (nor changed more than 6%) in the past century (Figure 2), and the total number of taxonomists has increased. Previously, we showed that there were no temporal trends in either the (a) skewness of the frequency distribution of species per author, (b) proportion of authors who described only one, two or more than two species, and (c) duration of the 'publication' life-time of authors (Costello et al. 2012). We found that since the 1980's there has been an increase in authors per species named, what is termed the 'et al.' effect. However, this did not affect the overall trends (Costello et al. 2012). Similarly, Joppa et al. (2011b) found that the 'et al.' effect did not significantly affect the trend of more taxonomists over time for over 100,000 flowering plants. Appeltans et al. (2012) found a similar proportion (42% to 44%), of authors described only one marine species per decade during the past century using a more recent (2012) version of the WoRMS database. The lack of a temporal trend in the proportion of the most prolific authors, and duration of their publication periods, suggests that the proportion of full- versus part-time taxonomists has not changed.

Exploration of new locations and habitats has become easier since the 1950's with greater availability of road, rail, ship and air travel internationally. New field methods, from canopy fogging and cranes, to scuba and underwater submersibles, provide greater access to previously poorly sampled habitats. When combined with advances in specimen preparation, use of traditional and molecular characters, photography and publication, these factors suggest increasing efficiency in taxonomic discovery. On the other hand, more exacting publication standards, the increasing number of publications and specimens that need to be studied by authors of taxonomic papers, or other factors, may partly offset the modern efficiencies in taxonomy. In addition, perhaps the remaining species are more time consuming to describe than the earlier ones. This may not be the case within a taxon, but it does appear that the larger and more conspicuous taxa such as vertebrates, are better known than small invertebrates (Costello et al. 1996, 2012, Costello and Wilson 2011). We are not aware of any quantitative data that may measure trends in the productivity or efficiency of individual taxonomists. However, we suggest that overall efficiencies have been improving. In addition, the data show an increasing number of active taxonomists and publications describing new species, who are now distributed more globally than before the 1950's and continue to increase in number in Asia. We are thus led to the conclusion that it is taking more effort to discover new species (Joppa et al. 2011, Costello et al. 2012).

The present discovery rate of about 17,000 species per year (Wheeler and Pennak 2012) is being maintained by an increased ability to sample less explored places, taxonomic efficiencies, and the increasing number of taxonomists. That this golden age of taxonomy has been accompanied by a decline in the number of species described per taxonomist suggested that a significant portion, probably over half, of all species on Earth, have already been described. The break or tipping point in species discovered per taxonomic effort may have been in the 19th or early 20th centuries. This break point in the discovery trend would be likely to change for different groups of species, whether classified taxonomically, geographically or ecologically. The trend prior to the 1766 break point for marine species was of such short duration (and not significant) that it may be due to variable effort in the early years of discovery rather than any change in the trend of species discovery. The smaller sample size and contrasting kinds of marine species may explain the absence of a break in the trend for this group. However, the long-term trend for non-marine species was almost a straight line until 1911 when it began to significantly decline.

Accounting for as yet unrecognised synonyms, 1.5 million species may be described (Costello et al. 2012). Thus estimates of there being 2 to 3 million species on Earth (Costello et al. 2012, 2013) may be more realistic that those exceeding 5 million. Recent expert analyses of the potential global species richness of macro- and micro-algae (Guiry 2012, De Clerck et al. 2012) and anemones (Fautin pers. comm.), support those on fish (Eschemeyer et al. 2010) and 0.5 million marine and non-marine taxa (Costello et al. 2012), that over two-thirds of species have already been named.

Nevertheless, at least hundreds of thousands of species remain to be discovered, and they will be increasingly difficult to find because many will be geographically rare and may not be abundant. However, continual re-focusing of the taxonomic effort to the under-studied places and taxa may enable the current rate of 17,000 species described per year (Wheeler and Pennak 2012) to continue if not increase, especially in Asia and the southern hemisphere where most undiscovered species occur (Costello et al. 2010, 2012, 2013). The greater rarity value of new species, and increased involvement of citizen scientists (Pearson et al. 2011), may help maintain the discovery effort (Wheeler et al. 2012, Costello et al. 2013). Because of their localised distribution, these species are especially sensitive to extinction due to habitat loss (Stork 2010), and their recognition is a key step in their conservation (Costello et al. 2013). It seems evident that descriptive taxonomy, discovering what lives on Earth, has been more successful than appreciated, and most species will be discovered in this century. Indeed, Costello et al. (2013) argue that most species will be discovered before they go extinct.

Instead of a decline in taxonomy, the field has never been stronger. There are tens of thousands of people doing taxonomy, both professionals and significant numbers of citizen scientists. Almost half of all recent animal species described in Europe were by amateur taxonomists (Fontaine et al. 2012). People are exploring species and habitats in the most remote places on Earth. The past decade saw more marine species discovered than any previous decade (Appeltans et al. 2012). The popular media regularly report stories of exciting new species, and society expects science to discover life on Earth as well as on other planets. There are more tools to discriminate and describe species, and online access is opening up taxonomic knowledge to a greater proportion of society than ever before. However, only two-thirds of species may be known (Costello et al. 2012), and significant numbers are yet to be described from specimen collections in museums and research institutes (Appeltans et al. 2012, Costello et al. 2013). Thus considering the threats to species and their habitat, increased effort is required to discover species, a fundamental first step in understanding and conserving life on Earth.

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SUPPLEMENTARY MATERIAL

The data used in this paper can be found in the Dryad data repository DOI ...

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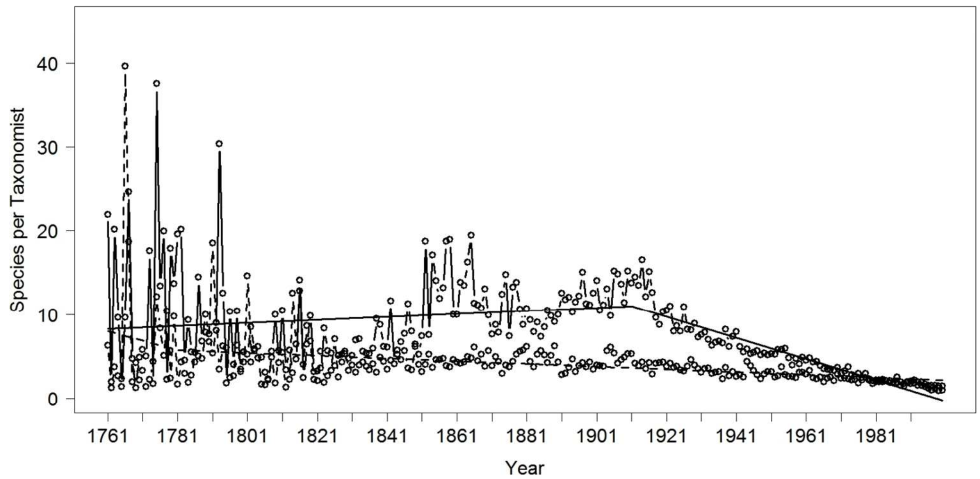
Figure legends

Figure 1. The number of species described per author each (upper) year for marine (dashed lines) and non-marine (solid lines) species from (data from Costello et al. 2012), and (lower) 5-year periods for chalcidoid (solid lines) and ichneumonoid (dashed lines) parasitic wasps from (data from Bacher 2012).

Figure 2. The proportion of authors who described only one species per decade in the marine (dashed line) and non-marine (solid line) datasets over time.



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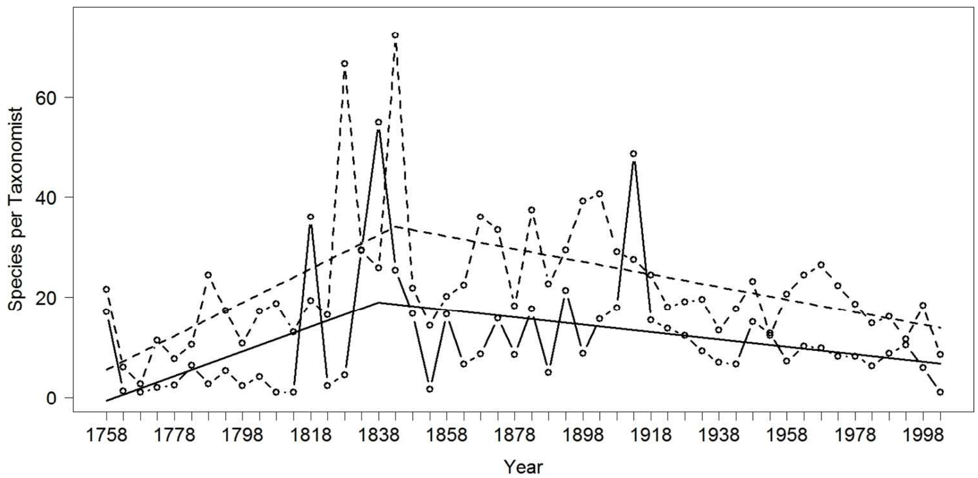

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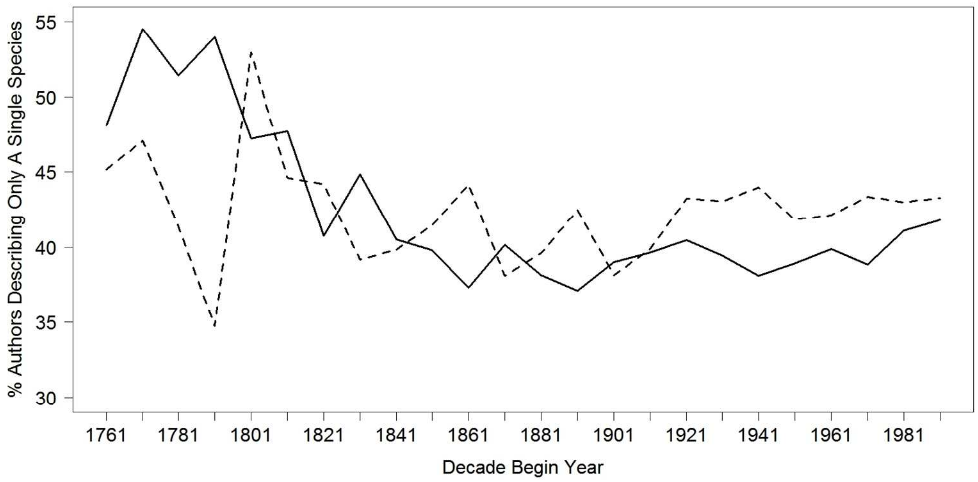

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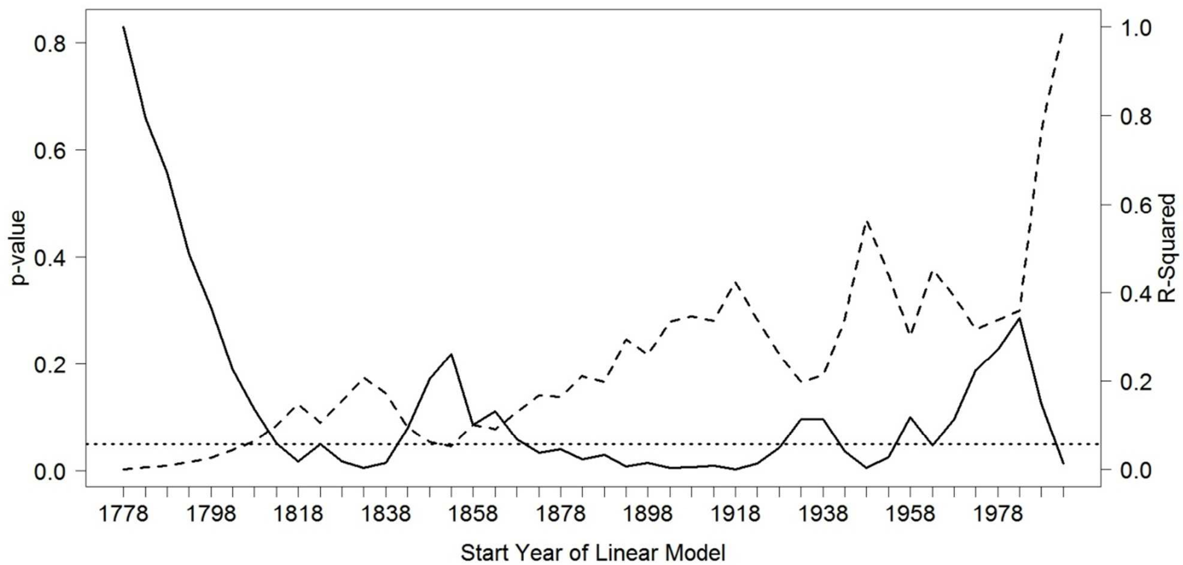
From: Costello MJ, Wilson S, Houlding B. 2013. More taxonomists describing significantly fewer species per unit effort may indicate that most species have been discovered. *Systematic Biology*.

Appendix 1.



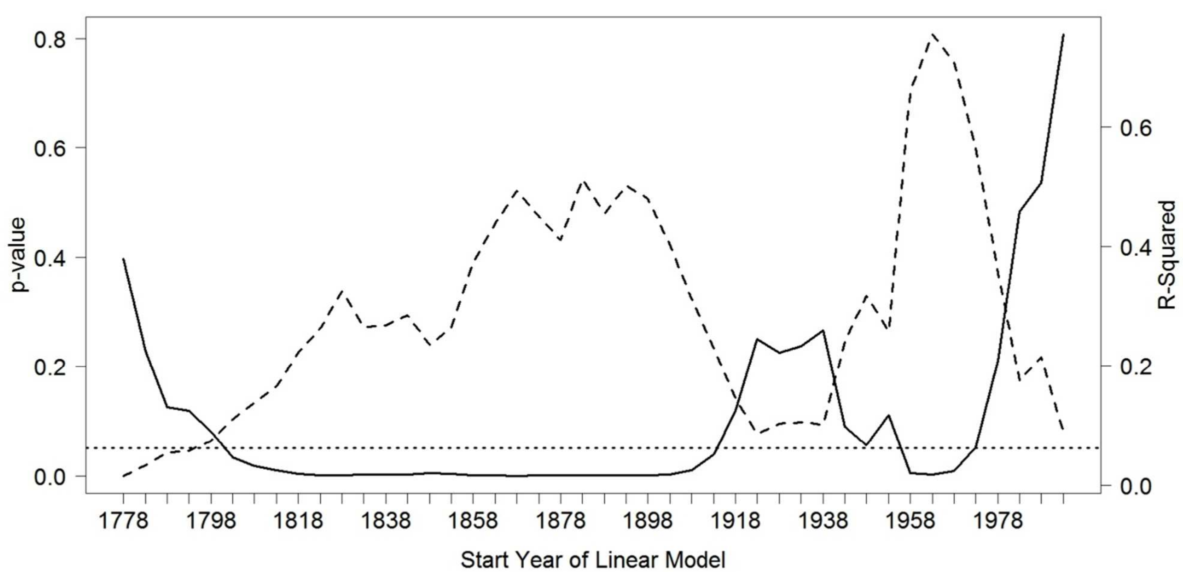


Figure 1A. The effect of starting the regression in terms of R^2 (dashed line) and P-value (solid line) from that year onwards, between number of species and taxonomists in 5-year periods for the chalcidoid (upper) and ichneumonoid (lower) wasps.

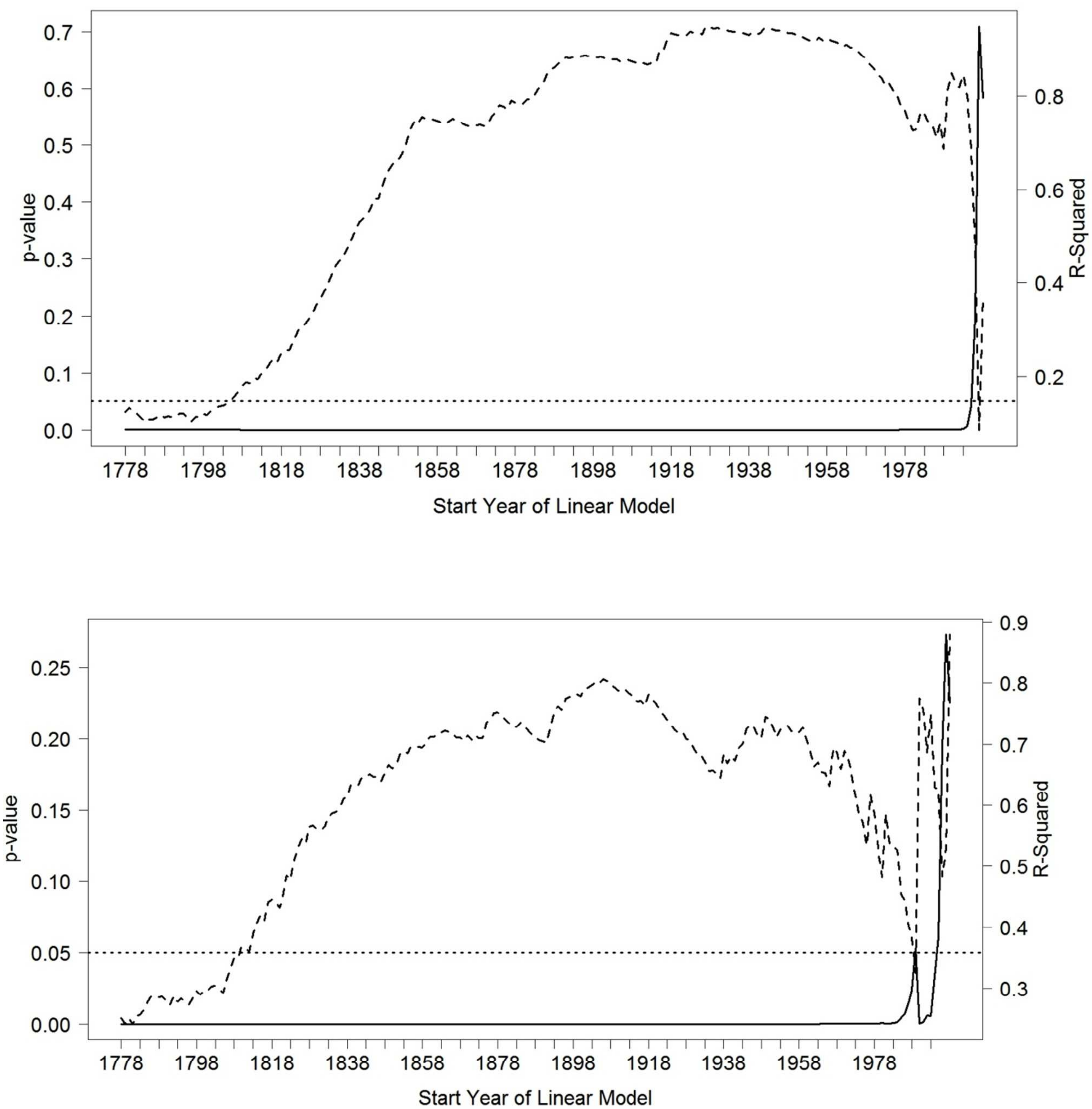


Figure 2A. The effect of starting the regression in terms of R^2 (dashed line) and P-value (solid line) from that year onwards, between number of species and taxonomists in 5-year periods for the non-marine (Catalogue of Life) (upper) and marine (World Register of Marine Species) (lower) wasps.

Table 1A. The data plotted in Figure 1A including the slope of the regression.

	Chalicoidea			Icheumenoidea		
Start Year	Fitted Slope	p-value	R^2	Fitted Slope	p-value	R^2
1758	0.0071	0.7494	0.0021	0.0036	0.8872	0.0004
1763	0.0104	0.6548	0.0043	0.0035	0.8962	0.0004
1768	0.0057	0.8131	0.0012	-0.0050	0.8556	0.0007
1773	0.0002	0.9951	0.0000	-0.0163	0.5553	0.0078
1778	-0.0055	0.8292	0.0011	-0.0241	0.3977	0.0163
1783	-0.0117	0.6600	0.0045	-0.0352	0.2273	0.0337
1788	-0.0163	0.5571	0.0083	-0.0460	0.1250	0.0551
1793	-0.0239	0.4067	0.0169	-0.0489	0.1191	0.0582
1798	-0.0308	0.3044	0.0263	-0.0571	0.0804	0.0745
1803	-0.0408	0.1889	0.0438	-0.0711	0.0338	0.1104
1808	-0.0508	0.1149	0.0641	-0.0822	0.0183	0.1379
1813	-0.0647	0.0507	0.0993	-0.0934	0.0100	0.1661
1818	-0.0807	0.0173	0.1475	-0.1110	0.0028	0.2217
1823	-0.0675	0.0493	0.1059	-0.1254	0.0012	0.2628
1828	-0.0838	0.0178	0.1542	-0.1444	0.0003	0.3250
1833	-0.1004	0.0059	0.2077	-0.1156	0.0015	0.2659
1838	-0.0930	0.0144	0.1730	-0.1208	0.0017	0.2675
1843	-0.0545	0.0790	0.0962	-0.1302	0.0014	0.2842
1848	-0.0438	0.1714	0.0614	-0.0844	0.0048	0.2358
1853	-0.0419	0.2185	0.0517	-0.0938	0.0031	0.2645
1858	-0.0601	0.0865	0.1013	-0.1148	0.0003	0.3716
1863	-0.0597	0.1110	0.0913	-0.1310	0.0001	0.4387
1868	-0.0746	0.0593	0.1301	-0.1464	0.0000	0.4931
1873	-0.0890	0.0342	0.1672	-0.1408	0.0001	0.4497
1878	-0.0930	0.0401	0.1640	-0.1375	0.0004	0.4110
1883	-0.1115	0.0209	0.2109	-0.1622	0.0001	0.5129
1888	-0.1141	0.0290	0.1987	-0.1502	0.0003	0.4553
1893	-0.1462	0.0074	0.2947	-0.1681	0.0002	0.5021
1898	-0.1434	0.0152	0.2605	-0.1717	0.0003	0.4803
1903	-0.1737	0.0061	0.3340	-0.1459	0.0020	0.4026
1908	-0.1893	0.0064	0.3455	-0.1047	0.0104	0.3124
1913	-0.1991	0.0094	0.3355	-0.0881	0.0385	0.2284
1918	-0.0883	0.0034	0.4244	-0.0696	0.1189	0.1450
1923	-0.0783	0.0141	0.3395	-0.0558	0.2507	0.0869
1928	-0.0700	0.0433	0.2607	-0.0666	0.2251	0.1032
1933	-0.0642	0.0963	0.1982	-0.0743	0.2363	0.1060
1938	-0.0737	0.0968	0.2128	-0.0804	0.2663	0.1017
1943	-0.1032	0.0366	0.3398	-0.1340	0.0896	0.2395
1948	-0.1482	0.0048	0.5649	-0.1739	0.0565	0.3174
1953	-0.1225	0.0262	0.4397	-0.1716	0.1104	0.2583
1958	-0.1009	0.1005	0.3011	-0.3003	0.0043	0.6602

1963	-0.1451	0.0468	0.4534	-0.3719	0.0024	0.7543
1968	-0.1523	0.0971	0.3915	-0.3917	0.0088	0.7087
1973	-0.1581	0.1887	0.3164	-0.3214	0.0516	0.5643
1978	-0.2032	0.2265	0.3376	-0.2528	0.2104	0.3571
1983	-0.2708	0.2858	0.3587	-0.2038	0.4833	0.1750
1988	-0.5582	0.1267	0.7626	-0.3163	0.5367	0.2147
1993	-0.9393	0.0135	0.9996	-0.2987	0.8073	0.0889

Table 2A. The data plotted in Figure 2A including the slope of the regression.

	Non-marine species from Catalogue of Life			Marine species from World Register of Marine species		
Start Year	Slope	p-value	R^2	Slope	p-value	R^2
1764	-0.02553	0.00000	0.11375	-0.01914	0.00000	0.15765
1769	-0.02609	0.00000	0.11765	-0.01539	0.00000	0.22443
1774	-0.02853	0.00000	0.13539	-0.01722	0.00000	0.26664
1779	-0.02614	0.00000	0.13150	-0.01591	0.00000	0.24128
1784	-0.02319	0.00000	0.10660	-0.01684	0.00000	0.26429
1789	-0.02460	0.00000	0.11356	-0.01806	0.00000	0.28628
1794	-0.02318	0.00000	0.10717	-0.01569	0.00000	0.28364
1799	-0.02471	0.00000	0.11592	-0.01619	0.00000	0.28939
1804	-0.02818	0.00000	0.14107	-0.01531	0.00000	0.29884
1809	-0.03333	0.00000	0.18629	-0.01686	0.00000	0.34767
1814	-0.03686	0.00000	0.21339	-0.01862	0.00000	0.40720
1819	-0.04145	0.00000	0.25612	-0.01538	0.00000	0.44098
1824	-0.04711	0.00000	0.31025	-0.01657	0.00000	0.51041
1829	-0.05421	0.00000	0.38168	-0.01767	0.00000	0.56629
1834	-0.06176	0.00000	0.45846	-0.01862	0.00000	0.58697
1839	-0.06959	0.00000	0.53567	-0.02019	0.00000	0.63322
1844	-0.07729	0.00000	0.60824	-0.02128	0.00000	0.65108
1849	-0.08538	0.00000	0.67722	-0.02216	0.00000	0.66657
1854	-0.09294	0.00000	0.75584	-0.02304	0.00000	0.68510
1859	-0.09239	0.00000	0.74275	-0.02429	0.00000	0.70168
1864	-0.09374	0.00000	0.74359	-0.02579	0.00000	0.72265
1869	-0.09358	0.00000	0.73896	-0.02583	0.00000	0.70602
1874	-0.10088	0.00000	0.77975	-0.02671	0.00000	0.71036
1879	-0.10315	0.00000	0.78126	-0.02861	0.00000	0.74734
1884	-0.11128	0.00000	0.81670	-0.02818	0.00000	0.73614
1889	-0.12155	0.00000	0.86751	-0.02744	0.00000	0.70723
1894	-0.12777	0.00000	0.88163	-0.02907	0.00000	0.76190
1899	-0.13121	0.00000	0.88308	-0.03090	0.00000	0.78153
1904	-0.13413	0.00000	0.87866	-0.03308	0.00000	0.80139
1909	-0.13040	0.00000	0.87152	-0.03051	0.00000	0.79354
1914	-0.12091	0.00000	0.86901	-0.02833	0.00000	0.77815

1919	-0.10645	0.00000	0.93188	-0.02880	0.00000	0.77409
1924	-0.10170	0.00000	0.93665	-0.02759	0.00000	0.73335
1929	-0.09735	0.00000	0.94399	-0.02662	0.00000	0.70587
1934	-0.09476	0.00000	0.93711	-0.02589	0.00000	0.65633
1939	-0.09394	0.00000	0.93583	-0.02767	0.00000	0.66885
1944	-0.09023	0.00000	0.94313	-0.03197	0.00000	0.72491
1949	-0.09259	0.00000	0.93423	-0.02996	0.00000	0.74564
1954	-0.09174	0.00000	0.91737	-0.03140	0.00000	0.72630
1959	-0.08702	0.00000	0.91874	-0.03168	0.00000	0.72746
1964	-0.08005	0.00000	0.90369	-0.02497	0.00000	0.65420
1969	-0.07656	0.00000	0.86761	-0.02796	0.00000	0.65959
1974	-0.06844	0.00000	0.82661	-0.02516	0.00000	0.58436
1979	-0.06402	0.00000	0.74438	-0.02581	0.00013	0.52789
1984	-0.08120	0.00001	0.74112	-0.03287	0.00097	0.52707
1989	-0.10374	0.00006	0.81260	-0.03545	0.05313	0.32461
1994	-0.10329	0.00653	0.80047	-0.06615	0.03336	0.62890