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世界上已知维管植物有多少种？基于多个全球植物数据库的整合

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摘要: 维管植物是地球上生物多样性的重要组成部分, 拥有超过200年的研究历史。然而, 世界上有多少种维管植物, 其中有多少种已被发现和描述等问题迄今仍未很好回答。本文整合分析了全球4个主要植物数据库, 以期回答全球已发现和描述了多少物种的问题。结果表明, 全球已发现和描述的维管植物有376,366种(包括自然杂交种)。排除自然杂交种后, 全球共包含369,054种维管植物, 其中广义蕨类植物13,810种, 裸子植物1,172种, 被子植物354,072种。我们的结果比已有的4个数据库中的任何一个的物种数都至少要多17,700种。

关键词: 被子植物; 有花植物; 裸子植物; 石松植物; 蕨类植物; 物种多样性

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How many known vascular plant species are there in the world? An integration of multiple global plant databases

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ABSTRACT

Aims: Despite that vascular plants constitute an important component of overall global biodiversity and have been studied well over two centuries, the questions of “How many species of vascular plants are there in the world and how many of them have been discovered and described?” remain open. Here, we address the second of the two questions.

Method: We synthesized four global plant databases.

Results & Conclusions: Our study shows that for the entire global flora of vascular plants (including natural hybrids), 376,366 species have been discovered and validly described. When natural hybrids are excluded, the global flora includes 369,054 species of vascular plant species, of which pteridophytes (ferns and lycophytes), gymnosperms and angiosperms have 13,810, 1,172 and 354,072 species, respectively. The number of vascular plant species derived from our study is larger than any of the other four databases by at least 17,700 species.

Key words: angiosperm, flowering plant, gymnosperm, lycophyte, pteridophyte, species diversity

维管植物包括广义蕨类(包括石松植物和狭义蕨类植物)、裸子植物和被子植物, 是生物多样性的重要组成部分(Borsch et al, 2020)。维管植物的重要

性不仅在于其多样性本身, 也在于它们能够影响许多其他类群的多样性(Pimm & Joppa, 2015)。自林奈以来, 维管植物已有两百多年的研究历史, 但世界

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上究竟有多少种? 其中有多少已被发现并描述? 这两个问题仍未很好地解决。基于统计模型或特定分类群(如科级水平), 不少研究已对全球维管植物物种的数量进行过估计, 结果差异巨大, 从不足25万到超过40万不等, 大部分估计在30万至40万之间。例如Christenhusz和Byng (2016)报道全球维管植物物种数为308,312种, 而Pimm和Joppa (2015)的报道为390,923种, 数量上至少有8万种的差距。

准确确定全球已发现和描述的维管植物物种数需要一个包含已发表的所有维管植物名称及其异名(synonyms)与接受名(accepted names)之间的对应关系的名录。The Plant List (TPL; version 1.0, 2010; version 1.1, 2013; <http://www.theplantlist.org>)是首个记录世界植物名称的名录, 涵盖了维管植物和苔藓植物。然而, 在TPL v1.1版本中, 22.8%的植物名被归类为未解决的名称, 很多学名被错误处理。例如, 基于TROPICOS数据库(<https://www.tropicos.org/home>), *Cyclosorus procurrens* (Mett.) Copel. 和 *Thelypteris procurrens* (Mett.) C. F. Reed 属于同一物种的同模式异名(homotypic synonyms), 但TPL将二者归为两个接受名(即两个不同物种)。维管植物名称的不规范化使用无疑会导致物种多样性被高估或低估。此外, TPL数据库自2013年以来长期处于更新停滞状态。

在过去的10年, 以TPL为主要基础, 新开发了5个全球植物数据库: World Flora Online (WFO; <https://www.worldfloraonline.org>)、Plants of the World Online (POWO; <https://www.plantsoftheworldonline.org>)、World Checklist of Vascular Plants (WCVP; <https://wcvp.science.kew.org/>)、The Leipzig Catalogue of Vascular Plants (LCVP; Freiberg et al, 2020)和World Plants (WP; <https://www.worldplants.de>)。与TPL相比, 这些数据库提供了全球维管植物物种多样性的更准确数据, 但每一个数据库都包含一些接受名不存在于另一个数据库中的情形。例如, 在WP数据库中(2021年2月21日查询), 2015年建立并发表的 *Hysterobaeckea* 属包含11种接受名, 但该属在LCVP中被遗漏, 其中3种被归类为 *Babingtonia* 属(*B. behrii* (Schltdl.) A. R. Bean) 和 *Baeckea* 属(*B. ochropetala* F. Muell. 和 *B. tuberculata* Trudgen) 的接受种, 另外8种(*Hysterobaeckea cornuta* Rye; *H.*

glandulosa Rye; *H. graniticola* Rye; *H. longipes* Rye; *H. occlusa* Rye; *H. petraea* Rye; *H. pterocera* Rye; *H. setifera* Rye)均未被包括在LCVP中。此外, 对于一个特定数据库, 由于拼写错误, 一些物种名称多次被误定为接受名, 如: *Helichrysum auronitens* Sch. Bip. 与 *Helichrysum aureonitens* Sch. Bip., *Senecio cinerifolius* H. Lév. 与 *Senecio cinerifolius* H. Lév.; *Stevia strotheriana* B. L. Turner 与 *Stevia strotherana* B. L. Turner; *Taraxacum idlomorphoides* Rail. 与 *Taraxacum idiomorphoides* Rail. 等在LCVP中存在误定。因此, 相比于仅使用其中一个数据库, 综合上述5个数据库中的信息才能更准确地估计全球维管植物物种数。

本文旨在整合WFO、POWO、LCVP和WP等4个主要全球植物数据库中的信息, 确定世界上已知维管植物物种数。本研究中我们未考虑TPL和WCVP两个数据库, 因为TPL是WFO的前身, 而WCVP和POWO都是由英国皇家植物园邱园建立, 且POWO包含了WCVP中的植物名。由于这4个主要的全球植物数据库中已涵盖了非常全面的、有关全球植物的信息(Freiberg et al, 2020), 本研究也未考虑其他维管植物特定类群的全球和区域植物数据库。

1 研究方法

LCVP数据库来自Freiberg等(2020)的LCVP名录, WFO、POWO和WP在各自网站中查询获得(访问时间为2021年2月)。采取以下步骤匹配每对数据库之间的植物名称: (1)通过拉丁名及其命名人名组合进行匹配; (2)对于第一步中未匹配上的名称, 先基于拉丁名进行匹配, 然后人工核实每一个命名人名是否与拉丁名匹配; (3)使用各种R语言软件包中的模糊匹配算法: Taxonstand (Cayuela et al, 2012)、WorldFlora (Kindt, 2020)、lcvplants (Freiberg et al, 2020)或在线名称匹配应用程序(如: Taxonomic Name Resolution Service, <http://tnrs.iplantcollaborative.org>)以匹配名称(包括学名和作者名), 并首先根据属名, 然后根据种加词、种下等级名称及作者名对匹配名进行核实; (4)从属名和种加词中均选取特定数量的字母进行各种组合(如属名的前10个字母加上种加词的前6个字母), 通过属名和种加词对匹配的名称进行人工核对。

在上述步骤中,我们也通过对拉丁名和命名人名微小修改来执行进一步匹配。例如,对于在使用原始拉丁名和命名人名进行初始匹配过程中未匹配到的名称,采取以下措施进行进一步匹配:(a)去掉拉丁名中的栽培种符号“x”和连字符“-”,并将“ae”、“ai”、“ei”、“yi”和“ii”替换为“i”;(b)删除命名人名中的点和空格,并将“fil.”替换为“f.”;(c)将原拉丁名和命名人名中的所有字母都改成对应的小写字母。在上述每个匹配过程中都会对匹配上的名称进行人工检查。这种多步骤的过程可以最大限度地匹配不同数据库间的名称。

本工作将LCVP数据库作为名称的主体。对于一个指定的接受名,如在一个或多个名称中,由于拼写错误(或变体)而出现重复,仅保留拼写正确的那个。对于在POWO、WFO和WP中被定为接受名的,如果它们及其异名没有任何一个作为接受名包括在LCVP中,将它们定为在LCVP之外的接受名。通过以下方法将每个物种归于一个目中:广义蕨类植物使用PPG I (Pteridophyte Phylogeny Group I)分类系统(Schuettpelz et al, 2016),裸子植物使用密苏里植物园数据库(<http://www.mobot.org/MOBOT/research/APweb>)中的分类系统,被子植物使用APG IV (Angiosperm Phylogeny Group, 2016)分类系统。

2 结果

全球已发现并描述的维管植物有376,366种(包括自然杂交种;表1;本文中的物种数目统计均不包含种下等级类群),其中广义蕨类14,307种,种子植物362,059种。种子植物中有1,217种裸子植物和360,842种被子植物。排除自然杂交种后,全球已发现和描述的维管植物有369,054种,其中广义蕨类13,810种,裸子植物1,172种,被子植物354,072种。

对所有维管植物目水平进行已描述和接受的物种统计后发现(表1),物种数最多的5个目是天门冬目(含杂交种为42,236种,排除杂交种为40,736种)、菊目(41,868种和41,459种)、唇形目(29,365种和28,447种)、豆目(26,412种和26,301种)和禾本目(25,379种和24,667种)。

3 讨论

本文旨在解决一个长期存在争议但极为重要

的问题,即世界上有多少种已知维管植物?由于许多植物名称是异名(即同一植物有很多不同的名称),且许多异名与它们的接受名之间的关系很难确定,因此回答这一问题并非易事。据统计,平均每个维管植物有2.7个学名(Kew, 2016)。当同种植物被不同学者在不同时期命名了不同学名时,一个物种有一个以上学名的情况就会出现。然而,相比于其他全球植物数据库,本研究中使用的主干数据库LCVP中未解决的植物名称数量相对较少,如:LCVP数据库有5%未解决,而TPL数据库有21%未解决(Freiberg et al, 2020)。本文通过综合4个数据库中的信息,梳理了它们之间错综复杂的关系,因此与之前基于统计模型的估计(Paton et al, 2008; Pimm & Joppa, 2015; Lughadha et al, 2016)或单一物种名录(Freiberg et al, 2020)相比,提供了目前已知的全球维管植物物种数的最准确估计(包括杂交种共376,366种,不包括杂交种共369,054种)。相比于LCVP (351,180个维管植物接受种)(Freiberg et al, 2020)、WP (351,263个接受种)(<https://www.worldplants.de>; 2021年2月21日访问)、POWO (348,705个接受种)(www.plantsoftheworldonline.org; 2021年2月21日访问)和WFO (350,510个维管和苔藓植物的已接受物种)(www.worldfloraonline.org; 2021年2月21日访问),本研究得到的维管植物物种数比4个数据库中的任何一个都至少要多17,700种。

本研究整理出的LCVP数据库以外的大多数物种源自POWO和WP数据库。Freiberg等(2020)在其附录1中指出LCVP使用了POWO数据。虽然他们没有将WP列为LCVP的直接源数据库,但确实提到使用了WP和Catalogue of Life数据库。值得注意的是:为什么LCVP遗漏了那么多在POWO和WP中可获取的植物名?其中一个原因可能是使用了过时的POWO和WP版本。Freiberg等(2020)表明LCVP中使用的POWO数据于2018年11月从Kew获得,仅包含约793,000个植物名称(~335,000个接受名,~458,000个被标记为异名)。而本文使用的POWO数据库版本包含了约110万个植物名,比用来构建LCVP的POWO数据库的版本多了约30万个名称。Freiberg等(2020)用来构建LCVP的WP数据库版本是由Hassler (2019)为Catalogue of Life生成的,因此这个版本相较于本研究中使用的版本而言已经过时。

表1 全球各维管植物目所包括的物种数

Table 1 Number of species that have been validly described for each of the orders of vascular plants in the world

目 Order	物种数量 Number of species		目 Order	物种数量 Number of species	
	包括杂交种 Incl. hybrid	排除杂交种 Excl. hybrid		包括杂交种 Incl. hybrid	排除杂交种 Excl. hybrid
蕨类植物 Pteridophyte			缨子木目 Crossosomatales	77	77
桫欏目 Cyatheales	793	782	葫芦目 Cucurbitales	3,232	3,215
木贼目 Equisetales	45	35	五桠果目 Dilleniales	567	567
里白目 Gleicheniales	177	173	薯蓣目 Dioscoreales	909	907
膜蕨目 Hymenophyllales	637	634	川续断目 Dipsacales	1,471	1,432
水韭目 Isoetales	208	203	杜鹃花目 Ericales	14,638	14,445
石松目 Lycopodiales	522	513	南鼠刺目 Escalloniales	154	147
合囊蕨目 Marattiales	151	151	豆目 Fabales	26,412	26,301
瓶尔小草目 Ophioglossales	132	128	壳斗目 Fagales	1,670	1,435
紫萁目 Osmundales	26	24	丝缨花目 Garryales	27	27
水龙骨目 Polypodiales	10,560	10,123	龙胆目 Gentianales	23,687	23,600
松叶蕨目 Psilotales	19	19	牻牛儿苗目 Geraniales	953	934
槐叶蕨目 Salviniales	82	81	大叶草目 Gunnerales	67	66
莎草蕨目 Schizaeales	224	213	腺椒树目 Huerteales	30	30
卷柏目 Selaginellales	731	731	茶茱萸目 Icacinales	187	187
裸子植物 Gymnosperm			唇形目 Lamiales	29,365	28,447
柏目 Cupressales	458	441	樟目 Laurales	3,955	3,954
苏铁目 Cycadales	376	375	百合目 Liliales	1,897	1,876
银杏目 Ginkgoales	1	1	木兰目 Magnoliales	3,565	3,542
买麻藤目 Gnetales	120	117	金虎尾目 Malpighiales	20,197	19,749
松目 Pinales	262	238	锦葵目 Malvales	7,770	7,605
被子植物 Angiosperm			水媳花目 Metteniusales	66	66
菖蒲目 Acorales	2	2	桃金娘目 Myrtales	15,400	15,203
泽泻目 Alismatales	4,832	4,729	睡莲目 Nymphaeales	109	101
无油樟目 Amborellales	1	1	酢浆草目 Oxalidales	2,164	2,160
伞形目 Apiales	6,400	6,377	露兜树目 Pandanales	1,699	1,698
冬青目 Aquifoliales	770	766	盔被花目 Paracryphiales	42	42
棕榈目 Arecales	2,814	2,784	无叶莲目 Petrosaviales	4	4
天门冬目 Asparagales	42,236	40,736	苦榄木目 Picramniales	57	57
菊目 Asterales	41,868	41,459	胡椒目 Piperales	4,512	4,512
木兰藤目 Austrobaileyales	91	91	禾本目 Poales	25,379	24,667
红珊藤目 Berberidopsidales	4	4	山龙眼目 Proteales	2,085	2,080
紫草目 Boraginales	3,711	3,674	毛茛目 Ranunculales	6,328	6,207
十字花目 Brassicales	5,502	5,393	蔷薇目 Rosales	11,985	11,428
绒球花目 Bruniales	90	90	檀香目 Santalales	2,636	2,632
黄杨目 Buxales	135	135	无患子目 Sapindales	7,071	7,036
白樟目 Canellales	129	129	虎耳草目 Saxifragales	3,359	3,134
石竹目 Caryophyllales	15,362	15,020	茄目 Solanales	5,493	5,469
卫矛目 Celastrales	1,437	1,437	昆栏树目 Trochodendrales	2	2
金鱼藻目 Ceratophyllales	7	7	黄漆姑目 Vahliales	5	5
金粟兰目 Chloranthales	75	75	葡萄目 Vitales	1,105	1,101
鸭跖草目 Commelinales	959	956	姜目 Zingiberales	2,999	2,986
山茱萸目 Cornales	744	731	蒺藜目 Zygophyllales	343	343


LCVP数据库约有63,000个植物名称为“未解决”状态。其中, 60,710个是种等级上的植物名称。然而, 约有14,500个名称在POWO和/或WP中被确定为接受名或异名。在本研究中, 未解决名称的比例从LCVP的5%下降到3.7%。尽管LCVP中有一些仍未解决名称将来可能成为接受名, 但我们支持Freiberg等(2020)的观点, 认为这些未解决名称中的多数仍可能是异名。

本研究通过整合LCVP、POWO、WFO和WP等4个主要的全球植物数据库, 报道了全球已知维管植物物种数。我们认为这些数据库至少包括了2019年之前发表的所有植物名称。Christenhusz和Byng (2016)及Cheek等(2020)的研究表明, 近十多年来, 每年发表的维管植物新物种(除新组合combinations外)的数量平均在2,000个左右。可以预测, 这一趋势在未来一段时间内还将持续。

本文的英文版参见网站<http://www.biodiversity-science.net/fileup/PDF/2022254-1.pdf>。

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•English Version•

How many known vascular plant species are there in the world? An integration of multiple global plant databases

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ABSTRACT

Aims: Despite that vascular plants constitute an important component of overall global biodiversity and have been studied well over two centuries, the questions of “How many species of vascular plants are there in the world and how many of them have been discovered and described?” remain open. Here, we address the second of the two questions.

Method: We synthesized four global plant databases.

Results & Conclusions: Our study shows that for the entire global flora of vascular plants (including natural hybrids), 376,366 species have been discovered and validly described. When natural hybrids are excluded, the global flora includes 369,054 species of vascular plant species, of which pteridophytes (ferns and lycophytes), gymnosperms and angiosperms have 13,810, 1,172 and 354,072 species, respectively. The number of vascular plant species derived from our study is larger than any of the other four databases by at least 17,700 species.

Key words: angiosperm; fern, flowering plant; gymnosperm, lycophyte; pteridophyte; species diversity

1 Introduction

Vascular plants, i.e. pteridophytes, gymnosperms and angiosperms, form a large taxonomic sample of biodiversity. They are important not only in themselves but also in directly determining the diversity of many other taxonomic groups (Pimm & Joppa, 2015). Vascular plants constitute the basis of most terrestrial ecosystems (Borsch et al, 2020). Despite that vascular plants constitute an important component of overall global biodiversity and have been studied well over two centuries, the questions of how many species of vascular plants there are in the world and how many of them have been discovered and described remain open. Several studies have reported estimates of these numbers based on statistical models or selected taxonomic groups (e.g. families), but the estimated number of the world's vascular plant species varies greatly among studies, ranging from fewer than 250,000 to more than 400,000, and most of the estimated numbers fall in the range from 300,000 to 400,000 species (e.g. 308,312 species in Christenhusz & Byng (2016), 390,923 species in Pimm & Joppa (2015).

Accurately determining how many species of

vascular plants in the world that have been discovered and described requires a synonymized checklist that includes all published names of vascular plants and the relationships between synonyms and their accepted names. The Plant List (TPL; version 1.0, 2010; version 1.1, 2013; <http://www.theplantlist.org>) was the first synonymized checklist of the world's plants, including both vascular plants and bryophytes. However, 22.8% of the plant names in the version 1.1 of TPL were not resolved. In addition, many names were incorrectly resolved. For example, according to TROPICOS (<https://www.tropicos.org/home>), *Cyclosorus procurrens* (Mett.) Copel. and *Thelypteris procurrens* (Mett.) C. F. Reed are homotypic synonyms for a single species, but TPL treated them as two accepted names (i.e. two different species). This would ultimately overestimate species diversity. TPL has been static since 2013.

Largely based on TPL, five other global plant databases have been developed in parallel in the past decade: World Flora Online (WFO; www.worldfloraonline.org), Plants of the World Online (POWO; www.plantsoftheworldonline.org), World Checklist of Vascular Plants (WCVP; wcvp.science.kew.org), The Leipzig Catalogue of Vascular Plants (LCVP; Freiberg et al, 2020), and World Plants (WP; <https://www.worldplants.de>).

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Although each of these plant databases can result in a more accurate number for global species diversity of vascular plants, compared to TPL, each of them includes a number of accepted species names that are absent from the other three databases. For example, according to WP (accessed on Feb. 21, 2021), the genus *Hysterobaeckea*, which was established and published in 2015, includes 11 accepted species; the genus was missing from LCVP; three species of the genus were treated as accepted species in the genera *Babingtonia* (*B. behrii* (Schltdl.) A. R. Bean) or *Baeckea* (*B. ochropetala* F. Muell.; *B. tuberculata* Trudgen) in LCVP and the other eight species were missing from LCVP (i.e. *Hysterobaeckea cornuta* Rye; *H. glandulosa* Rye; *H. graniticola* Rye; *H. longipes* Rye; *H. occlusa* Rye; *H. petraea* Rye; *H. pterocera* Rye; *H. setifera* Rye). In addition, for a particular database, some species names were treated as accepted names more than once due to misspellings in species names (e.g., *Helichrysum auronitens* Sch. Bip. versus *Helichrysum aureonitens* Sch. Bip.; *Senecio cinarifolius* H. Lév. versus *Senecio cinerifolius* H. Lév.; *Stevia strotheriana* B. L. Turner versus *Stevia strotherana* B. L. Turner; *Taraxacum idiomorphoides* Rail. versus *Taraxacum idiomorphoides* Rail.), which would have necessarily led to overestimate of species diversity in LCVP. Synthesizing the information available in the above-mentioned global plant databases can lead to a more accurate estimate for the number of vascular plant species known to science, compared to considering any one of the databases alone.

The objective of this study is to synthesize the botanical information available in four major global plant databases (i.e. WFO, POWO, LCVP and WP) to determine how many species of vascular plants known to science there are in the world. We do not consider TPL because it is a predecessor of WFO. We do not consider WCVF because both WCVF and POWO were generated by Royal Botanic Gardens, Kew, and plant names of WCVF were included in POWO. We do not consider other global databases for particular groups of vascular plants and regional plant databases in this study because the information in them has already been included in the four major global plant databases considered in the present study (e.g., see Online-only Table 1 of Freiberg et al, 2020).

2 Methods

For LCVP, we used the checklist published in Freiberg et al. (2020). For WFO, POWO and WP, we retrieved data from their websites as shown above (last time accessed in February 2021). We took multiple steps to

link plant names between each pair of the databases. First, we matched names using the combinations of Latin names and their authorities. Second, for those names that were not matched in the first step, we matched names based on Latin names and visually checked authorities for the matched Latin names. Third, we used fuzzy matching algorithms implemented in various software packages (e.g. Taxonstand, Cayuela et al, 2012; WorldFlora, Kindt, 2020; lcvplants, Freiberg et al, 2020) or online name matching applications (e.g. Taxonomic Name Resolution Service, <http://tnrs.iplantcollaborative.org>) to match names (with or without name authorities) and visually checked the matched names first by their generic names and then by specific and infraspecific epithets. Fourth, we used various combinations of a given number of letters from a generic name and a given number of letters from a specific epithet (e.g. the first 10 letters of the generic name plus the first 6 letters of the specific epithet of a Latin name) and visually checked the matched names first by their generic names and then by specific epithets. In each of the above-outlined steps, we conducted several matching processes by slightly modifying Latin names and authorities. For example, for those names that were not matched in the initial matching processes using the original Latin names and authorities, we removed the hybrid sign 'x' and hyphen and replaced 'ae', 'ai', 'ei', 'yi' and 'ii' with 'i' in Latin names; we removed dot and space and replacing 'fil.' with 'f.' in authorities; we changed all letters in the original Latin names and authorities to letters in their respective lower cases. Visual checking for matched names was applied in each matching process. These multi-step processes would have maximized matching for names among different databases.

We used the LCVP database as the nomenclature backbone of our study. For a given accepted species, if there are duplicate accepted species names due to misspellings (or orthographic variants) in one or more names, we only retained the one with correct spelling. For those names that were treated as accepted species names in one or more of the other three databases (i.e. POWO, WFO and WP), if none of them and their synonyms in the three databases were included in LCVP as either accepted names or synonyms, we considered them as accepted species names in addition to those in LCVP. We assigned each species to an order using the classification system developed by Pteridophyte Phylogeny Group (Schuettpelz et al, 2016) for pteridophytes, the classification system available at Angiosperm Phylogeny Website (<http://www.mobot.org/MOBOT/research/APweb/>) for gymnosperms, and APG IV (Angiosperm Phylogeny

Group, 2016) for angiosperms.

3 Results

For the entire global flora of vascular plants (including natural hybrids), 376,366 species have been discovered and described (Table 1). These include 14,307 species of pteridophytes and 362,059 species of seed plants. When gymnosperms and angiosperms are considered separately, the world flora includes 1,217 species for gymnosperms and 360,842 species for angiosperms. When natural hybrids are excluded, the global flora includes 369,054 species of vascular plant species. When different major taxonomic groups are considered separately, pteridophytes, gymnosperms and angiosperms have 13,810, 1,172, and 354,072 species, respectively.

We reported a list of all vascular plant orders with the numbers of described and accepted species in Table 1. The five largest orders are Asparagales (42,236 and 40,736 species with and without hybrids, respectively), Asterales (41,868 and 41,459), Lamiales (29,365 and 28,447), Fabales (26,412 and 26,301), and Poales (25,379 and 24,667).

4 Discussion

Our study aims at addressing the long-standing question: How many species of vascular plants in the world have been discovered? Answering this question is difficult because many plant names are synonyms (i.e. different names given to the same plant) and the relations of many synonyms to their accepted names are difficult to resolve. Many vascular plants have more than one scientific name (averaging 2.7 names per vascular plant; https://stateoftheworldsplants.org/2016/report/sotwp_2016.pdf). This happens when the same plant species has been given different names, mostly by different people at different times. Nevertheless, the number of unresolved plant names in the backbone database that we used in this study (i.e. LCVP) is relatively small, compared some other global plant databases (e.g. 5% in LCVP versus 21% in TPL; Freiberg et al, 2020). By synthesizing the botanical information in the four databases of the world's plants, we provide the most accurate estimate for the number of the world's vascular plant species known to science (i.e. 376,366 and 369,054 species with and without hybrids, respectively), compared to previous estimates based on statistical models (e.g. Nic Lughadha et al, 2016; Paton et al, 2008; Pimm & Joppa, 2015) or a single synonymized checklist (e.g. Freiberg et al, 2020). For example, for vascular plants, LCVP includes 351,180 accepted species (Freiberg et

al, 2020), WP includes 351,263 accepted species (<https://www.worldplants.de/world-plants-complete-list/total-species-count>; accessed Feb. 21, 2021), and POWO includes 348,705 accepted species (www.plantsoftheworldonline.org; accessed Feb. 21, 2021). WFO includes 350,510 accepted species for both vascular plants and bryophytes (www.worldfloraonline.org; accessed Feb. 21, 2021). Thus, the number of vascular plant species derived from our study is larger than any one of the other four databases by at least 17,700 species.

The vast majority of the species that are additional to LCVP were taken from POWO and WP. In their Online-only Table 1, Freiberg et al (2020) stated that LCVP used data in POWO. Although they didn't directly list WP as a source database for LCVP, they did list WP along with Catalogue of Life as one of the data sources that they used. An interesting question is: Why did LCVP miss so many plant names that are available in POWO and WP? One possible reason may be that LCVP used substantially outdated versions of POWO and WP databases. As Freiberg et al (2020) stated, the POWO data used in LCVP was obtained directly from Kew in November 2018, which included only ~793,000 plant names (~335,000 accepted species names, ~458,000 names of vascular plants marked as synonyms). The version of the POWO database that we used, which included ~1.1 millions of plant names, had ~300,000 more names than the version of the POWO database that Freiberg et al (2020) used to build LCVP. The version of the WP database that Freiberg et al (2020) used to build LCVP was generated by Hassler (2019) for Catalogue of Life. This was a substantially outdated version of the WP database, compared with the version of the WP database that we used in the present study.

About 63,000 of the plant names in LCVP are unresolved. Of these names, 60,710 are plant names at the species rank. However, ~14,500 of these names were resolved in POWO and WP as either accepted names or synonyms. Thus, the proportion of unresolved names was reduced from 5% in LCVP to 3.7% in our study. Although some of the still unresolved names in LCVP may become accepted names in future, the result of our study supports the notion of Freiberg et al (2020) that most of these unresolved names are likely synonyms.

The number of accepted species of the world's vascular plants known to science that was reported in this study was based on four major global plant databases (i.e. LCVP, POWO, WFO and WP). We believe these databases have collectively included all published plant names up to at least 2019. Christenhusz

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Table 1 Number of species that have been validly described for each of the orders of vascular plants in the world


Order	Number of species		Order	Number of species	
	Incl. hybrid	Excl. hybrid		Incl. hybrid	Excl. hybrid
Pteridophyte			Crossosomatales	77	77
Cyatheales	793	782	Cucurbitales	3232	3215
Equisetales	45	35	Dilleniales	567	567
Gleicheniales	177	173	Dioscoreales	909	907
Hymenophyllales	637	634	Dipsacales	1471	1432
Isoetales	208	203	Ericales	14638	14445
Lycopodiales	522	513	Escalloniales	154	147
Marattiales	151	151	Fabales	26412	26301
Ophioglossales	132	128	Fagales	1670	1435
Osmundales	26	24	Garryales	27	27
Polypodiales	10560	10123	Gentianales	23687	23600
Psilotales	19	19	Geraniales	953	934
Salviniales	82	81	Gunnerales	67	66
Schizaeales	224	213	Huerteales	30	30
Selaginellales	731	731	Icacinales	187	187
Gymnosperm			Lamiales	29365	28447
Cupressales	458	441	Laurales	3955	3954
Cycadales	376	375	Liliales	1897	1876
Ginkgoales	1	1	Magnoliales	3565	3542
Gnetales	120	117	Malpighiales	20197	19749
Pinales	262	238	Malvales	7770	7605
Angiosperm			Metteniusales	66	66
Acorales	2	2	Myrtales	15400	15203
Alismatales	4832	4729	Nymphaeales	109	101
Amborellales	1	1	Oxalidales	2164	2160
Apiales	6400	6377	Pandanales	1699	1698
Aquifoliales	770	766	Paracryphiales	42	42
Arecales	2814	2784	Petrosaviales	4	4
Asparagales	42236	40736	Picramniales	57	57
Asterales	41868	41459	Piperale	4512	4512
Austrobaileyales	91	91	Poales	25379	24667
Berberidopsidales	4	4	Proteales	2085	2080
Boraginales	3711	3674	Ranunculales	6328	6207
Brassicales	5502	5393	Rosales	11985	11428
Bruniales	90	90	Santalales	2636	2632
Buxales	135	135	Sapindales	7071	7036
Canellales	129	129	Saxifragales	3359	3134
Caryophyllales	15362	15020	Solanales	5493	5469
Celastrales	1437	1437	Trochodendrales	2	2
Ceratophyllales	7	7	Vahliales	5	5
Chloranthales	75	75	Vitales	1105	1101
Commelinales	959	956	Zingiberales	2999	2986
Cornales	744	731	Zygophyllales	343	343

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& Byng (2016) and Cheek et al (2020) showed that the numbers of new vascular plant species published per year (excluding new combinations) was, on average, ~2000 in the last two decades, including recent years (Cheek et al, 2020). We predict that about 2000 new vascular plant species will be discovered annually in the next few years or decade.

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