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OPINION

As in other taxa, relatively fewer beetles are being described by an increasing number of authors: response to Löbl and Leschen

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Introduction

Hundreds of taxonomists are sharing their knowledge through publishing online checklists of species names as part of the Catalogue of Life (CoL) and World Register of Marine Species (WoRMS) (Boxshall *et al.*, 2013; Costello *et al.*, 2013a; Roskov *et al.*, 2013a,b). Like the print literature, these species inventories are never as complete and accurate as readers may wish, but they can be more regularly improved than print publications, and they are freely and easily available online. Furthermore, because taxonomy is a rapidly progressing science, these lists will constantly need updating as new species are described and new knowledge revises species' classification and nomenclature (Costello *et al.*, 2013a). It is unfair to criticise such databases as being incomplete and containing errors as if the print literature was immune to such problems. Rather, experts could share their knowledge through open-access databases to improve them, instead of limiting their contributions to more conventional and sometimes expensive print publications (Costello *et al.*, 2013b). For example, the seven volumes of the 'Catalogue of Palaearctic Coleoptera' cited by Löbl & Leschen (2013) would cost over €1000. We have used CoL and WoRMS to estimate the rate of progress in discovering species – including the number of people naming new species – and to predict how many more species remain to be discovered (Costello & Wilson, 2011; Costello *et al.*, 2012, 2013c). Here we respond to criticisms from Löbl & Leschen (2013) of these studies.

Data quality

Having been involved in the publication of species inventories for 25°years, including national checklists and reviews (Costello, 1988, 2000; Costello *et al.*, 1990; Holmes *et al.*, 1997), regional (Costello *et al.*, 1996, 2001, 2006) and global (Costello *et al.*, 2010, 2013a; Boxshall *et al.*, 2013) databases, and revisions of genera and new species descriptions (Myers & Costello, 1984, 1985; Myers *et al.*, 1987), we are well aware of the potential weaknesses therein, and the need to take care when using such data that they are fit for purpose. Thus, when conducting an analysis of species inventories in CoL, we filtered the data through 26 steps resulting in our using 444 307 of the 2 million potential species names available (Costello *et al.*, 2012, Supplementary Material). Löbl & Leschen (2013) have overlooked this part of our analysis and our history of study in this area when they accuse us of 'naive data mining'. Furthermore they incorrectly say we 'considered [the data] as taxonomically … robust' when we never used that term in the paper.

Löbl & Leschen (2013) point out that some families of beetles in CoL were incomplete and included nomenclatural errors. It is not clear which version of CoL they refer to because they do not cite it as requested either for the online 'Dynamic' or compact-disc 'Annual' CoL Checklists (Roskov *et al.*, 2013a,b), and cite the date accessed as 17 October 2013 when their paper was accepted for publication on 6 September 2013. However, as we described in the Supplementary Material of our paper, these families were not included in our data analysis. Even if they were, they would have contributed < 1% of the species we analysed and thus would not have had any noticeable effect on the overall trends.

Although incomplete, CoL is by far the leading initiative to list all species on Earth, and is thus the primary source of accepted species names by many organisations and researchers, including the Global Biodiversity Information Facility (GBIF) and Encyclopedia of Life. Errors are also inevitable in an initiative with over 2°million species names. Nearly all of the Global Species Databases (GSD) in CoL have been updated since the 2009 version used in our study and many new ones have been added. For example, since our analysis, the number of butterflies and moths in CoL has decreased to 62% of what it was in 2009 due to reconciliation of synonymies, whereas the number of scarab beetles has more than doubled. Furthermore, Species 2000 is pioneering in subjecting GSD to similar peer-review as papers in scientific journals. New analyses of the data may thus modify our findings, and the

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data are freely available in digital form should anybody wish to do so.

It is inevitable that databases, as with the literature, contain errors of omission, commission and data entry. In addition, some of our current knowledge will in the future be discovered to be in error. The issue is not whether some errors may exist, but whether they would bias the analysis. We recognised in our methods that there could be mistakes in the spelling of authors' names, that different authors may have the same names, that some authors changed their names during their career, there may be mistakes in data entry (e.g. incorrect year), and that some accepted names would be found to be synonyms and some synonyms may be found to be valid species. We also stripped accents and diacritical marks because these are sometimes accidentally omitted in databases and thus may give the appearance of different author names. We treated Linné and Linnaeus as the same person. Our analysis assumed such errors and variations were random, and neither we nor Löbl & Leschen (2013) provide any reason as to why this may not be the case. It is thus incorrect for Löbl & Leschen (2013) to say that we ignored these issues.

Known rates of synonymy in taxa can vary between 32 and 93% (reviewed in Costello *et al.*, 2013c), and are at least 40% across all marine species (Appeltans *et al.*, 2012). Löbl and Leschen say that 20% would be a 'meaningless' proportion of beetle names to be considered synonyms but do not provide an alternative, or suggest whether it is too high or low. We did not use CoL as a source for synonyms as that is not its purpose, and have used 20% as a minimum level (Costello *et al.*, 2012, 2013e). We may agree with Löbl and Leschen that synonymy rates are probably much higher than 20%, especially considering that more will be discovered.

One error that may not be random is that it takes time for synonyms to be discovered so there is a rapid decline in the number of known synonyms over time (Appeltans *et al.*, 2012). When synonymising species names, usually the earliest name is accepted. This would thus remove more recently named species from checklists of accepted names and reduce (i) the recent rate of species description, and (ii) estimates of how many more species remain to be discovered. Although no analyses have been published to show that rates of creation of synonyms have been declining, we suggest that they are due to more rigorous peer-review and publication standards in recent decades.

Data quantity

That CoL is incomplete does not compromise our analysis because even a complete checklist would still not include all species on Earth. Science invariably works with samples of the real world. These samples are inevitably biased by what, where, when and how samples were taken and analysed. Thus, new data should always be used to test prevailing paradigms. When combined with marine data from WoRMS, our analysis had the largest sample size ever used to study the rate of description of species on Earth. Thus, this data synthesis challenged paradigms about the rate of species discovery and numbers of people involved. Nevertheless, Löbl & Leschen (2013) conclude that a 'larger and more accurate meta-analysis is needed'. This is possible at any time.

Data analysis

Löbl & Leschen (2013) may have misunderstood our analyses of authorships. They are incorrect in stating that our analysis 'fails to account for occasional isolated descriptions, such as those from students in systematics who discontinue'. The data we used included all species descriptions, regardless of whether there was one or more species described in any given publication. Furthermore, we had studied not just the total number of authors at any time, but also the duration of their publication 'lives' and the number of species per author. Thus, we showed that the number of authors only describing one species has remained remarkably stable over time at about 40–42% per decade for nonmarine (CoL) and marine (WoRMS) species (Costello *et al.*, 2013c), the same percentage found for flowering plants of the world by Bebber *et al.* (2014) and for marine species by Appeltans *et al.* (2012). There is no indication in our and others' data that the proportion of more or less productive authors, or their publication lifetimes, has tended to increase or decrease over the past century. One may speculate that more comprehensive species descriptions and demanding publication standards increase taxonomic productivity by making it less likely that species will need to be described more fully at a later stage or be synonymised, although potentially decreasing the number of species an individual may describe. However, modern efficiencies of communications, travel, access to literature, sampling and laboratory methods, information technologies, and faster publication times, must also reduce the time it takes to discover and publish new species descriptions. Although changes in the productivity of individual scientists over time remains unquantified, the actual number of authors of new species has increased three-fold since the 1950s and taxonomic publications at more than twice this rate (Bebber *et al.*, 2014; Costello *et al.*, 2013c,d). This suggests that overall taxonomic productivity has increased.

Variation between taxa

It is well known that the patterns of description of different taxa vary significantly (e.g. Costello *et al.*, 1996, 2012, 2013d; Wilson & Costello, 2005; Costello & Wilson, 2011; Appeltans *et al.*, 2012), such that some are well known and others have many species remaining to be discovered. Differences in patterns of description and trends in authors between taxa are therefore not surprising. Löbl & Leschen (2013) draw attention to examples of hundreds of new beetle species being discovered in south-west Pacific islands. Such discoveries are to be expected in places with high endemicity. Yet, they use these local data to state that our findings, based on 0.5°million species, are 'erroneous for all beetles' when neither we nor they have actually studied trends in all beetles of the world.

Because the rate of species description varies between taxa and over time, it is important to be cautious in using the historic record to predict future discoveries. This is especially important with sample sizes where a few authors may alter the trends. Our methods accounted for this variation between authors over time and applied 95% confidence limits to predictions of how many more species remained to be discovered. In some cases, this variation was so large that no prediction was reasonable (Wilson & Costello, 2005; Costello & Wilson, 2011; Appeltans *et al.*, 2012; Costello *et al.*, 2012). This may be the case for some groups of beetles as suggested by Löbl & Leschen (2013).

The overall trends we found for 1/3 of all named species in (1) a constant rate of species description in recent decades, (2) an increasing number of authors involved, and (3) a decreasing number of species per year compared to authors describing species in that year (since the early 20th Century), are also the case for fossil mammals (Alroy, 2002), marine fish (Eschmeyer *et al.*, 2010), all marine species (Appeltans *et al.*, 2012), parasitic wasps (Bacher, 2012; Costello *et al.*, 2013c), flowering plants, spiders, amphibians, birds and mammals (Pimm *et al.*, 2010; Joppa *et al.*, 2011a,b), algae (De Clerck *et al.*, 2013), and for flowering plants (Bebber *et al.*, 2014). The key point is that when all taxa are combined the data show a decreasing catch of species per number of people describing them. Löbl and Leschen conclude that their own data on Palaearctic beetles confirm this. The fact that the same trends in species description occur in widely different taxa – plants and animals, marine and terrestrial, large and small – suggests a common causality.

Discussion

Löbl and Leschen suggested that we use more authoritative databases, but do not cite which ones, and that we work with experts. They fail to mention that we used two databases, CoL and WoRMS, and found the same trends in both. In fact, we recently published a paper with over 100 experts on marine species that support our findings (Appeltans *et al.*, 2012), and co-authored a database with over 260 taxonomic experts (Boxshall *et al.*, 2013). That paper examined individual taxa in detail, including numbers of cryptic species and the numbers of undescribed species in specimen collections. It reviewed the number of undescribed species sampled in over 100 field studies containing 33 000 species, and found the average proportion of species that could not be named was 31% (median 37%). A similar percentage of undescribed species was predicted by statistical modelling of the rate of species descriptions, although expert opinion estimated 2/3 of species remained to be discovered. Marine species are more difficult to sample than terrestrial and have shown a relatively higher rate of discovery since the 1950s (Costello *et al.*, 2012). In addition, recent specialist assessments of a variety of taxa have found that about two-thirds or more of their species have been named globally, namely 77% of marine fish (Eschmeyer *et al.*, 2010), 61% of micro and macro-algae (Guiry, 2012; De Clerck *et al.*, 2013), 70% of anemones (Fautin *et al.*, 2013), and 75% of flowering plants (Bebber *et al.*, 2014). Thus, it is likely that the proportion of species on Earth remaining to be described is closer to 1/3 than 2/3. Even if only half the species on Earth are named to date, this suggests there are about 3°million species on Earth, as suggested by eminent authors over 20°years ago (May, 1988; Gaston, 1991). Our findings are therefore consistent with an increasing number of specialist studies, as well as past studies that have been sometimes been overlooked in favour of more dramatic numbers.

Unfortunately Löbl & Leschen (2013) perpetuate unsubstantiated myths about a ‘worldwide downturn in numbers of taxonomists’ when their own data and other analyses show that there have never been so many people naming species. They say that ‘In museums worldwide taxonomic studies are in retreat’ without any supporting evidence or references. Undoubtedly, some museums, as with any group of organisations including universities and government agencies, may change priorities and suffer from financial cutbacks. However, this does not mean that taxonomy is in retreat worldwide. Continuing increases in the number of people describing species, estimates of perhaps 47 000 people involved in taxonomy (Costello *et al.*, 2013c), and more marine species described in the past decade than any previous one, appear to contradict this view. While it is likely that part-time authors, many of whom only describe one or a few species in their lifetime, may not call themselves taxonomists, it is evident that they have done some taxonomy. We have not found any trend in the proportions of most and least productive authors over time (Costello *et al.*, 2012, 2013c, 2014). Thus, there is no evidence that the increase in authors of new species is anything other than due to more people doing taxonomy, whether or not they are called taxonomists.

Löbl & Leschen (2013) tabulated the number of Palaearctic beetle species from selected families described in 10- and 50-year time periods since 1750, and the number of authors of those species. By 2009, 18 642 species had been named. They found a decreasing number of species described per author over time and agreed that it supported our data (and thus the other studies cited above). Since 2000, over 854 people have named new species of beetles from those families and geographic area (Löbl & Leschen, 2013), perhaps the largest ever number of authors of new species (per unit time) in this group.

We can understand that some people may find it difficult to accept the trends and patterns in taxonomic progress when it overturns widespread beliefs that taxonomy is declining and memorable hyper-estimates of global species diversity (Costello *et al.*, 2013d,e, 2014). The concluding sentences in Löbl & Leschen (2013) indicate a fear that such success will mean less funding for their science. Maybe such fears were a factor behind articles complaining about declines in taxonomic staff in particular institutions, and/or in hyperestimates of richness of particular taxa. We do not believe such concerns should influence the analysis or interpretation of the data. In any case, we have argued the opposite (Costello *et al.*, 2010, 2013d,e, 2014). The discovery of species has never been more urgent because of the threats of extinction; and discovery includes taxonomic revisions, species identification guides, and associated biology and ecology. This knowledge provides a greater appreciation of the diversity of life, formalised through naming species, that supports conservation efforts and understanding of the functioning of biodiversity from genes to ecosystems. We argue that the case for taxonomy has never been stronger. It is popular in science and wider society, is fundamental to biology, and making good progress.

We welcome and encourage further analyses of trends in taxonomy. These analyses will be facilitated by the publication of data in open-access databases such as CoL, WoRMS, GBIF and the Ocean Biogeographic Information System (OBIS) (Costello & Wieczorek, 2013; Costello *et al.*, 2013f). This cooperative approach will enable new syntheses and insights beyond the ability of a few scientists working in isolation. It is dependent on the continuing taxonomic revisions of species and their descriptions, study of specimen collections, and strategic field studies to fill taxonomic and geographic gaps.

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