Article

What Does It Take To Further Our Knowledge of Plant Diversity in The Megadiverse South Africa?

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Abstract: Although South Africa is well known for its incredible biodiversity, targeted efforts are still required to accelerate the discovery and description of the still-unknown species in this floristically mega-diverse country. In addition, new species discovery is a new opportunity for the development of ethnobotanical knowledge. In the present study, we collected data on current knowledge of plant richness in the country and expert taxonomists' opinions and used statistical modelling technique to predict what might still be missing in South Africa's flora. According to experts' opinions and our modelling, we might be missing 1400-1575 plant species in the country. We predicted that we might take 40-45 years to identify and describe these species and that between 64 and 315 taxonomists will be required. The pool of taxonomists who took part in this study have spent a total of R 680 670 000 (US $40 039 411) to describe 419 species. This implies that, in theory, R 1 624 510.74 (US $95 559) was spent, on average, to describe 1 species. At this rate, R 2 558 604 415.00 (US $150 506 142) would be required to describe the 1575 (modelling) or R 2 274 315 036.00 (US $133 783 237) for the 1400 remaining species (expert opinion) in the current context where both full- and part-time taxonomists are committed to biodiversity assessment in the country. It is important to highlight that this estimate does not correspond to what is required specifically for only species description but does integrate all connected activities, e.g., running cost, bursary, salaries, grants, etc. Furthermore, we must bear in mind that these estimates do not account for the possibility of taxonomic revision which, on its own, needs to be funded, nor do they account for molecular laboratory requirement. However, if we consider that 15% of the predicted funds are spent solely on taxonomic activities, this means that we would need ~R243 673 (US$ 14 334) on 1 species. Overall, our study provides an important figure that can inform policy development including funding and recruitment strategies of taxonomists to fuel efforts towards a comprehensive assessment of the unique South Africa's biodiversity. The implication of new species discovery is that it opens windows for traditional knowledge development.

Keywords: Biodiversity; floristically mega-diverse; ethnobotanical knowledge; biodiversity assessments; taxonomic activities; comprehensive assessment

1. Introduction

How many species are there on Earth? This is an important question for all conservation biologists, as it is not possible to conserve biodiversity effectively if we have a biased knowledge of its extent [1-4]. Several studies have investigated the question [1,3-5] to estimate not only species diversity on Earth but also to quantify the remaining efforts to be deployed to maximize the chance of discovering and describing currently unknown species. These studies reported strikingly different estimates that are, in all cases, dramatically greater than the currently known 1.5 million species [6]. Early studies variously predicted species richness to be ~100 million [5,7-9], 8.7 million [3] or ~2 million species [10]. More recent studies escalated the predictions to ~1 trillion [11] or 1-6 billion species on Earth [4].

The striking difference in estimates is due to the fact that some studies focus preferentially on certain taxonomic groups, and they mostly did not use the same predictive tools. For example, in their analysis, Larsen et al. [4] incorporated for the first time morphologically cryptic species discovered through molecular analyses, and this increases exponentially the predicted global species richness in comparison to previous studies (e.g., [3]). Interestingly, even with these dramatic changes in predictions, one constant remains across all predictions; for example, ref. [3]'s prediction for plant species richness on Earth (298,000 species) is similar to the number of plant species currently described, which is roughly ~300,000 species [6]. In addition, ref. [3]'s predictive model has a strong power (R^2 =96%), suggesting that, in a given taxonomic level (e.g., genera, families or orders, etc.), 96 out of 100 of its species richness are correctly predicted by the model.

While these studies are assisting us in picturing the extent of biodiversity at global scale, the estimate of biodiversity at local scale, e.g., at country level, receives relatively less attention. This is an important knowledge gap that needs to be addressed, given that conservation efforts start from country level towards the global conservation effort. Although the ecosystem services provided by biodiversity contribute strongly to human well-being [12-15], species providing these services are being lost at an unprecedented rate, corresponding to the modern biodiversity crisis or the sixth mass extinction [16,17]. This crisis is characterized by an exponential loss of biodiversity, irrespective of the scenarios adopted – highly conservative or conservation scenarios [17]. Ref. [17]'s study reveals that species loss that occurred in the last 114 years could have taken 800 to 10,000 years to go extinct under a scenario of sustainable biodiversity management. An earlier report indicated that the current biodiversity loss may be 1,000-10,000 times greater than the background rate of species loss [13].

However, the vast majority of studies that demonstrate this biodiversity crisis focus on vertebrates. For example, 800 bird species described in recent decades in the islands of Oceania went extinct in the last 2,000 years due to anthropogenic pressure [18]. In the 1600s, extinctions of various vertebrate taxonomic groups (e.g., large mammals, birds, reptiles, amphibians, and fishes) were also reported [17,19-21]. For plant species, there is less information about the pattern of extinction rate as compared to vertebrates, and only 5% of described plant species are IUCN-assessed for their extinction status [22]. In addition, among the IUCN-assessed plant species, over 70% are at risk of extinction, a much higher proportion than the 22% reported for vertebrates [22]. The much conservative estimate of species loss suggests that the proportion of at-risk plant species might be similar to that of vertebrates. Specific predictions also suggest that some entire ecosystems may even go extinct in only 110 years (e.g., mangrove forests) if current anthropogenic pressures are maintained on the environment [23]. The loss of species is perhaps the most critical concern of our times, given that species loss would drive the loss of valuable ecosystem services and thus compromising human wellbeing [14,24,25].

In light of the alarming statistics of this biodiversity crisis, pre-emptive and urgent actions are required to prevent species loss at all costs. However, how can such actions take place in an effective way if we have limited knowledge of the extent of existing species diversity? More concerning is the fact that currently known extinction rate may be greater than the reality because several unknown species are undoubtedly sliding into extinction unnoticed, and we would not be able to account for them in our current estimate of the extent of biodiversity crisis since these species are not known to science. This calls for strong commitments to estimate the potential number of currently unknown species so that appropriate efforts (number of taxonomists, funds, time, and resources required) can be estimated, planned for, and deployed [3,26]. Given the ongoing biodi-

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versity crisis and the tremendous ecosystem services that may be at risk (due to loss of biodiversity), integrating taxonomic efforts into policy development documents becomes a national priority for all countries, particularly those that are known as megadiverse, e.g., South Africa, due to their incredible species richness.

South Africa has about 24,000 plant species and is home to 10% of the world's plant species richness [27,28] with more than 50% being endemic plant species. The terrestrial vegetation is classified into nine (09) biomes, including the Albany thicket, Dessert Forest, Fynbos, Grassland, Indian Ocean coastal belt, Nama Karoo, Savannah, and Succulent Karoo [29]. Furthermore, from the six renowned global floral kingdoms, South Africa hosts one in its entirety, that is, the Cape Floral Kingdom. This Floral Kingdom is deemed the smallest, richest and the most threatened of all [27,30]. Moreover, South Africa also has three recognised biodiversity hotspots i.e., the Cape Floristic Region, the Succulent Karoo and the Maputaland-Pondoland-Albany hotspot [27]. Unfortunately, 9% of South African plants are threatened, and these threatened plants are mostly found in the fynbos biome [30]. In addition, an early assessment of 427 vegetation types revealed that 5% of them are critically endangered, 12% are endangered and 16% are vulnerable, mostly in the Cape Floristic Region [31].

This South African context of plant and biome conservation status means that there is a need to accelerate taxonomic assessment so that measures and plans can be put in place not only for their conservation but also for the development of ethnobotanical knowledge. Although South Africa has a long rich history of taxonomic assessment, "there is still a need for further exploration of South Africa's biodiversity, so that improved foundational biodiversity information can be provided to end-users" [36]. Efforts towards such improvement cannot be done randomly; they have to be focused, targeted, prioritized and informed with knowledge of what potentially remains to be discovered and described. In response to these requirements, the present study aims to estimate not only the number of unknown vascular plant species in South Africa's flora but also the efforts required (time, funds, number of taxonomists) for a comprehensive botanical assessment of the mega-diverse South Africa.

2. **Materials and Methods**

2.**1. Study area**

South Africa, with its 1 219 602 km^2, is located at the southernmost tip of the African continent (Figure 1) from 22°S to 35°S Latitudes and from 17°E to 33°E to Longitudes [33]. Climatically, South Africa is a moderately dry country: ~67% of the country receives less than 500mm annual rainfall [34] and this rainfall generally occurs in summer, except around Cape Town, which witnesses a winter rainfall [35]. South Africa's climatic conditions generally range from Mediterranean in the southwestern corner of the country, to subtropical in the northeast corner [33]. In term of biodiversity, two thirds of the world plant diversity (~ 24,000 species) are found in South Africa, making it one of 17 megadiverse countries in the world. This huge biodiversity is found across nine biomes, including Nama-Karoo, Succulent Karoo, Fynbos, Forest, Albany Thicket, Savannah, Dessert, Indian Ocean Coastal Belt, and Grassland [29]. A vast network of protected areas is delimited in South Africa, including 1527 National Parks, nature reserves, wilderness areas, mountain catchment areas, and World Heritage sites [36]. Three major biodiversity hotspots are identified in South Africa, namely the Cape Floristic Region, the Succulent Karoo and Maputaland-Pondoland-Albany biodiversity hotspot. South Africa is the only country that hosts an entire floral Kingdom, the Cape Floral Kingdom, which is the smallest of the world's six floral Kingdoms [37. The Cape Floral Kingdom harbours > 9,000 plant species with ~ 70% endemic plants. However, evidence points to more species to be described, especially from biomes that are botanically less explored, e.g., Indian Ocean costal Belt. Revealing the extent of the country's diversity is key for policy development in the field of taxonomic and conservation.

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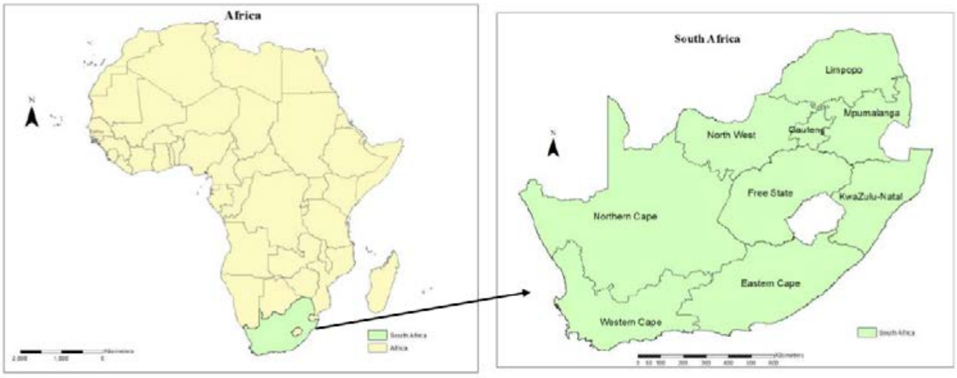

Figure 1. Location of South Africa

2.2. Data collection

To predict the number of unknown plant species, we collected two types of data: the number of native plant species currently known and catalogued in South Africa collected from the South African National Biodiversity Institute (SANBI, https://www.sanbi.org/), and the publication years (Table S1) of all catalogued South African native plant species collected from the International Plant Name Index (https://www.ipni.org/). A database consisting of the list of native species and their corresponding dates of publication was then created on an excel spreadsheet.

Next, we estimated the effort required to identify and describe the unknown species. In this study, effort is defined as time, fund, and number of taxonomists that could be required for the discovery and taxonomic description of unknown species. To collect data on these variables (time, fund, and number of taxonomists), we relied on expert knowledge collected through questionnaires (Supplemental Information), cell phone discussions, and office visits. These experts were identified from a SANBI record known as 'SANBI biodiversity series 26' [38]. This record identified 34 plant taxonomists; these taxonomists are certified professionals currently employed in academic, private, or governmental (e.g., SANBI) research institutions. We also considered retired taxonomists, some of whom were suggested by taxonomists that we contacted during data collected which resulted in the total number of taxonomists being 42. However, the challenge was that we could not reach the retired taxonomists even after contacting the institutions they were based prior to retirement. Prior to the questionnaire being distributed, a pilot study was conducted with two of the highly ranked taxonomists in South Africa. We used the outcomes of the pilot study to revise our questionnaire. To reach potential International Taxonomists and collaborators, who have at least described one species in South Africa, a google survey was created and the link was shared. Unfortunately, there were no international respondent even with all the efforts made to reach them. The goal was to collect as much quantitative data as possible regarding the effort (time, money, and work force) required to identify a species.

The questionnaire was divided into two parts; the first part focused on the demography, which highlighted the relevant qualifications and current employment status of the taxonomist (active or retired), etc. The second part of the questionnaire focused on the taxonomic activities of experts, which required the taxonomists to highlight the history of their job as taxonomist, how many species they have identified during their career, and most importantly, their estimation of the average efforts it took to identify a single species (Supplemental Information). All data collected are in Table S2.

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2.3. Data analysis

All quantitative analyses in this research project were done in R version 3.5.3 [39].

2.3.1. Number of unknown plant species in South Africa

We first tested, using the Dickey-Fuller test [40], that the number of species described in South Africa over time (1696-2019) follows a non-constant variance. After confirming the non-constant variance, we fitted a generalized autoregressive conditional heteroskedasticity (GARCH) model to the data. GARCH model was developed by ref. [41] to model volatile time-series data, i.e., data with a nonconstant variance. Different GARCH models were fitted with various starting time intervals for the modelling ((0,0), (1,1), (2,2),….). The best GARCH model was selected using Akaike Information Criteria (AIC). The selected model was then used to predict the future trend of the number of species over the next 120 years. This trend allows for the identification of the year Y_1 where the number of species to describe become 0 (Y_1 means the year all species are described). The difference between Y_1 and Y_0 (the present) corresponds to how long it will take to describe the remaining species in the country (See R-Script in Supplemental Information).

Apart from the modeling approach, expert's opinion approach was also used to estimate the number of unknown species. This method was also used in a similar study that Carbayo and Marques [42] conducted in Brazil. In their study, Carbayo and Marques surveyed 44 taxonomists (almost 9% of employed and doctoral taxonomists in Brazil) to estimate resources required to describe an entire animal kingdom. In the present study, a question was included in the questionnaire asking taxonomists to estimate, given their respective experiences as taxonomists, the number of remaining species that they believe are yet to be discovered in South Africa.

2.3.2. Determination of efforts required to identify and describe the unknown plant species

2.3.2.1 Time

For the time variable, the total number of respondents to our questionnaire (N) was considered as well as the respondent's career duration (Δt), and the number of species described by respondents during their respective careers (n_i). Then, the estimated time required to describe the remaining unknown plant species (Ts) was estimated as summarized below:

N = total number of respondents (taxonomists)

Δt = duration of career

n_i = number of species described during the career of a taxonomist (i)

If a taxonomist i describes n_i species during his/her career that lasts the time t_i, this implies that this taxonomist takes, on average, the time t_i/n_i to describe 1 species. As a result, for all the N taxonomists, the time ts to describe 1 species is:

ts = (1/N)∑(ti/ni) = average time to describe 1 species, considering all respondents.

Then the total time T_s required to describe all the unknown species $N_{unknown}$ is:

$Ts = ts\ x$ $N_{unknown}$ (estimated time required to describe the remaining unknown plant species).

2.3.2.2 Funds

The funds variable (fi) was determined by adding three factors (grants, salaries, and training fund of taxonomists). Research grants are the grants awarded to run and maintain a lab; salaries are the net salary per month of the principal investigator of the

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lab, and training funds are the total funds used to obtain a relevant qualification by a student (undergraduate – PhD in taxonomy). The funds required to describe all unknown species was estimated as follow:

f_i= (grants + salaries + training fund) = total fund spent by a taxonomist i to describe n_i species during his entire career.

f_i/n_i = funds to describe 1 species by a taxonomist i.

f =(1/N)$\sum(f_i/n_i)$ = average fund to describe 1 species by all N respondents.

F= f x $N_{unknown}$ = (total funds required to describe all unknown species)

Since this fund is not solely used for taxonomic studies, we also calculated the 15% of the fund reported elsewhere as the portion of the fund F used specifically for taxonomic projects [42].

2.3.2.3 Number of taxonomists

To determine the number of taxonomists needed to identify and describe $N_{unknown\ species}$, this was done as follows:

The total number of species described by N respondents is $\sum n_i$, n_i being the number of species described by a taxonomist i during his career.

As such the number of taxonomists required to describe $N_{unknown\ species}$ is:

Number of taxonomists = $\frac{N\ x\ Nunknown}{\sum ni}$.

3. Results

3.1. Structure of the population of taxonomists who took part in this study

3.1.1. Demography of taxonomists

The population of plant taxonomists (Figure 2A) who took part in this study are made up of a majority of male (63%). The vast majority of this pool of taxonomists is categorized as of middle-age (68%); a few of them are in their youth (20-40 years old) and a low percentage of currently active taxonomists is categorized as reaching mature age (11%; Figure 2B). Interestingly, these taxonomists are of high academic rank: Professors (32%), Associate Professors (21%), and PhD-graduates (26%; Figure 2C) who are mostly affiliated with universities (68%) or research institutions (32%; Figure 2D).

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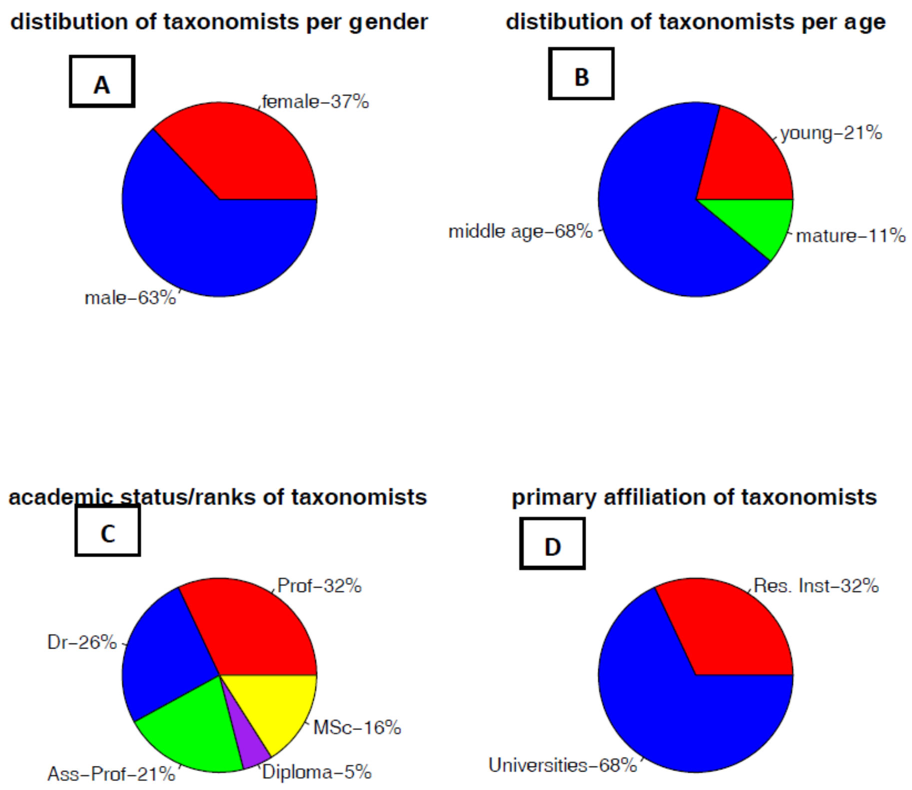

Figure 2. Summary of the demographic structure of the population of taxonomists who took part in this study. Dr= Doctor; Ass-Prof.= Associate Professor; Prof.=Professor; Res. Inst=Research Institutions

3.1.2. Taxonomic activities

The analysis of data collected through questionnaires shows that taxonomists in South Africa are very active. In terms of publications, some have published over 200 papers in taxonomy; others, 50-80 papers and many have published 20-50 papers (Figure 3).

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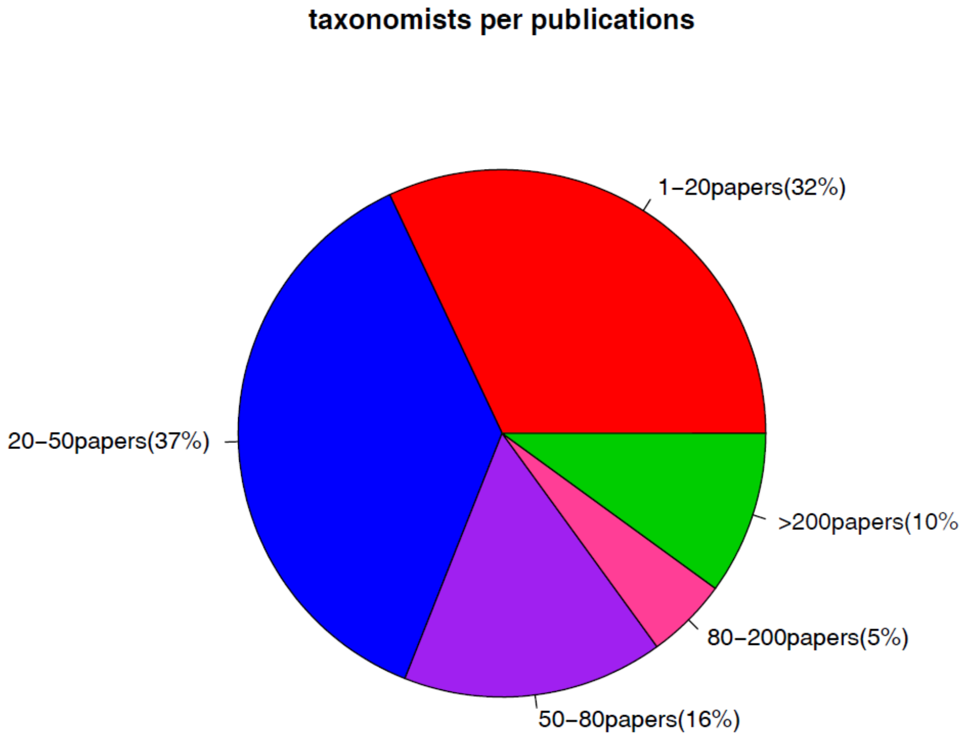

Figure 3. Distribution of taxonomists according to taxonomic papers published

Furthermore, taxonomists in South Africa work on almost all biome types found in the country (Figure 4A). Fynbos and Grasslands were the most cited biomes of interest for taxonomists, followed by Savannah and Nama Karoo. However, no one published taxonomic research on Indian Ocean Costal Belt and Desert. Most of the taxonomists have accumulated 10-20 years of experience in taxonomy (42%) whereas some taxonomists have accumulated 20-30 years of experience (37%) and a low percentage over 30 years (Figure 4B). In terms of species description, most taxonomists have described 1-10 species (55%), some have described 10-20 species (22%) and 6% of taxonomists have described more than 90 species in their career (Figure 4C).

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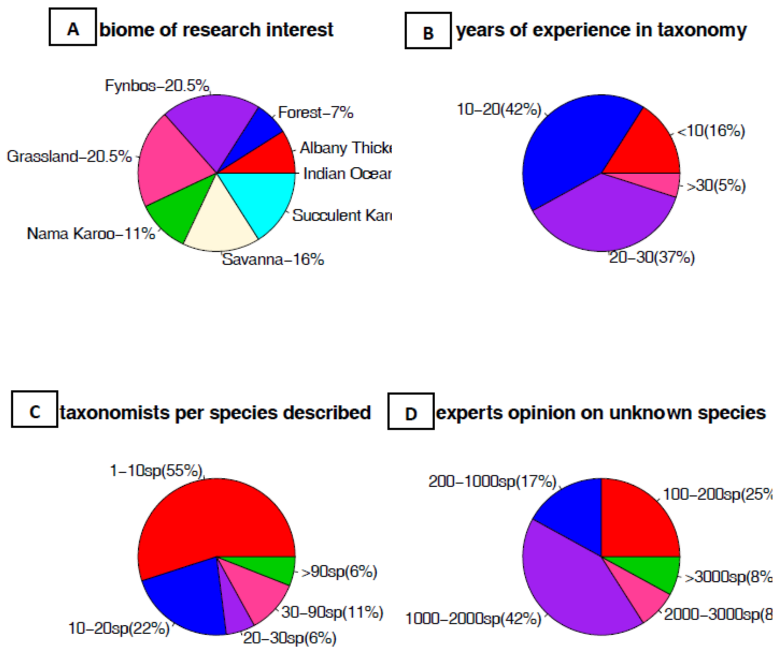

Figure 4. Summary of taxonomic activities of plant experts in South Africa

3.2. Prediction of the richness of potentially unknown species

This number was predicted in two ways: experts' opinions and statistical modelling. According to experts' opinions, the number of missing species varies between 100-3000 (Figure 4D). The average of all experts' predictions is 1400 species.

Prior to statistical modelling, we first showed that the 11208 species in our dataset have been described in a very inconsistent way over the 323 years (Figure 5) that it took for those species to be described.

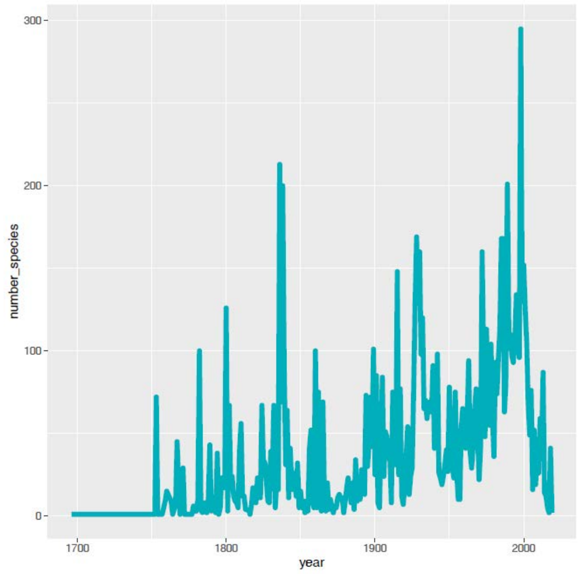

Figure 5. Change in the number of native plant species described over time in South Africa.

This means, on average, 35 species are described annually. The GARCH model predicts that it would take 45 years for all remaining species in South Africa to be described (Figure 6). This implies that, if the current description rate is maintained (35 species/year), in those 45 years, 1575 species would have been described (i.e., it remains potentially 1575 species still to be described).

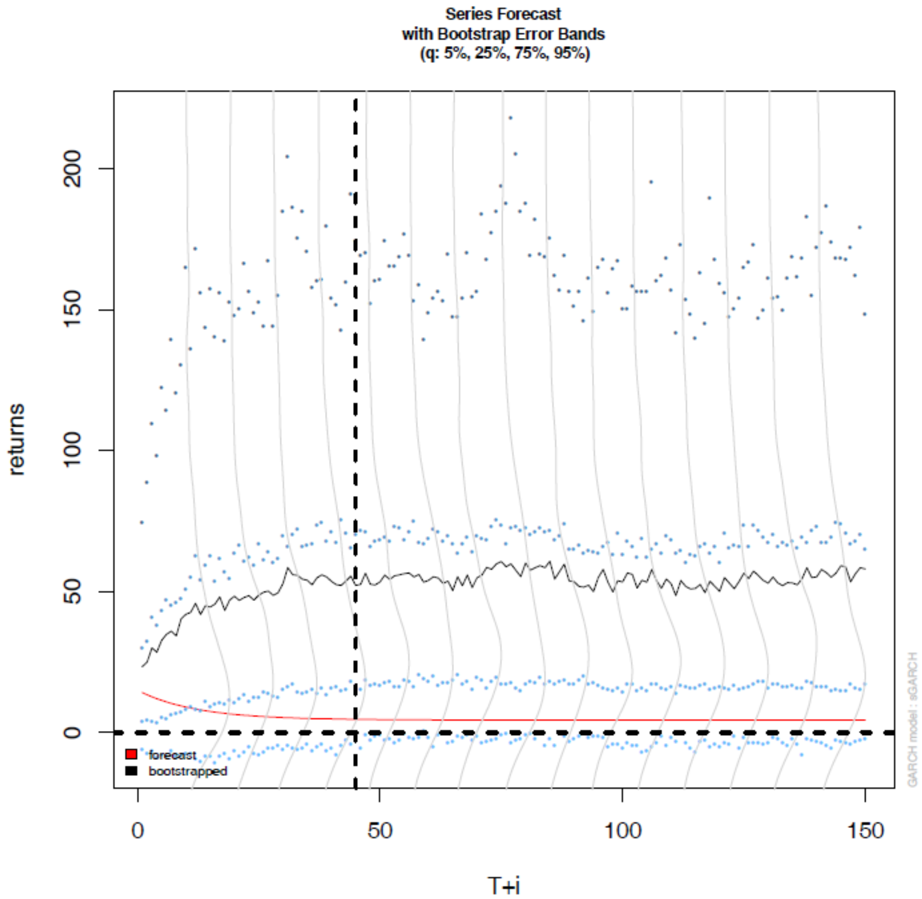

Figure 6. Prediction of trend in number of species to be described over time in South Africa. This prediction was done by fitting GARCH model to the number of South Africa's native species described from 1696 to 2019. The red line corresponds to the prediction of how the number of species to be described would be changing over the next 150 years. The vertical dashed bold line indicates the number of years in which the number of species to be described would be 0, meaning that the total number of species in the country would have been described. On the figure, this number corresponds to 45 years. Clearly, after 45 years, the number of species to be described (red line) does not change anymore, implying after 45 years the total number of species in the country would have been described.

3.3. Efforts required for a comprehensive plant diversity assessment

Taking into consideration the fact that, in the past 323 years, 11208 species have been described, implying a description rate of 35 species per year on average, it would take 45 years to describe the remaining 1575 species. This timeframe would be reduced to 40 years to describe the 1400 species predicted as unknown by experts.

According to the results obtained from experts in this study, taxonomists have spent a total of R 680 670 000 (US $40 039 411) to describe 419 species. This implies that, in theory, R 1 624 510.74 (US $95 559) was spent, on average, to describe 1 species. At this rate, R 2 558 604 415.00 (US $150 506 142) would be required to describe the 1575 (modelling) remaining species or R 2 274 315 036.00 (US $133 783 237) for the 1400 (expert) remaining species. Since this estimated fund is not used solely for taxonomic studies, we applied the estimated 15% reported elsewhere as the portion used for taxonomic studies: this means that ~R243 673 (US$ 14334) is used on average for 1 species description.

3.4. Number of taxonomists required for a comprehensive plant taxonomic assessment

In the data collected using questionnaire, 19 taxonomists have described 419 species during their careers; this means that 64 or 71 taxonomists would be required to describe the 1400 species (expert opinion) or 1575 species (modelling) remaining to be described in South Africa, respectively. However, the data collected from IPNI indicate that 2,239 taxonomists have described the 11,208 native species in South Africa. The number of authors who did this massive species description has changed tremendously over time (Figure 7). The number first increases until around the year 1920 after which it starts decreasing until today (Figure 7). At the rate of description, the description of the 1400 species (expert opinion) or 1575 species (modelling) that remain to be described would require 280 or 315 taxonomists, respectively.

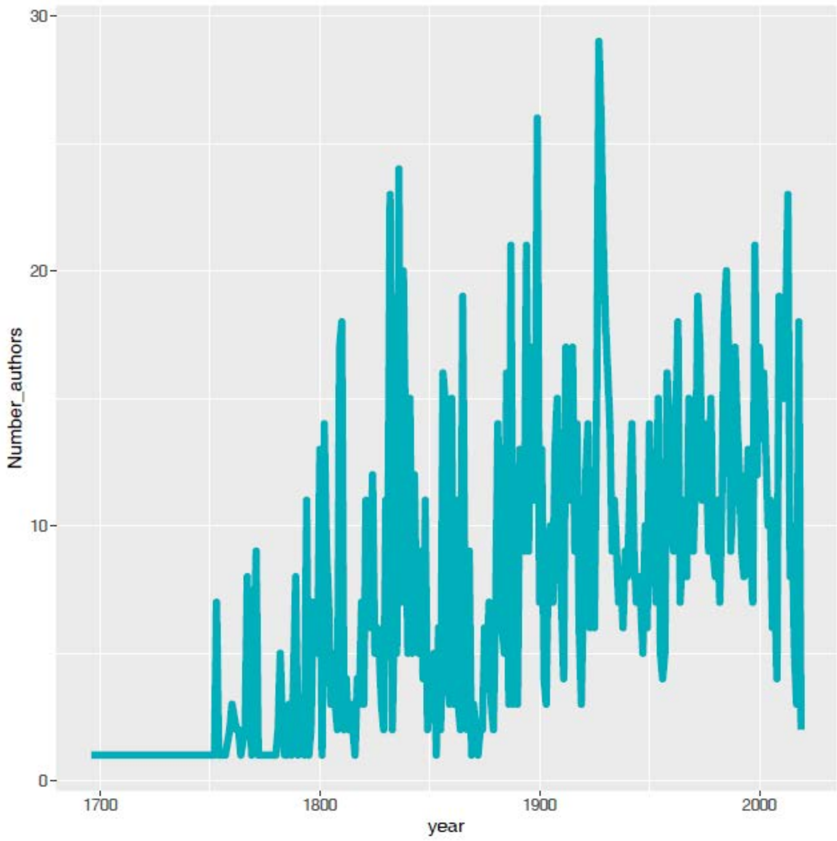

Figure 7. Changes in the number of authors who describe all South Africa's native species.

4. Discussion
4.1. Structure of the population of taxonomists who took part in this study
4.1.1. Gender inequality in taxonomic studies

This study highlights an unequal representation of gender in plant taxonomy in South Africa: 63% male and 37% female taxonomists. This inequility seems to be a global issue in both plant and animal taxonomy. Morgan [43] emphasised that there is an important gender issue in taxonomy that needs to be addressed, since women are underrepresented in the discipline. Morgan noticed that few women are currently employed in natural history collections or as professors of taxonomy and systematics at universities [43]. This observation seems to be a reality in South Africa too, given that, of the 19 respondents who took part in this study, 17 are employed at university as lecturers or professors and, from this pool, 41% are female and 59% are male. This gender bias in the field of taxonomy could be due to historical legacy: in the past, women were regarded as "home makers" and did not really advance their education on their careers [44]. Another reason could be that fewer females apply for taxonomic positions but due to conscious or unconscious gender bias on the part of male academics dominating the hiring committees, women may not eventually be hired [43].

There are no scientific studies in South Africa or the World that have addressed or focused solely on issues related to gender inequality in plant taxonomy. However, the inequality in animal taxonomy has drawn some attention. The journal *ZooKeys* celebrated its 500th issue on the 27th of April 2015, and they created a series of Top 10 posters. This recognized the editors, reviewers, and authors who helped the journal become one of the most important venues for zoological taxonomy over seven (07) years [43]. Of the 35 people who were recognized for their contributions to publishing, only one was a woman [45]. Similarly, the field of systematic biology also has an alarming gender inequality representation with a female representation of only 19%, while Systematic Entomology has a female representation of only 17% [46]. Moreover, a study using IPNI as a source of data, revealed that over the past 260 years, women have only contributed 3% to naming species [47].

Fortunately, in South Africa, SANBI is committed to employment equity which promotes the employment priority of females over males as part of strategies to address the existing gender inequality [48]. Also, the representation of females in botanical societies in South Africa is better compared to other countries. A good example of this is the current 50% representation of female (six (6) out of 12) in the South African Association of Botany. This gives hope to the future of gender equality in plant biodiversity science in the country.

Unfortunately, countries such as Canada still have this battle of gender inequality. In 2010, the Canadian Expert Panel on Biodiversity Science surveyed taxonomists in Canada, and reported that, of the 432 surveyed respondents, only 30% were female [43]. Ironically, the panel itself only included 21% female, of which only 17% of the reviewers were female [43]. Moreover, the UK's House of Lords Science and Technology committee on Taxonomy and Systematics reported that only 17% of their taxonomists were female. This shows that the issue of gender inequality in plant taxonomy is global and, as such, it should be included in agenda towards addressing "taxonomic impediments".

4.1.2. Patterns of age of taxonomists

Apart from gender inequality, it seems age representation is a dilemma globally (South Africa included). The vast majority of taxonomists in this study (68%) is categorized as of middle-age (40-60 years old), and 11% of currently active taxonomists is categorized as reaching a maturity age (> 60 years). This quick statistic implies that most of the current active taxonomists in South Africa will be at retired age in 10 years. When this happens, it will have negative implications on the plant taxonomic/conservation activities because if most prolific taxonomists retire, species identification and description would slow down. The study revealed that there are only a few young taxonomists (20%) already in the pipeline, and this shows that the future of plant taxonomy in South Africa in the next 10-15 years may not be looking good, unless actions are taken right now. There will be less taxonomists than the current number of approximately 40 active plant taxonomists, if training and hiring of plant taxonomists is not prioritised.

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Interestingly, this study, amongst others (e.g., [49]), has shown that age does not necessarily decrease publication activity. This can be seen through the findings of the present study which reveals that older taxonomists have published more than the younger taxonomists. This is because the longer time one spent in the field, the more experience one accumulates, and the more effective one becomes. Specifically, the annual description rate of species during careers of the particularly prolific taxonomists shows high taxonomic activity during the last 15 years of career at the age of about 50-60 years [38;50]. As publications and species description increase with age, taxonomists eventually retire in the middle of their prolific years. Unfortunately, Coleman [43] reported that young people are not interested or attracted to taxonomy for reasons (not fully elucidated) that still need to be addressed.

Interestingly, the taxonomists who took part in this study are of high academic rank: approximately 75% of the active taxomists have a doctorate and 50% are employed as Associate Professors or Professors at universities. The increased academic rank corrolates with increasing age: the professors are almost at retirement age and this is a call for concern because this will create a gap in taxonomic expertise in South Africa (loss of valuable 'taxonomic living library'). There is a need to employ the expertise of trained and experienced taxonomists to train new taxonomists and help reach biodiversity conservation goals. The decreasing number of practicing professional taxonomists in general is a global challenge [51].

The training and recruitment of the next generation of taxonomists gets increasingly difficult with university education globally facing a significant decrease in both organismic focus and taxonomy in the respective curricula [51]. If proactive action is not taken, taxonomy will undoubtedly lose the battle of inventorying the diversity of life. This situation is further worsened by a change in research directions in those institutions that were considered the last remaining supporters of taxonomic research [52].

4.2. Prediction of the richness of potentially unknown species in South Africa

According to the opinion of taxonomist experts, we might be missing 1400 species in South Africa whereas the modelling approach predicted that there are 1575 missing species. However, irrespective of the approach used (expert opinions or modelling), the estimates should be considered as conservative for the following reasons. Firstly, the present study focusses only on vascular plants, meaning the missing species would be higher than predicted in the present study if non-vascular plants are included. Secondly, new species that may arise from the needed taxonomic revisions of some genera are not factored in the estimate. For example, Victor et al. [53] estimated that on average there might be 2200 new species in South African plant genera that have not been revised since 1980, particularly those with a predominantly small habit [53]. Furthermore, the estimates reported here do not include the molecular or DNA-sequences approach which is known to increase the discovery of new species [54,55], although an early study called for caution on the tremendous increase of new species due to molecular data [56]. Overall, it is likely that the remaining species (1400-1575 species predicted here) are rare species with narrow-ranged geographic distributions [55], making them difficult to find. More efforts (manpower, funds, time, etc.) than usual are therefore required if we are to find, describe and catalogue comprehensively plant diversity in the country.

4.3. Estimate of remaining time for a comprehensive assessment of plant diversity

If we assume that the experience of the 19 taxonomists who responded to the questionnaire of this study is shared among taxonomists in the country, then, on average, 1.07 species is described in South Africa on an annual basis. This rate of description implies that it would take 1308 years to describe all the remaining 1400 (expert opinion) vascular plant species, and it would take 1472 years to describe the remaining 1575 vascular plant species predicted by the modelling approach. This is scary, given that the risk that unknown species slide into extinction is very high [10,57,58]. However, the true rate should be higher than the 1.07 species/year given that all native species described are not always done only by South Africa-based taxonomists but through collaborations with international taxonomists. Given that the respondents to the questionnaire of this study are all South Africa-based, the rate reported might not be the true reflection of the reality. Nonetheless, this rate corresponds to the rate at which currently active South Africa-based taxonomists are working.

Globally, according to an early study, the rate of species loss is currently 1,000 times greater than the past rate, and if nothing is done, the rate may become 10,000 times greater [59,60] due to climate change, anthropogenic pressure characterized by habitat loss, pollution, and alien invasive species [16,61]. In a biosphere reserve in Canada, Elliot & Davies [62] reported the loss of 70 different species in only 50 years, suggesting the need to accelerate efforts towards a comprehensive assessment of biodiversity before its extinction. Specifically, in South Africa, 20% of all endemic plant species (2165) are at high risk of extinction and the risk status of 8% (902 species) is still unknown due to lack of taxonomic and ecological information [63]. Even protected areas which supposed to prevent the loss of species seem to be performing poorer than expected, given that 163 threatened species in South Africa occur outside all protected areas [63]. This pattern of extinction risk and limited effectiveness of protected areas [63] mean that we can't afford to take longer time than we have already taken before serious efforts and commitments are made to identify and describe all unknown species in the country before they go extinct.

Interestingly, this long duration of more than 1000 years can be drastically reduced to only 40 to 45 years to identify the remaining unknown species depending on whether we rely on expert opinions (1400 species) or statistical modelling (1575 species) regarding the number of species remaining unknown, respectively. These 40-45 years would be required if we consider the rate of 35 species described annually (from IPNI source, 11208 native species to South Africa were described in 323 years). For this to happen, massive efforts have to be deployed in training, funding and recruitment of taxonomists who will be exclusively devoted to taxonomic activities. It is also important that such taxonomic activities be focused on poorly sampled biomes, e.g., Nama-Karoo and Savannah biomes [64], and given that none of taxonomists who took part in the present study specializes on Indian Ocean Costal Belt biome, it is critical that this biome too should be given priority in botanical exploration. Only such focused activities could accelerate species discoveries and descriptions [65]. Such efforts should be global if we are to reduce considerably the unaffordable timeframe (1200 years) predicted for a global assessment of biodiversity (see [3]). The urgency to reduce this timeframe resides in the unprecedented rate at which biodiversity is lost [16,59-61].

4.4. Funds required for a comprehensive taxonomic plant diversity assessment (expert)

According to the results obtained from experts in this study, taxonomists have spent a total of R 680 670 000 (US $40 039 411) to describe 419 species. This implies that, in theory, R 1 624 510.74 (US $95 559) was spent, on average, to describe 1 species. At this rate, R 2 558 604 415.00 (US $150 506 142) would be required to describe the 1575 (modelling) remaining species or R 2 274 315 036.00 (US $133 783 237) for the 1400 (expert) remaining species. On these estimates, it is important to note the following.

First, these estimated funds are not exclusively spent on taxonomic activities since most of the respondents to our questionnaire are not full-time taxonomists; they are mostly primarily academics, and as such, the funding reported include funding to run their laboratories, cover student scholarships and even funding for activities that may not be strictly taxonomy related [42]. For example, in Brazil (animal taxonomists), 15% of funding secured is allocated for taxonomist training, 50% in salaries of full-time taxonomists in scientific institutions and only 15% allocated to project itself [42]. If this 15% is applied to South Africa's case (15% of R 1 624 510.74), it means that we should expect R 243 677 to be exclusively spent in a species description.

However, if taxonomic activities are to be led in majority by academic taxonomists, the estimates reported in the present study (R 1 624 510.74 per species) could be considered a true reflection of what would be needed. This is because academic taxonomists cannot be detached from their other academic duties, which also need to be funded concomitantly with their taxonomic works. One major issue raised by the respondents is that it is very difficult nowadays to obtain funding exclusively for taxonomic studies, and this seems to be a global issue [43] in comparison to activities that focus primarily on ecological and conservation studies. This is surprising since it is impossible to effectively conserve biodiversity and related ecosystem services [59] if we do not know the extent of what needs to be conserved.

One possible solution to this general lack of funding for exclusive taxonomic projects are for South Africa to establish, through SANBI, an exclusive taxonomic funding for training, targeted botanical expeditions and incentive for taxonomic studies. Another solution would be to promote full-time taxonomists in research institutions, e.g., SANBI, to complement what academic taxonomists are currently doing to accelerate biodiversity assessment in the country. This would reduce considerably the funding required for taxonomic works. This reduction could even be more pronounced, given the increased number of amateur taxonomists, molecular identification tools, increased international collaboration, and access to new areas of exploration [3].

4.5. Number of taxonomists required for a comprehensive plant taxonomic assessment

In the results obtained through survey of expert taxonomists in South Africa, 19 taxonomists have described 419 species during their careers. This gives an average rate of 22.05 species per taxonomists which is not far off from the Brazil rate of 24.8 species described per taxonomist [42]. The South African rate of species description is quite impressive considering that the Brazil description rate is for animals. It is easier to describe animals than plants mainly because of their difference in size. Applying the South African rate of description, 64 taxonomists would be required to describe the 1400 (expert) species. To describe 1575 species (modelling) 74 taxonomists would be needed. This value is attainable. South Africa has over 10 university institutions that offer Taxonomy as field of study. However, 64 to 74 taxonomists seem to be a very low number especially because the missing species are rare and will be difficult to identify. The data collected from IPNI indicate that 2,239 taxonomists have described 11,208 native species in South Africa. Using the rate of description from the data from IPNI, the model predicted that it would require 315 taxonomists to describe 1575 (modelling) species. Applying this rate to the 1400 (expert) species it would require 280 taxonomists. The number of taxonomists predicted from the model seem to be more realistic compared to what the questionnaire survey suggested. In consideration of the fact that the unknown species might be rare and difficult to identify, more taxonomists will be needed on the ground.

Unfortunately, there has been a shift from a balance between basic and applied research to a strong focus on revenue-generating science in the past few decades, with governments rarely allocating up to 30% of their research budgets to basic science [66,67]. This has particularly affected taxonomy [49,68]). Globally, the classic paid position of a full-time taxonomist practically does not exist anymore, and institutions that still maintain such slots are likely waiting for their personnel to retire [69].

Modern professionals, university-based taxonomists are mostly professors that do taxonomy as well as their supervisory, technical, and administrative works: they do not focus solely on taxonomy on a regular basis [69]. Another problem is that taxonomists

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who have the privilege of being paid to do taxonomy may not live up to their responsibilities [70], taking away unique opportunities from highly talented and potentially prolific early-career taxonomists that cannot find a job [70]. Additionally, the pressure to generate revenue has forced taxonomy to shift into a misleading direction of "applied taxonomy". Particularly in biodiversity-rich countries such as South Africa, students in the field of biodiversity research are focusing on laboratory-based research such as natural product screening, without notion for the fundamentals of taxonomy. The pressure of publishing and completing a qualification in a given timeframe has an impact on the quality of taxonomic research. Taxonomy and systematics are being marginalized in many university curricula, leading to a decline in the number of available competent next-generation taxonomists.

Overall, there might be +/- 1500 species to be found in South Africa. The present study provides estimates of what it will take to advance towards a comprehensive plant diversity assessment in the country. To move towards a comprehensive assessment, Carbayo & Marques [42] suggested that "the most essential action now would be a concerted effort to raise the image of taxonomy from being seen merely as an 'old' and 'simple' task of biologists that is unfashionable and horribly constricted to low-impact-factor journals to being viewed instead as a fundamental, indispensable, and vibrant branch of the life sciences". Only when new species are discovered that its ethnobotanical knowledge can be documented.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, **Table S1.** All data collected through questionnaire; **Table S2**. Time series data on number of species described and number of authors who did the description (1696 – 2019); **Questionnaire; R script; Ethics approval**

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