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Review

# A timely systematic review on pangolin research, commercialization, and popularization to identify knowledge gaps and produce conservation guidelines

Sean P. Heighton *, Philippe Gaubert

*Laboratoire Evolution et Diversité Biologique, UPS/CNRS/IRD, Université Paul Sabatier, 118 route de Narbonne, Bât. 4R1, 31062 Toulouse, France*

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ABSTRACT

Conservationists can benefit from encompassing research, social, and economic aspects of conservation issues to produce holistic conservation guidelines. Pangolins have become a taxon of conservation eminence as they continue to be poached and trafficked to extinction, and have been mislabeled as potential intermediary hosts of SARS-CoV-2 which is responsible for the COVID-19 pandemic. Applying a systematic review approach, we extracted pangolin-related publications since 1865 from five research databases (814 publications), as well as data on 5296 patents, online news trends (43,176 articles) and societal interest (Google Trends and Wikipedia Pageviews). Although we detected a significant increase in pangolin-related publications through time, we observed glaring knowledge gaps in contextually important categories including immunology, education, and implications of trade or poaching to populations. All eight species have literature knowledge gaps, however African species are less represented. Fifteen African range-states have no pangolin literature, while the number of publications with non-range-state lead authors increased from 8% to 42.9% since 2017. Pangolin media output and societal interest have remained low relative to other flagship species, however COVID-19 is shifting these dynamics. Pangolin patent production was linked to Traditional Chinese Medicine, which was neither driven by science nor traditional pharmacopoeia. To help conserve pangolins, we suggest increased effort in health and field-based conservation research, while directing more attention towards Africa. We highlight the importance of maintaining range-author contributions, and of factors that may lead to increased public interest in pangolins. Our approach can be used to devise integrative conservation guidelines for other species.

## 1. Introduction

The illegal wildlife trade is a global conservation threat as it has accounted for 132,144 seizures in 120 countries between 2004 and 2014, and has an average of 100 million organisms traded annually (Harfoot et al., 2018; UNODC, 2016). Its clandestine and multi-layered nature involving complex interactions between conservation organizations, law enforcement agencies, economic wealth, and society requires a multi-disciplinary intervention approach (Akella and Allan, 2012; UNODC, 2016).

Pangolins (Pholidota, Mammalia), comprised of eight species in Africa and Asia (Fig. 1; Gaubert et al., 2020), have been given the unfortunate label of being the most heavily trafficked wild mammals on earth (Challender et al., 2014, 2020a; Heinrich et al., 2017). All eight species are listed on Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 2017), and either as Vulnerable, Endangered or Critically Endangered on the IUCN Red List of Threatened Species™, almost exclusively due to the illegal trade (Fig. 1; IUCN, 2019). The most recent estimates suggest that around 895,000 pangolins were trafficked between August 2000 and July 2019, notably from Africa to Asia (Challender et al., 2020a). However, this represents only a fraction of absolute trade volumes (Phelps and Webb, 2015), while other studies predict larger estimates through regional analyses (see: Ingram et al., 2018). The main driving force of this trade is the use in Traditional Chinese Medicine (TCM), but other traditional medicine, ornamental, and meat markets have been known to contribute (Baiyewu et al., 2018; Heinrich et al., 2017; Ingram et al., 2018; Shairp et al., 2016).

The illegal wildlife trade has made pangolins one of the most iconic animals amongst conservationists. Paradoxically, these nocturnal,

* Corresponding author.
*E-mail addresses:* sean-paul.heighton@univ-tlse3.fr (S.P. Heighton), philippe.gaubert@univ-tlse3.fr (P. Gaubert).

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myrmecophagous mammals have widely been considered understudied (Challender et al., 2014; Pietersen and Challender, 2020). In the only review on pangolin research, Pietersen and Challender (2020) identified six study fields requiring urgent attention, including trade networks, forensics, biology and ecology, genetics, husbandry and veterinary health, and the effects of climate change. Two reviews have been published on the public interest aspect of pangolin conservation, pointing to the importance of seizure records and accompanying 'shocking' imagery, conservation events and organizations, specific Google Doodles, documentaries, and celebrities in pangolin popularization (Harrington et al., 2018; Thomson and Fletcher, 2020). However, with the last systematic review on public interest possesing data up until 2016 (Harrington et al., 2018), new peaks in interest and their determining factors have likely emerged, which could aid conservationists and researchers in increasing public awareness regarding pangolins. One point of particular interest is that pangolins have recently been thrusted into the public spotlight after being suggested as the intermediate host of SARS-CoV-2 which is responsible for the COVID-19 pandemic (Zhang et al., 2020b), despite concrete evidence for this claim (Frutos et al., 2020). Critical information on the economic aspects of pangolin trade such as drivers and market dynamics are still lacking ('t Sas-Rolfes and Challender, 2020; Challender et al., 2015), while there is limited information on the commercialization of pangolin products by the TCM industry (Xu et al., 2016).

Conservation biology is part of a multifaceted system where solutions to conservation issues require a holistic, multidisciplinary approach integrating biological data (e.g. knowledge on the species), society, economics, and governance across multiple scales (Blair et al., 2017). Thus, establishing accurate conservation strategies relies on the availability of biological knowledge of conservation issues (Conenna et al., 2017; Williams et al., 2020), together with knowledge on public awareness and interest in a conservation problem (Olmedo et al., 2018; Phillis et al., 2013), and on the commercial determinants that result in species being exploited (e.g. Masters et al., 2020). For these reasons, we present an unprecedented systematic review on scientific knowledge of pangolins since 1865, build on our knowledge of their popularization, and delve, for the first time, into their commercialization in the form of patent production. We identify the research, commercial, and popularization trends, together with the major knowledge gaps in natural sciences, from which we propose timely, holistic recommendations that may help conserve pangolins and mitigate their trade. We found no evidence of a review of this nature from the query 'pangolin' in the Conservation Evidence (https://www.conservationevidence.com/) database (query results: Heath and Coulson, 1997; Shepherd et al., 2017). We hope these methods and insights may be useful for other species of conservation importance, particularly those affected by the illegal wildlife trade.

## 2. Methods

### 2.1. Pangolin scientific research database

To conduct this study we followed systematic review guidelines of conservation literature (Collaboration for Environmental Evidence, 2018). Boolean search terms were used to broadly capture pangolin literature from five databases covering natural sciences, engineering, biomedical sciences, and humanities and social sciences. We extracted literature containing "pangolin" OR "scaly anteater" OR "spiny anteater" NOT "drosophila" (*pangolin* gene described in drosophila) NOT "Tachyglossus" (echidna genus, often referred to as "spiny anteater") in

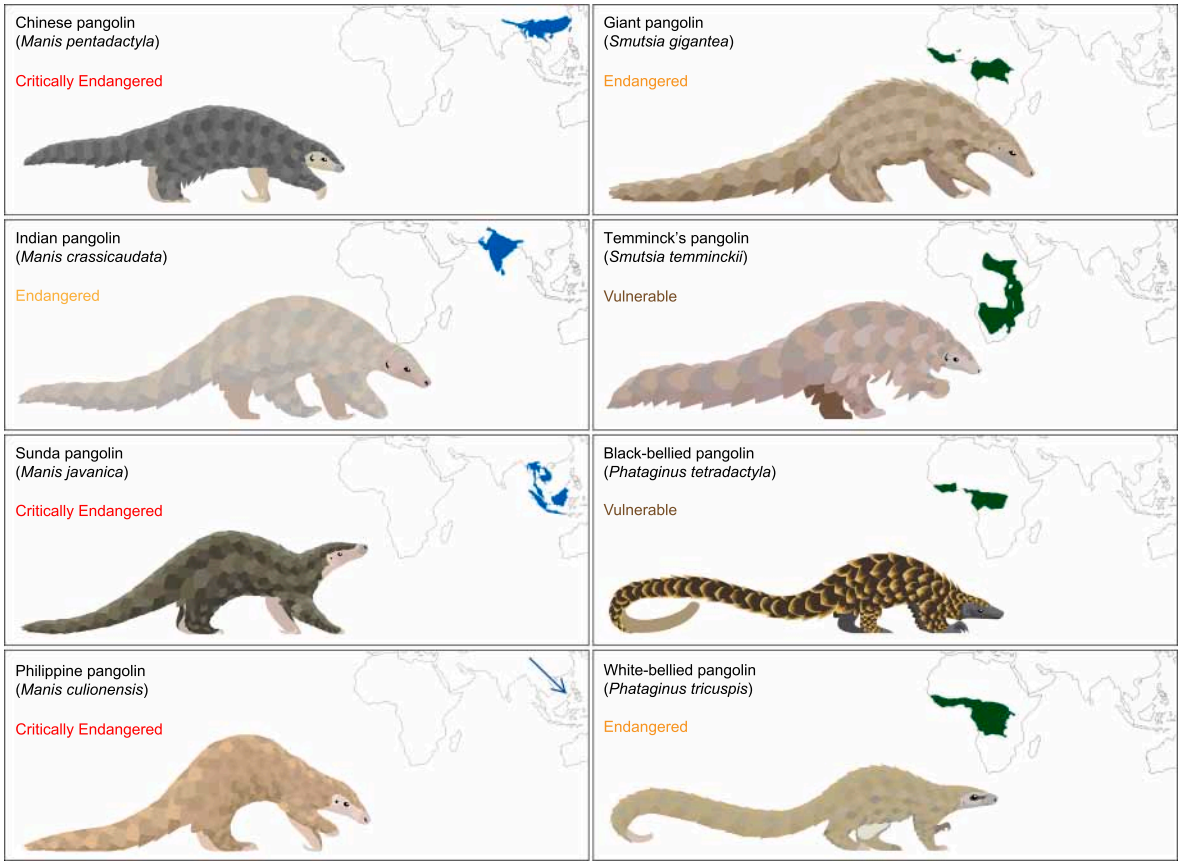


**Fig. 1.** Global conservation status, taxonomy, and distribution of the eight extant pangolin species. Distribution maps are from The IUCN Red List of Threatened Species™ 2019. Modified from Gaubert et al. (2020), illustrations by Sheila McCabe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

their titles, abstracts or keywords from Web of Science ($n$ = 1033; extracted 14/11/2019 from "all databases"), Scopus ($n$ = 431; extracted 14/11/2019), Engineering Village ($n$ = 40; extracted 6/12/2019), Project MUSE ($n$ = 11; extracted 23/12/2019), and a personal dataset of older scientific literature compiled by PG ($n$ = 158; extracted 9/12/2019). For the humanities and social science database (Project MUSE), the default was to search through all literature content rather than just titles, abstracts and keywords, whilst only articles were included due to limited access to most books.

The five datasets were combined ($n$ = 1631), and duplicated literature by title were deleted with sed and awk Linux commands followed by manual inspection. The resultant global database ($n$ = 997) included books, book chapters, reports, conference and workshop proceedings, and scientific articles (Appendix A). Titles and abstracts of this database were manually reviewed with 183 pieces of literature (from herein: publications) being omitted due to no mention of pangolins, whilst the remaining 814 publications were assigned a "Focus" ($n$ = 561) or "No Focus" ($n$ = 253) tag. "Focus" was assigned if the literature's main focus was on pangolins or they were part of a direct comparison (*contra* "No Focus" literature). Additionally, a scientific domain was assigned to these 814 publications (Appendix B). As the "natural sciences" domain encapsulates the bulk of knowledge of pangolins ($n$ = 662) and our main research interest, a theme (nine in total), corresponding primary and occasionally secondary category (30 in total; some publications had more than one category and corresponding theme), as well as whether it was a review or not, were additionally allocated to each publication (Appendix B). Themes and their corresponding categories were strictly defined by our list of definitions (Appendix C) which guided decision making. Definitions were outlined prior to selection of a subset of around 100 publications, which were then independently vetted by a second reviewer after which discrepancies were discussed and amended in the definitions. This process was repeated twice over with smaller subsets of data during the selection process. Focused, "natural sciences" literature ($n$ = 467) were then manually reviewed to identify whether lead authors (i.e. first and/or last authors) were affiliated to range-states or not ($n$ = 454), which species were under study ($n$ = 466), and the range-states involved in the publications through study or specimen collection site (excluding museum collections) as a proxy ($n$ = 335). The use of multiple databases allowed us to include literature from different domains, accessibility, and languages (51 languages are suggested to be covered between Scopus and Web of Science alone), however there is still likely a bias towards English literature (Vera-Baceta et al., 2019). There is also a possibility of missing publications, particularly from rare languages, grey literature sources, books, and novel or cryptic journals, while not all published studies have equal merit. However, considering the volume of literature included in this review, we believe this may not have significantly altered our results.

### 2.2. Online news and societal interest trends

Daily global online news article counts (both subject count and total monitored article count in over 100 different languages) were collected from the Online News Summary dashboard in GDELT Project (Global Database of Events, Language, and Tone; https://www.gdeltproject.org/) with "(pangolin OR pangolins)" as the query, starting between 01/01/2017–31/03/2020. We obtained a relative daily value of pangolin articles by dividing daily pangolin article counts by the daily number of monitored articles. The aforementioned process was repeated with the "Raw Timeline" (non-normalized) output type in "Comparison Visualization" to compare global online news coverage of pangolin(s), elephant(s), and lion(s). We extracted the same monthly animal comparison data from Wikipedia's Pageviews Analysis (https://tools.wmflabs.org/pageviews/) between 01/07/2015–31/03/2020. Monthly societal interest was collected in the same manner as that of online news articles, however we used the global "Web Search", "News Search" and "Image Search" in Google Trends (https://www.google.com/trends) of the "Animal" topic "pangolins" from 01/01/2008–31/03/2020. Whilst Wikipedia provides raw counts of page views, Google Trends uses a relative search count of all searches by the chosen region and period of interest (Kämpf et al., 2015). Although there may be a slight geographic or language-specific bias in these tools, Google is still the largest search engine globally while Wikipedia has pages in over 304 languages (https://meta.wikimedia.org/wiki/List_of_Wikipedias).

### 2.3. Patents

Pangolin commercialization was represented in the form of patents that were mined from the Web of Science database ($n$ = 5296; extracted 14/11/2019) with the same Boolean search terms used for the extraction of scientific literature (Appendix D). Class codes from the Derwent Innovations Index on Web of Science were extracted for all patents except two ($n$ = 5294).

### 2.4. Data analyses

Negative binomial generalized linear models (best fit model by AIC; see Appendix E) with package "mass" (Ripley et al., 2013) were applied to investigate the total, focused and non-focused literature count trends through time. Due to some databases including literature for the beginning of 2020, this year was excluded for the aforementioned analyses as the incomplete count for this year would affect the trend. A likelihood ratio test with package "lmtest" (Hothorn et al., 2019) was utilized in order to test whether focused and non-focused literature slopes were significantly different. A Chi-squared goodness-of-fit and Chi-squared multi-pairwise-comparison test with Bonferroni correction were run with package "RVAideMemoire" (Hervé and Hervé, 2020) to investigate whether domains (total literature) were significantly different from the expected equal distribution of literature count, and if so, which domains differed significantly from one another. From this point, only focused data of domain "natural sciences" were analyzed and the process above was repeated for themes, categories and species. However, for species, the expected values for the chi-squared goodness-of-fit analysis was weighted by the relative area of each species' distribution, which was extracted from the IUCN Red List of Threatened Species™ (IUCN, 2019) and transformed in QGIS v3.4.10 (QGIS Development Team, 2016). Each piece of literature was treated as a separate data point except for focused "natural sciences" publication analyses by category (and corresponding theme; $n$ = 112), species (n = 112), and range-state origin ($n$ = 2) where each instance was treated as a separate data point as more than one instance may occur per publication.

Heatmaps were used to visualize trends in focused "natural sciences" literature and to facilitate comparisons of multiple factors at once. Heatmaps of literature count for species versus category and theme, species versus year of publication, and category versus year of publication were created through the packages "ComplexHeatmap" (Gu, 2015) and "RColorBrewer" (Neuwirth, 2014). These heatmaps, along with all statistical analyses and their relevant assumptions, were considered or tested in the Rstudio interface of R v3.6.1 (Rstudio Inc., Massachusetts, U.S.A; Appendix E).

To gain further insight into pangolin scientific knowledge, focused "natural sciences" publications were scrutinized in VOSviewer v1.6.14 (van Eck and Waltman, 2010) by the program constructing co-occurrence networks of important terms mined from the titles and abstracts. Instead of a relevance threshold as determined by VOSviewer, we used a manually curated thesaurus file based upon an initial network of 353 terms (Appendix F). This allowed us to combine multiple terms used for each species and decide which terms were irrelevant for the co-occurrence network. The process was repeated for patent records, but differed by extracting terms from the titles only and utilizing a relevance threshold of 60% of the most relevant terms instead of a thesaurus file.

## 3. Results

### 3.1. Pangolin science overview

The pangolin science trend encapsulating all publications (focused and non-focused; $n = 814$) is significantly positive through time from 1865 onward (Estimate = 0.048, $z = 19.31$, $p < 0.001$, CI = 0.044–0.053; Fig. 2). The average growth rate for all pangolin-related publications between 1980 and 2012 is 19.97%, more than 6.75-fold the 2.96% publication growth rate of modern science estimated by Bornmann and Mutz (2015) during the same period. Publication count differed significantly according to domain ($\chi2 = 2456$, df = 5, $p < 0.001$), with "natural sciences" ($n = 662$) being significantly higher than all the other domains ($p < 0.001$ across all pairwise comparisons with other domains). For the other five domains ($n = 152$ combined), spikes in publications are observed in the early 1990's (1990–1995) and middle 2000's (2002–2008 with the exception of 2004; Fig. 2). During this second peak, "biomedical sciences" appears to be a predominant alternative domain which is followed by an increase in patent count per year (2004–2010; Fig. 2).

### 3.2. Pangolin (focused) natural sciences trends

We concentrated on literature that had a pangolin focus (vs. non-focus literature) for further analyses as they are more likely to be seen as literature aimed at increasing our knowledge of pangolins (see Appendix E for statistics on each trend and their difference). In the "natural sciences" domain, themes differed significantly from expected equal counts ($\chi2 = 345.04$, df = 7, $p < 0.001$), with the theme "conservation" ($n = 179$) being significantly higher than all other themes ($p < 0.05$), apart from "physiology and anatomy" ($n = 146$; $p = 1.00$). The themes "ethnozoology and society" ($n = 16$), "general description of pangolins" (n = 16), and "veterinary" (n = 17) grouped together and were significantly lower than other themes in research output ($p < 0.05$). "Veterinary" was less well distributed across species, including gaps in the literature for Philippine (*Manis culionensis*), giant (*Smutsia gigantea*) and black-bellied pangolins (*Phataginus tetradactyla*; Fig. 3).

Although categories differed significantly from expected equal counts ($\chi2 = 658.67$, df = 26, $p < 0.001$), no categories were significantly different from all the other categories, or could be grouped together in the multiple pairwise comparison test ($p > 0.05$). "Anatomy" and "range/density/habitat/niche/behavior/predation" were joint highest ($n = 94$), while "volume or nature of trade and poaching" followed with 53 publications. However, unlike the other two, "anatomy" was heavily skewed towards the top three species by count, namely Chinese pangolin (*M. pentadactyla*), Sunda pangolin (*M. javanica*), and in particular white-bellied pangolin (*P. tricuspis*; Fig. 3).

A total of 51.85% of categories had missing information for at least one of the eight species ($n = 27$ including "veterinary" and "general description of pangolins") with "education" (n = 2) and "immunology" ($n = 3$) being the least represented across species and in literature output (Fig. 3). Categories like "anthropogenic effects other than trade or poaching" ($n = 6$), "implications of trade or poaching to populations" ($n = 8$) and "people's perception and awareness of pangolins" ($n = 5$) are significantly lower ($p < 0.05$) than the publication count of "volume or nature of trade and poaching" ($n = 53$). Publications on "captive breeding" ($n = 29$) are more than double that of "rehabilitation" ($n = 13$). Although many categories are not prominent in pangolin research, through time there has been an increase in the number of categories being studied (Appendix G).

By publication count alone, African pangolin species are generally less represented (Fig. 3). *Manis pentadactyla* ($n = 161$), *M. javanica* ($n = 137$), and *P. tricuspis* ($n = 125$) are more studied relative to the other five pangolin species, with the former two Asian species receiving good coverage across categories, missing three out of 27 categories (Fig. 3). *Manis culionensis* ($n = 31$) is the most understudied, whereas *S. gigantea*

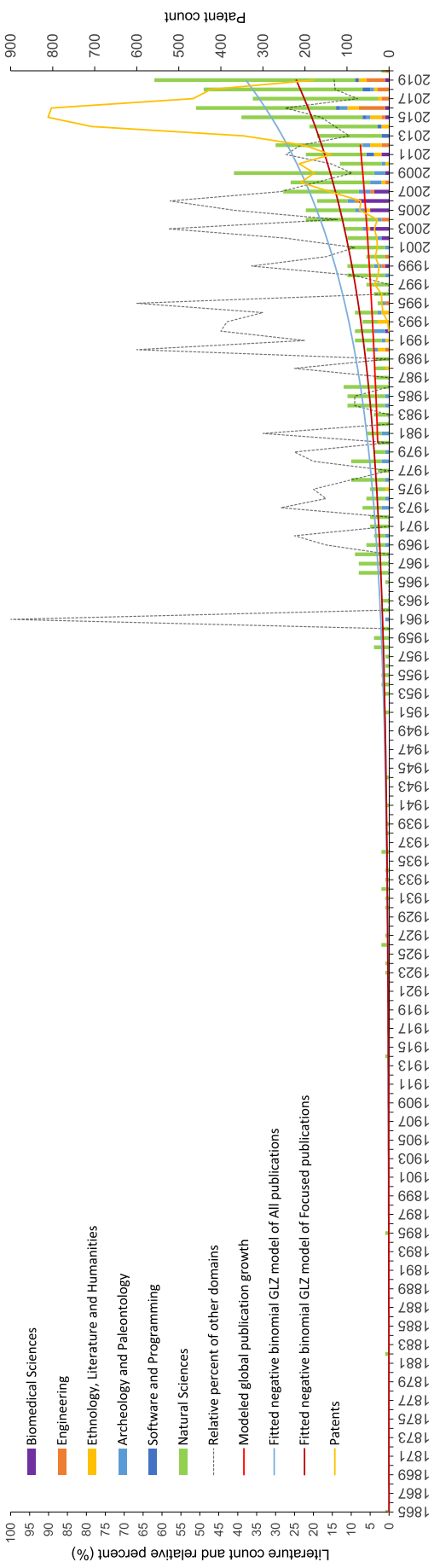


**Fig. 2.** Pangolin research (literature focused and not focused entirely on pangolins) from 1865 to 2019. Each bar plot represents the literature count per year (1st y-axis) split into the six scientific domains. Trend lines from 1865 to 2019 are fitted values of the negative binomial generalized linear (GLZ) models for all publications (focused and non-focused literature) and focused publications (focused literature only) during this period. The line from 1980 to 2012 is the modeled global publication growth during that period, as estimated by Bornmann and Mutz (2015). The patents line is fitted to the patent count per year (2nd y-axis). The proportion of other scientific domains relative to "natural sciences" (1st y-axis) commences at 1961 as the first publication we could find from a domain other than "natural sciences" was from this year.

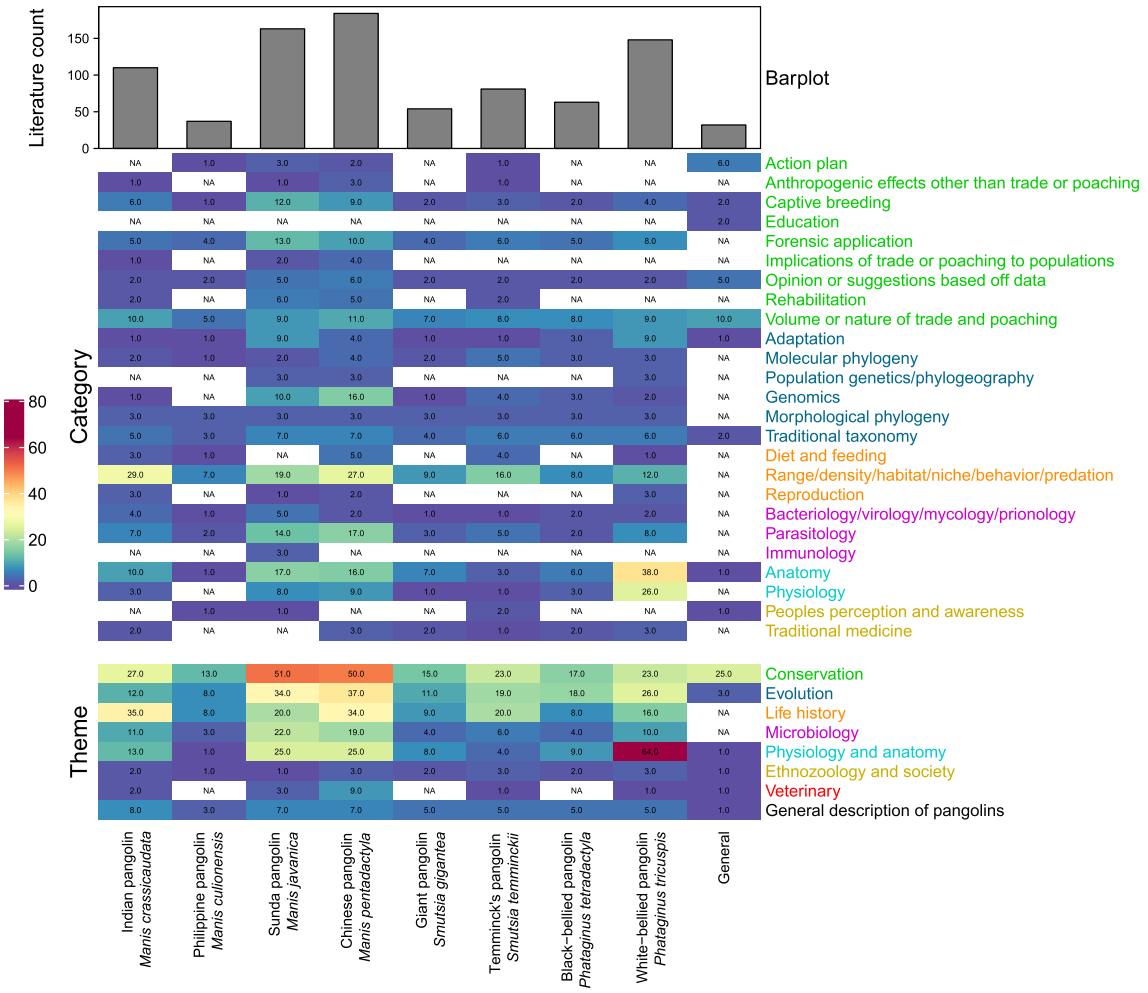


**Fig. 3.** Heatmap of literature count in research themes and categories by species from literature with a pangolin focus and in the scientific domain "natural sciences". Except for the "Veterinary" and "General description of pangolins" themes, which do not have categories, each set of categories are colour coded to their corresponding research theme. An additional species slot named "General" is specified for literature that refers to pangolins in general and does not concentrate on a specific species. Each block in the heatmap contains the number of pieces of literature relating to a theme/category by species, whilst "NA" refers to absence of data.

($n = 54$), the second least studied, is close to *P. tetradactyla* ($n = 62$) and Temminck's (*S. temminckii*; $n = 69$) pangolin publication counts (Fig. 3). The three species with the lowest publication counts also have the highest number of missing categories, each missing literature in 11 out of 27 categories (40.74%; Fig. 3). The two African species, *S. gigantea* and *P. tetradactyla*, share the same missing categories, whilst commonalities in missing categories can be observed for all species (Fig. 3). As time progresses, more research interest is being shared across all species rather than focused on historically prominent species like *M. pentadactyla* and *P. tricuspis* (Appendix H). By controlling for the area of distribution of each species, the Indian (*M. crassicaudata*; $n = 94$, $p > 0.05$) and *P. tetradactyla* (n = 62, $p > 0.05$) did not differ significantly from their expected publication counts. *Manis culionensis* (n = 31, $\chi2 = 2651.382$, df = 1, $p < 0.001$), *M. javanica* (n = 137, $\chi2 = 99.897$, df = 1, $p < 0.001$), and *M. pentadactyla* (n = 161, $\chi2 = 115.801$, df = 1, $p < 0.001$) were significantly higher than expected after accounting for their area of distribution, whilst *S. gigantea* ($n = 54$, $\chi2 = 93.2236$, df = 1, $p < 0.001$), *S. temminckii* (n = 69, $\chi2 = 130.846$, df = 1, $p < 0.001$), and *P. tricuspis* (n = 125, $\chi2 = 9.125$, df = 1, $p = 0.02$) were significantly lower.

We identified five clusters based on relationships between phrases from the titles and abstracts of focused, "natural sciences" publications with VOSviewer (Fig. 4). The first cluster reflects rehabilitation and captive breeding with a large occurrence of terms relating to disease and parasites. The second cluster reflects anatomy and physiology, with *P. tricuspis* situated as a central term and heavily linked to comparative studies with bats and rats. The third relates to pangolin trade which is the largest and most densely populated cluster with a large proportion of links with other clusters (apart from the anatomy and physiology cluster). A fourth cluster relates to evolution and phylogeny with a subset of terms evidencing a molecular forensic link with the trade cluster ("identification", "number" and "region" linking to "illegal trade", "sample", "protection" and "conservation"). Ecology, the fifth cluster, is the smallest, with *M. crassicaudata* being a prominent point. *Manis pentadactyla* and *M. javanica* are central to the entire cluster network.

### 3.3. Pangolin natural sciences research dynamics

Publications with lead authors from range-states (i.e. either first or last authors from countries with pangolins; $n = 314$) were 2.24-fold higher than publications without ($n = 140$; Fig. 5). In the last three years this trend is starting to change, with publications involving non-range-state lead authors increasing from 8% of the publications in 2017 ($n = 2$) to 42.86% in 2019 ($n = 15$; Fig. 5). Formulated on sample origin or study site, literature involving Asian range-states ($n = 288$) are 2.29-fold more than that of African range-states ($n = 126$), however there is also a shift in dynamics from 2017 (n = 5, 21.74% of publications from Africa) to 2019 ($n = 11$, 36.67% from Africa; Fig. 5). There

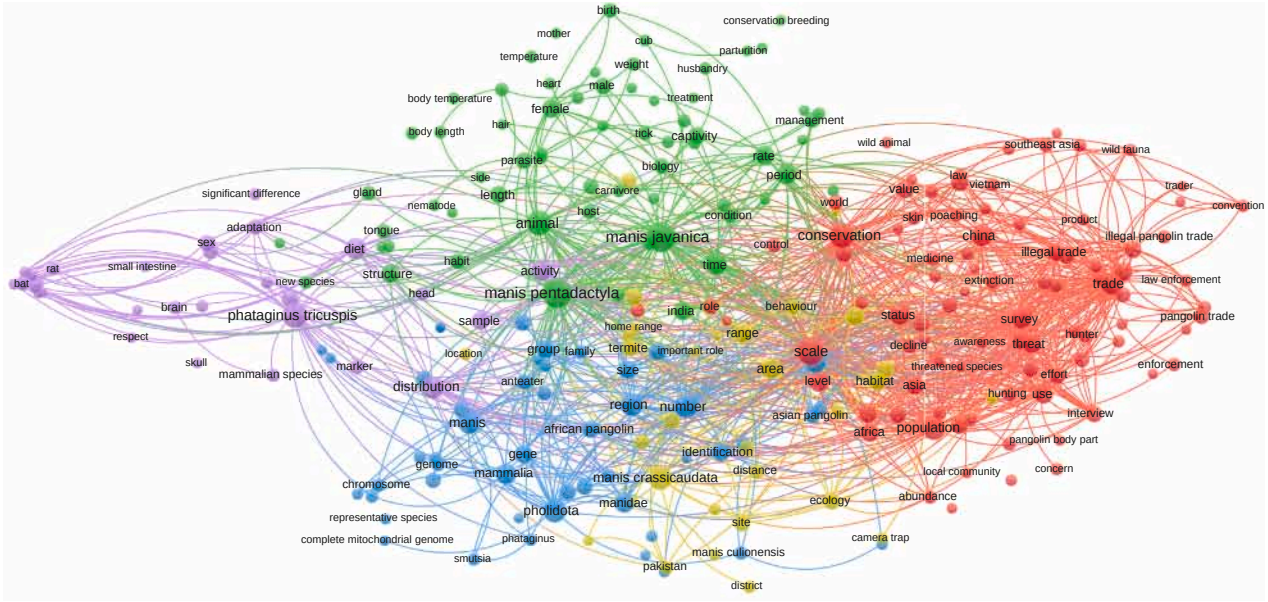


**Fig. 4.** A co-occurrence network of terms and their links extracted with text mining algorithms in VOSviewer, from titles and abstracts of literature, with a pangolin focus and in the scientific domain "natural sciences". A binary counting approach (presence or absence of a term per publication) was employed with a minimum term occurrence count of five and a manually curated thesaurus file to filter irrelevant terms (Appendix F). Phrase occurrence was used for weighting the network. The clusters are separated into rehabilitation and captive breeding (green), anatomy and physiology (purple), evolution and phylogeny (blue), ecology (yellow), and trade (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are 15 African range-states and one Asian range-state (Bhutan) having no publication records of pangolins derived from sample collection or study sites (Fig. 5). Nigeria ($n = 32$) is the African country that is most heavily involved in pangolin research, accounting for 9.5% of all research by country ($n = 337$), placing it third behind China ($n = 69$, 20.47%) and India ($n = 52$, 15.43%; Appendix I).

### 3.4. Pangolin popularization

We found four noticeable peaks of news and/or societal interest in pangolins since 2014, including April 2015 and February 2017 with similar sized peaks, May 2018 with the second-largest peak, and February to March 2020 with the largest peak (Fig. 6a). These peaks of interest surpassed those caused by the record-breaking seizures of trafficked pangolins made in February, April and December 2019, however the former two seizures received a comparatively large response by online news media (Fig. 6a). In fact, apart from the two largest peaks in public response, peaks of societal interest did not always appear to correlate with peaks in news media outputs. Although news articles mentioning pangolins did not surpass those of lions or elephants, Wikipedia page views did, with over 1 million views in March 2020 (Fig. 6b).

### 3.5. Pangolin patents

The most noticeable growth in patents per year occurred from 2011 to 2016, after which it dropped dramatically (Fig. 2). A total of 96.35% ($n = 5101$) of patents are related to the Derwent Class Code B04 which are patents in pharmaceuticals containing natural products and polymers (Appendix J) and thus likely related to Traditional Chinese Medicine (see also: Appendix K). The first patent recorded was in 1993, a year after the first biomedical study we found containing pangolins in the study. The majority of top patent assignees were single authors with a few biomedical companies found across the upper part of the list, although the biomedical research author affiliations did not match with these companies (Appendix L).

## 4. Discussion

### 4.1. Pangolin research

Pangolin research has seen a significantly positive, exponential growth since 1865, 6.75-fold higher than that of the global research average. The knowledge garnered has been substantial enough to culminate in the first comprehensive book on pangolins (Challender et al., 2020b). "Natural sciences" is the most studied domain, although important knowledge gaps exist (see below).

#### 4.1.1. High count research areas require direction

"Conservation" is the most studied theme (significantly different to all, except "physiology and anatomy"), due to pangolins notoriety in the illegal wildlife trade. Prominence in "physiology and anatomy" may be attributed to it being comprised of comparatively older science categories (Habbal, 2017; Pinter and Pinter, 1993), as observed for pangolins (Appendix G). Additionally, pangolins – as 'scaly anteaters'– have unique anatomical and physiological features (Gaudin et al., 2020) that may explain why "anatomy" is the joint highest category for pangolins (with "range/density/habitat/niche/behavior/predation"), though it is skewed by species, particularly towards *P. tricuspis* (Fig. 4).

Pangolin ecological data ("range/density/habitat/niche/behavior/predation") is well studied, with *M. crassicaudata* flagged as a well-represented species in the VOSviewer network. Nevertheless, it is suggested that there is a lack of population density and home-range estimates for some species (most notably *S. gigantea* and *P. tetradactyla*) and locations (e.g. *S. temminckii's* eastern and northern ranges), as well as knowledge of factors affecting distribution and habitat preferences (Pietersen and Challender, 2020). These are integral in determining baseline estimates for measuring the effects of habitat degradation and illegal trade on populations. Given the pangolins' elusive nature, direct ecological monitoring studies may be challenging and costly, hence the use of proxy methods such as burrow counts, community interviews and molecular techniques have been suggested as alternatives (Ingram et al., 2019). Meta-analyses on the theme "checklist and monitoring" (36 publications in 19 countries under non-focused data) created in our

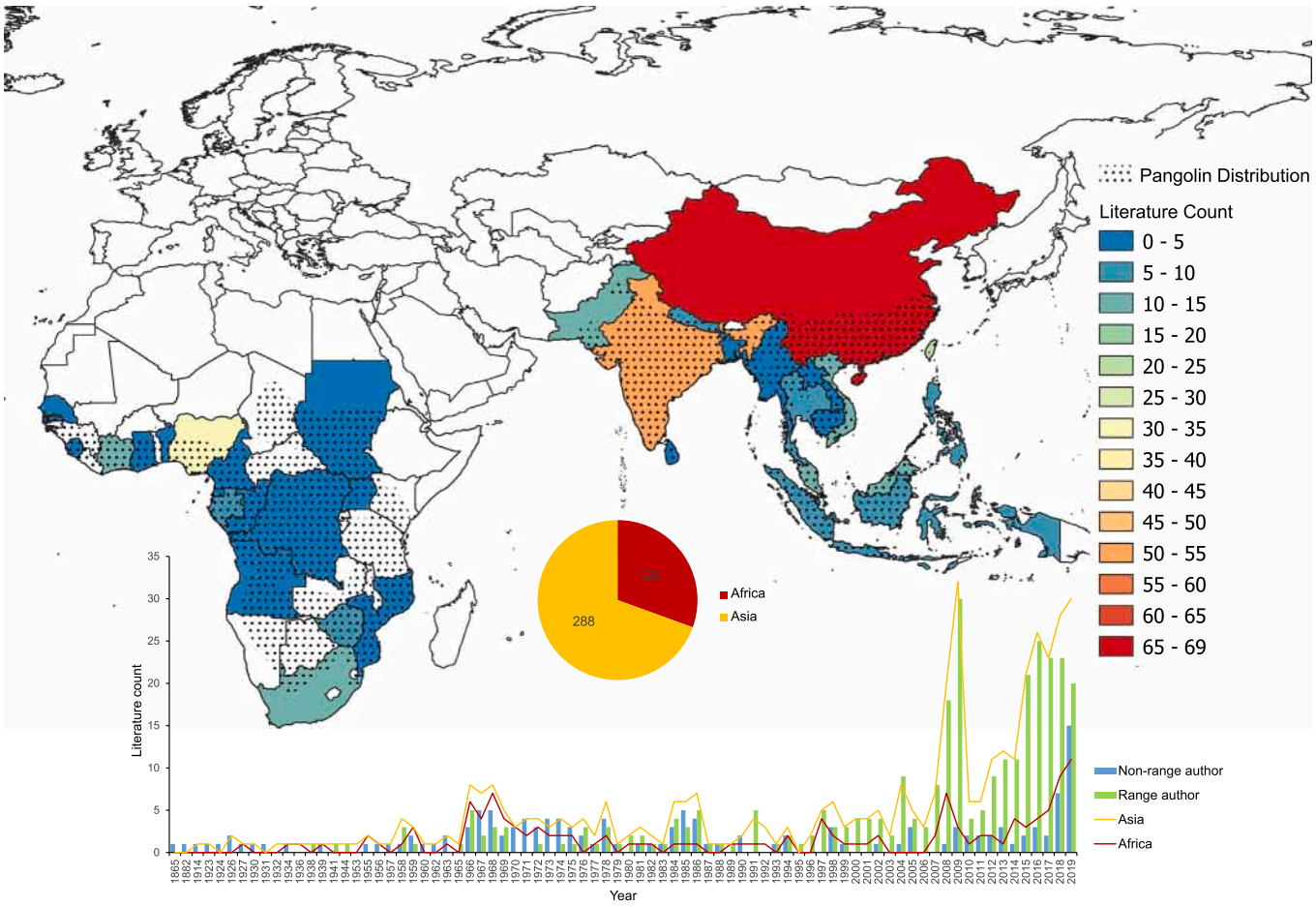


**Fig. 5.** Pangolin research dynamics by range-state (map), continent static (pie chart), continent temporal (line graph), and authorship through time (bar plot). Publications used for the literature count are of a pangolin focus and in the scientific domain "natural sciences". The map was created by adding the count data per country to a world map shapefile in QGIS v3.4.10 (QGIS Development Team, 2016) by merging a CSV file containing data of count per country to the shapefile with the FIPS country code as a common merging string. Pangolin distribution is comprised of the IUCN Red List of Threatened Species™ (2019) distributions of the eight extant pangolin species. Values on the pie chart refer to literature count. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

review database (Appendix A) can be used as a new proxy method. Since literature was only screened by title, abstract and keywords, it is likely that more checklist or monitoring literature is available.

The third highest category, "volume or nature of trade and poaching", has a high count as a result of the illegal trade being the principal conservation concern for pangolins (Challender et al., 2014). The number of links noted in the trade cluster of the VOSviewer analyses also highlighted that China is frequently indicated in trade-related topics, likely as it is the main market driving demand (Heinrich et al., 2017). However, local consumption and bushmeat market trade is also a contributor to wild pangolin offtake and needs to be investigated further (Ingram et al., 2018). Tackling this illegal trade requires various approaches (Akella and Allan, 2012), one of which could be molecular forensic identification of species and geographic origins of illegally traded specimens, as noted in the VOSviewer linking words (Gaubert et al., 2018; Zhang et al., 2020a). Despite its potential reach, there is a lack of georeferenced population genetic/phylogeographic inferences to trace the trade and determine evolutionary significant units (Zhang et al., 2015), while there are currently only two species with published full genomes (Choo et al., 2016; Hu et al., 2020), and limited development of population genetic markers (e.g. Aguillon et al., 2020; Luo et al., 2007). Forensic approaches (including stable isotopes and morphometrics) are a means of direct conservation interventions involving law enforcement and conservation organizations (Kotze et al., 2020; see also "forensic application" category in our database), and should be considered in more depth.

Although certain evidence-based outputs played an important role in pangolins receiving their conservation icon status through their trade (Heinrich et al., 2017; Pantel and Chin, 2009; Xu et al., 2016), we still only have limited examples of accurate data pertaining to the role that the illegal wildlife trade plays in pangolin population declines and extinction (Irshad et al., 2015; Wu et al., 2004), genetic variation loss (Hu et al., 2020), and likelihood of disease epidemics (e.g. Clark et al., 2009; Liu et al., 2019). These demographic (population structure, abundance and density), epidemiological (disease transmission and reservoirs), and evolutionary (population genetics) lines of evidence are integral for management decisions of populations (Cleaveland et al., 2007; Lande, 1988).

#### 4.1.2. *Inequality in conservation research effort*

The aforementioned examples of risks associated with illegal wildlife trade fall within "implications of trade or poaching to populations", which is a substantially underrepresented conservation category, particularly when compared with "volume or nature of trade and poaching". The same is noted for "anthropogenic effects other than trade or poaching" and "people's perception and awareness of pangolins". The extent of the former is limited to electric game-fencing (Pietersen et al., 2014), domestic dogs (Sun et al., 2019), road mortalities (Murthy and Mishra, 2010), and habitat destruction (Maddox, 2007). Further research is required to elucidate the full spectrum of threats faced by

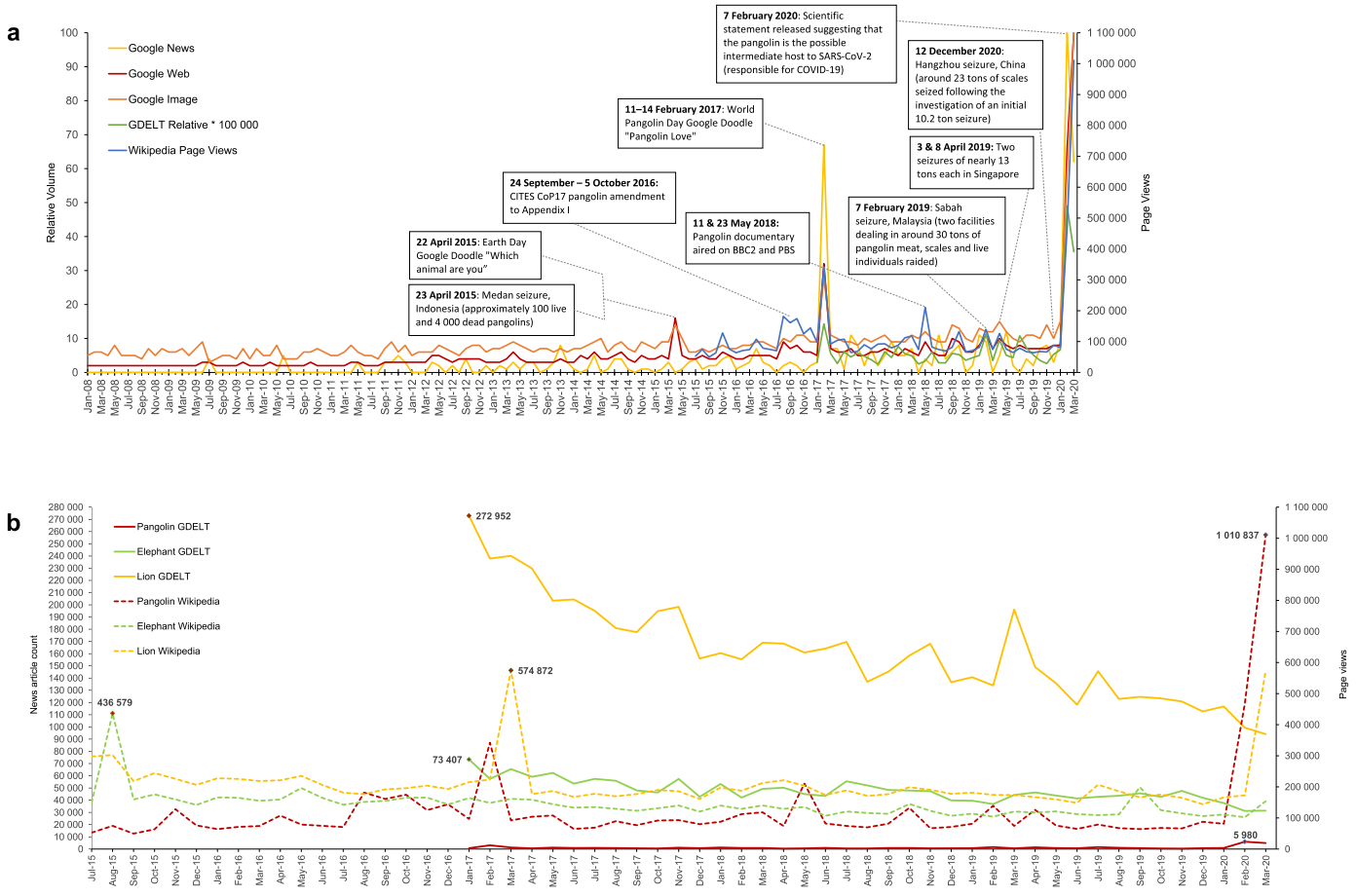


**Fig. 6.** Public interest in the form of societal interest and online news article trends. a) Monthly societal interest is displayed by Google News, Web, and Image relative search volumes (1st y-axis) and Wikipedia page views (2nd y-axis), while online news articles are displayed by GDELT relative values (1st y-axis). GDELT relative values were calculated by dividing the daily pangolin article count by the total number of articles monitored per day, and multiplying this value by 100,000 in order to fit on the relative volume axis (1st y-axis). Peaks of public interest and the largest seizures recorded are indicated in text boxes. b) GDELT article count (1st y-axis) and Wikipedia Page views (2nd y-axis) per month for lions, elephants and pangolins are displayed for comparative purposes between these iconic conservation species. The highest count for online news article and page views are displayed for each trend.

pangolins (e.g. climate change). Research into "people's perception and awareness of pangolins" is integral in determining the roots of demand, as well as awareness of pangolin legislation and their plight, which may better guide educational, awareness, and behavioral change programs (Baiyewu et al., 2018; Zanvo et al., 2020).

This contrast in research effort also applies to other categories, for instance references to "captive breeding" are double those of "rehabilitation". Literature on best practices for rehabilitation and release is a necessity considering the high level of live pangolins trafficked (Heinrich et al., 2017) and the conditions under which they are trafficked, which leads to complications or mortalities during rehabilitation (Clark et al., 2009). Nonetheless, data on nutrition and welfare practices (Cabana et al., 2017; Zhang et al., 2017) in "captive breeding" are also important for rehabilitation.

### 4.1.3. The major knowledge gaps

The two lowest themes by publication count, "veterinary" and "ethnozoology and society", are of conservation concern. The latter relates to "people's perception and awareness of pangolins" but also includes pangolin use in traditional medicine and food. More research in this theme would allow for better insight into demand through traditions and social norms, as well as when hunting pressure shifts from local to global, often unsustainable, commercial trade (Baiyewu et al., 2018; Ingram et al., 2018). Understanding the intricacies behind the demand from the perspective of the consumers may provide insights into reducing it (Wang et al., 2020). Regarding the "veterinary" theme, the lack of literature on veterinary procedures and guidelines is concerning considering the aforementioned live trade and complications surrounding confiscated individuals. Research and conservation practices may also cause pangolin mortality and morbidity if the proper standards of anesthesia and veterinary care are not adhered to (see: Connelly et al., 2019). A recent chapter reviewing veterinary procedures for a variety of complications and diseases (Wicker et al., 2020) is an important step, but as noted by the authors and our research, there is limited information on *P. tricuspis*, *S. gigantea* and *M. culionensis*. *Phataginus tricuspis* requires particularly urgent attention in the veterinary field considering it has been the most traded pangolin species in recent years (Challender et al., 2020a).

Literature count of the category "education", namely knowledge of the effectiveness or description of education programs, is alarmingly low, whereas such knowledge is critical to pangolin conservation and should be shared when possible (Ardoin et al., 2020). "Immunology" is an important research avenue that requires more effort as many pangolins in rehabilitation or captive breeding die from infections (Clark et al., 2009), diseases found through veterinary examination are likely linked to pathogens (Wicker et al., 2020), and innate immune defenses are suggested to be reduced in pangolins (Choo et al., 2016; Fischer et al., 2020). These, along with recent studies isolating pathogens of public health concern from pangolins (Liu et al., 2019; Wang et al., 2019) and high levels of trade highlight the urgent need for research into

pangolin health, immunity and epidemiology.

#### 4.1.4. Species bias

By accounting for the area of distribution for each species, different species bias results were produced when compared with species literature count alone. Both of these measures are important, depending on the types of studies conducted. Ecological monitoring, phylogeographic, poaching, and epidemiological studies may benefit from taking into account species distributions as these are location-specific measures, whilst anatomical, veterinary, rehabilitation, and reproduction studies may only require species-specific measures.

By literature count alone, although African species are less represented, it is clear that *M. culionensis* is the most understudied species, likely as a result of it having the smallest distribution and subject to reduction in population sizes across its range (Schoppe et al., 2019). It may also be a result of the species only recently being described as distinct to the *M. javanica* (Gaubert and Antunes, 2005; Gaubert et al., 2018). Data on ecological monitoring of *S. gigantea*, the second-most understudied species, suggest that population estimates of the species are likely low, and thus less likely to be studied (Bruce et al., 2018).

There is a difference between the number of categories covered by the top two species by count (11% missing for *M. pentadactyla* and *M. javanica*) and those by the bottom three species (41% missing for *M. culionensis*, *S. gigantea*, and *P. tetradactyla*). Furthermore, in the VOSviewer analysis, *M. pentadactyla* and *M. javanica* are central to the network, suggesting that these two historically prominent species are well represented in pangolin literature. This along with more than half of the 27 categories having missing literature for at least one species, suggests that there is a clear species bias. We suggest that targeted funding and research effort on underrepresented species at a per category basis may be an accurate and cost-effective method in gaining the critical missing knowledge for each species (Williams et al., 2020). The commonality in categories missing for all species, particularly between the *S. gigantea* and *P. tetradactyla*, is possibly linked to the formation of novel categories in pangolin biological science (i.e., "population genetics/phylogeography", "implications of trade or poaching to populations"; see: Appendix G) or difficulty in studying certain categories (i.e., "reproduction", "immunology", "diet and feeding").

#### 4.1.5. Research dynamics

With an increasing trend in non-range-state lead authors in recent years, probably due to increased global awareness of pangolins, range-state authors are playing less of a leading role. Although this trend is over a small timescale (since 2017) and we only analyzed lead author dynamics, conservation research is often conducted outside of biodiverse areas by foreign researchers, whilst researchers from countries of high conservation importance have little representation in international fora (Reboredo Segovia et al., 2020; Wilson et al., 2016). Collaboration with local researchers, experts, and institutions is needed to surpass some of the barriers encountered in developing research countries, in which the majority of pangolin distributions lie (Reboredo Segovia et al., 2020). It also provides research and conservation projects with local knowledge, access to local conservation actors, and a basis to initiate long-term studies, all of which are critical for successful conservation action (Kainer et al., 2009).

The dominance of research in Asian range-states relative to African range-states is clear through literature count per year and per country, as well as by number of range-states having no associated pangolin research. This could be due to Asian species being of greater conservation concern through their historical dominance in the illegal trade for TCM, which only shifted to African species within the last decade (Challender et al., 2020a). Relative increase in proportion of studies in African range-states over the last few years suggests this to be true, but also may have been influenced by increased research effort of foreign researchers. Africa is also comparatively less populated, has a lower GDP per capita, higher incidence of poverty and civil war due to political instability, and lacks research resources (Elbadawi and Sambanis, 2000; UN, 2019). These influence its research and conservation potential, suggesting that increased pangolin research, collaboration and funding effort in Africa is required.

The high GDP, human population, and illegal pangolin trade may explain why China (main trafficking import country), India, and Nigeria (major trafficking source country) have the highest research output of all range-states (Heinrich et al., 2017; Meijaard et al., 2015). The two Asian countries are also the most populated countries in the world, whilst Nigeria is the most populated country in Africa (UN, 2019). Due to the large distribution of pangolins, we did not analyze the species and category publication count per range-state trends in this review, however our database (Appendix A) provides the means to do so for future, localized reviews (region/country).

### 4.2. Pangolin popularization

Determining underlying events that create large peaks in public interest is a systematic method that can be used to inform conservationists of how best to gain public support and funding (Phillis et al., 2013). Our findings concurred with Harrington et al. (2018) and Thomson and Fletcher (2020), namely: 'shocking' imagery receives greater societal interest than any other seizure information (April 2015), documentaries from large broadcasting platforms can create a large response while concurrently providing detailed awareness (May 2018), and Google Doodle's have had the largest influence on societal interest and news media coverage (April 2015 and February 2017). That is until scientists from South China Agriculture University released a statement (7/02/2020) that pangolins were a possible intermediate host to SARS-CoV-2, which is responsible for the COVID-19 pandemic. Regardless of there being no concrete evidence backing this claim thus far (Frutos et al., 2020), it resulted in pangolins having a higher societal interest by Wikipedia Pageviews than either elephants or lions for the first time since 2015. However, the peak in online media output was substantially lower than that of elephants and lions during the same time period. Our results also indicate that despite record-breaking seizures receiving a comparatively large online news output, societal interest was comparatively low and that the two do not always correlate. This could be related to the influence of social media which may amplify societal interest without the need for large news media output (Harrington et al., 2018). Whether these peaks of interest or media outputs are related to awareness raising and behavior change is unclear, however peaks in Wikipedia Pageviews corresponding to the latter two types of peaks suggest that some form of awareness raising is occurring.

The peak related to the claim that pangolins were possible intermediate hosts of SARS-CoV-2 may be considered bad publicity for pangolins. Whether it will result in the increased awareness of their plight or a new-found negative public perception is of great importance to their conservation (see: López-Baucells et al., 2018 for an example on bats). Although more costly and difficult, proactive programs creating new peaks of interest, and awareness or behavioral change programs aimed particularly at people in range-states should also be considered (Olmedo et al., 2018; Ploeg et al., 2011; Thomson and Fletcher, 2020).

### 4.3. Commercial interest in pangolins through patents

The relationship between patent production and biomedical research trends in pangolins was not obvious in our study, and further superficial analyses did not provide concrete links by treatments or author affiliations (between patent assignee and biomedical researcher affiliation). Although the first pangolin patent was registered in 1993, a year after the first biomedical study testing the effect that pangolin scales have on lactation in mice (Nagasawa et al., 1992), the patent related to pangolin scales was used for cancer treatment (Chen, C: CN1062658-A). It is therefore likely that the 1992 revision of the "Patent Law of the People's Republic of China" (since 1985), which allowed protection of TCM drugs

and increase in grants, may have initiated patent production and biomedical study trends (Qiao and Zhu, 2009). If patented treatments and medicines are being used without the guidance of science, they may pose a risk to patients and are a misuse of limited pangolin resources (Jin et al., 2021; Xu and Xia, 2019).

Official Traditional Chinese Medicine pharmacopoeia only prescribe pangolin (*Chuan Shan Jia*) scales to promote lactation, improve circulation, reduce swelling, drain pus, and treat skin diseases (Chinese Pharmacopoeia Commission, 2015). Nevertheless, we found examples of research and patents in treatment of hepatic fibrosis (Huang, 2003; Li, X and Che, Y: CN103948877-A), kidney disease (Xiong et al., 2015; Zhao, Q and Wang, D: CN108245632-A), AIDS (Zhao, S: CN106362127-A), and cancer (Chen, C: CN1062658-A). Although no medicinal properties of pangolin scales have been identified through reliable evidence gathering (Jacobs et al., 2019; Jin et al., 2021), the argument of entrusting in TCM through thousands of years of practice is questioned if medicine and treatments are based on recent patents rather than traditional pharmacopoeia that are the embodiment of historical practices. However, we caution that our results are limited and require more in-depth analyses of these patents (major role-players, medicines derived from pangolins, and ailments targeted), along with more evidence for the connection between the legal and illicit pangolin supply chains (Horner et al., 2020; Xu et al., 2016). This is necessary if profitability is driving pangolin-derived patented medicine, a possibility supported by the growth of the TCM industry, along with its profit margin and international reach, whilst large private corporations are suggested to be outcompeting the state-based industry (Tommaso et al., 2017; Xu and Xia, 2019). Further investigating patented medicinal use may be needed to discredit illegal activities as recent evidence suggests that pangolins are still included in TCM Pharmacopoeia (EIA, 2020), contrary to previous announcements (Liu, 2020).

Although it is unclear what may have caused the substantial increase in the number of registered patents from 2011 onwards, the dramatic decrease in new patents being registered from 2016 onwards could be linked to the decision to up-list all eight pangolin species to Appendix I at the seventeenth meeting of the CITES Conference of the Parties in 2016. This decision prohibits the international trade of wild-caught pangolins and their derivatives for commercial purposes, and thus may have resulted in the creation of new patents for legal medicine production no longer being financially viable.

### 4.4. Conclusion of a holistic review on pangolins for their conservation

In this study, we provide a curated pangolin research database (Appendix A) which could be used as a source of information for researchers and practitioners alike. From our in-depth review of pangolin research dynamics combined with an updated overview of public interest (as explored in: Harrington et al., 2018; Thomson and Fletcher, 2020) and an unprecedented assessment of patents, we provide a series of recommendations to fill the knowledge gaps on pangolins for the benefit of their conservation (Table 1).

Although a multitude of conservation issues surround pangolins, the illegal poaching and trade is a major problem. Tackling this issue will require knowledge from a multitude of aspects (popularization, commercialization, and research) as well as conservation actions (Akella and Allan, 2012). The latter is an aspect that we did not review directly, however from knowledge garnered from key publications through the review process, we suggest the following conservation actions to tackle the trade issues that are additional to those previously suggested by Challender et al. (2014): (1) horizon scanning analyses of patents for future trade trends (Masters et al., 2020), (2) clinical trials for pangolin-derived medicine through accredited, unbiased protocols (Jin et al., 2021), (3) forensic registers (DNA, isotope, morphology) to identify trade routes, sources, volumes, and legality (Kotze et al., 2020), (4) audits of breeding farms and stockpiles to prevent links between legal and illegal supply, and unethical treatment (Challender et al., 2019;

**Table 1**
Global recommendations to fill the knowledge gaps on pangolins for their conservation as identified through the review process on pangolin research, popularization and commercialization.

| Issue | Expansion and recommendation | Conservation aspect |
|---|---|---|
| Limited public interest and awareness raising | Given the lack of societal interest and news media outputs on pangolins compared to other iconic species, garnering public interest is a necessity for pangolin conservation. Conservationists should consider previously successful endeavors as a guiding factor, such as 'shocking' imagery, documentaries through large broadcasting platforms, and fun, interactive learning such as Google Doodles. Monitoring peaks of interest for reactive awareness raising (Clements, 2013), while development of more behavior change and awareness raising programs, with response feedback loops should also be considered ( Olmedo et al., 2018). For example, does the COVID-19 peak of interest result in the public knowing more about the plight of pangolins and how to help conserve them? | Popularization |
| COVID-19's role in public perception | With the largest spike in public interest of pangolins following the news of their suggested link with COVID-19, gathering of global data on people's perceptions of pangolins is important (increased awareness of their plight or a new-found 'vermin-like' persona). Conservation of pangolins is likely to rely heavily on how they are perceived. | Popularization |
| Influences of other large traditional medicine industries that use pangolin-derived products | Our results suggest that TCM is the sole contributor of patented pangolin medicines, however it is unclear what the influence of other traditional medicine industries may be on the pangolin trade. | Commercialization |
| Drivers of pangolin patents | With patents seemingly neither being driven by science nor TCM guideline texts, further insights into the main drivers of patent production is required, so as to prevent future peaks in patent production. | Commercialization |
| Limited information on patented products | More in-depth patent analyses should be undertaken to identify the major patented medicines/compositions in which pangolins derivatives are used, the major ailments treated, and the effect that these patents have on the demand for both legal and illicit products. | Commercialization |
| Major knowledge gaps in pangolin literature (natural sciences) | Researchers and funding bodies should target the large natural sciences gaps identified by research category ("veterinary", "immunology", | Research |

(*continued on next page*)

**Table 1** (*continued*)

| Issue | Expansion and recommendation | Conservation aspect |
|---|---|---|
| | and "education"), species (*M. culionensis*, *S. gigantea* and *P. tetradactyla* by publication count), and country-specific (mainly African range-states) levels for more efficient knowledge generation. We suggest using this study as a reference as it provides details of each level, including a level linking species by categories. | |
| Top three research areas by publication count are biased | Anatomical and physiological research mainly focused on *P. tricuspis*, ecological research on certain species in certain regions, and trade-related research on volumes and networks. Due to the limited amount of research on pangolins, biases are likely to be common. More research on pangolins will likely reduce this effect (as seen in: Appendix G). | Research |
| Research areas of conservation importance are missing critical information | There are knowledge gaps in the implications of trade (populations and public health) and means to counter it (forensics, education, rehabilitation, and people's perception and awareness of pangolins), as well as in population density and distributions, especially through time. Due to limited funding and time, conservation research on pangolins should focus on generating new data for these key areas requiring urgent attention. Meta-analyses on literature that performed checklist and monitoring analyses of conservation areas (see: Appendix A) may also be an important tool for mining population density and distribution data. | Research |
| Limited knowledge on health risks surrounding pangolin trade | We suggest screening both natural pangolin populations (baseline estimates) and individuals in the trade (or derivatives thereof) to determine public and pangolin health risks associated with trafficking and releasing seized individuals. This is in light of the recent COVID-19 pandemic. | Research |
| Africa is trailing in research while lead authors from range-sates are becoming less prominent | More conservation and research effort is needed on the African continent, particularly in its central and western states (where the *P. tricuspis*, *P. tetradactyla* and *S. gigantea* occur) since these have become a major source for traffickers in recent years (Heinrich et al., 2017). Additionally, the inclusion of local stakeholders and communities in range-states is important to successful conservation and research. | Research |

Horner et al., 2020), (5) multinational collaboration of law enforcement agencies utilizing a database of jurisdictions across the supply chain (see Legal Atlas: https://www.legal-atlas.com/), (6) monitoring of financial crime to trace the trade and provide evidence for prosecution (FATF, 2020), and (7) pan-stakeholder working groups tasked specifically with generating and compiling knowledge for standard operating procedures of less readily published conservation action fields (rehabilitation and relocation, veterinary procedures, education and awareness raising, tourism, and law enforcement and seizure processing). This broad, multidisciplinary review comes at a time when public and scientific interest in pangolins is at its greatest, and is thus useful in concentrating foreseeable increased research and popularization for more effective conservation measures. Many of the methods employed and insights garnered throughout this study are likely to be applicable to the conservation of other species as well, notably those in the wildlife trade.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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