



UNIVERSIDADE FEDERAL DE GOIÁS  
INSTITUTO DE CIÊNCIAS BIOLÓGICAS  
PROGRAMA DE PÓS GRADUAÇÃO EM ECOLOGIA E EVOLUÇÃO

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**Extinção, descrição de espécies e estratégias de conservação da  
biodiversidade**

GOIÂNIA

2022



UNIVERSIDADE FEDERAL DE GOIÁS  
INSTITUTO DE CIÊNCIAS BIOLÓGICAS

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**Extinção, descrição de espécies e estratégias de conservação da  
biodiversidade**

Tese apresentada ao Programa de Pós-Graduação em Ecologia e Evolução, do Instituto de Ciências Biológicas, da Universidade Federal de Goiás (UFG), como requisito para obtenção do título de Doutor em Ecologia e Evolução.

Área de concentração: Ecologia e Evolução

Linha de pesquisa: Ecologia e conservação

Orientador: Professor Doutor Matheus de Souza Lima-Ribeiro

GOIÂNIA

2022

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Moreira, Mateus Atadeu

Extinção, descrição de espécies e estratégias de conservação da biodiversidade [manuscrito] / Mateus Atadeu Moreira. - 2022. 86 f.

Orientador: Prof. Dr. Matheus de Souza Lima-Ribeiro.

Tese (Doutorado) - Universidade Federal de Goiás, Instituto de Ciências Biológicas (ICB), Programa de Pós-Graduação em Ecologia e Evolução, Goiânia, 2022.

Bibliografia.

Inclui gráfico, tabelas, lista de figuras.

1. Conservação da Biodiversidade. 2. Descrição de espécies. 3. Extinção. 4. Mamíferos. 5. Tetrápodes. I. Lima-Ribeiro, Matheus de Souza, orient. II. Título.

CDU 574



UNIVERSIDADE FEDERAL DE GOIÁS

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### ATA DE DEFESA DE TESE

Ata Nº 121 da sessão de Defesa de Tese de **Mateus Atadeu Moreira** que confere o título de Doutor em **Ecologia e Evolução**, na área de concentração em **Ecologia e Evolução**.

Aos **trinta e um dias do mês de agosto do ano de dois mil e vinte e dois (31/08/2022)**, a partir das **08h00min**, por videoconferência, seguindo Resolução CONSUNI/UFG Nº 141 de 13 de maio de 2022 e orientações do Ofício Circular no. 34/2022/PRPG/UFG (SEI 23070.030951/2022-07), realizou-se a sessão pública de Defesa de Tese intitulada “**EXTINÇÃO, DESCRIÇÃO DE ESPÉCIES E ESTRATÉGIAS DE CONSERVAÇÃO DA BIODIVERSIDADE**”. Os trabalhos foram instalados pelo Orientador, **Prof. Dr. Matheus de Souza Lima Ribeiro (UAECIBIO/UFJ)**; com a participação dos demais membros da Banca Examinadora: **Profa. Dra. Levi Carina Terribile (UAECIBIO/UFJ)**, membro titular interno; **Prof. Dr. Fausto Nomura (DECOL/ICB/UFG)**, membro titular interno, **Prof. Dr. Frederico Augusto Martins Valtuille Faleiro (ICB/UFG)**, membro titular externo, **Prof. Dr. Paulo Vitor dos Santos Bernardo (Campus Altamira/UFPA)**, membro titular externo. Durante a arguição os membros da banca não fizeram sugestão de alteração do título do trabalho. A Banca Examinadora reuniu-se em sessão secreta a fim de concluir o julgamento da Tese tendo sido o candidato **aprovado** pelos seus membros. Proclamados os resultados pelo **Prof. Dr. Matheus de Souza Lima Ribeiro**, Presidente da Banca Examinadora, foram encerrados os trabalhos e, para constar, lavrou-se a presente ata que é assinada pelos Membros da Banca Examinadora, aos **trinta e um dias do mês de agosto do ano de dois mil e vinte e dois (31/08/2022)**.

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Ao Senhor Jesus e à minha família: meus pais Elpídio e Soraia, minha esposa Rebecca, meu irmão André, e meu recém falecido cachorro (filho e melhor amigo) Bartolomeu.

"Pois Ele conhece a nossa estrutura; Ele se lembra de que somos pó. Quanto ao homem, os seus dias são como a erva; como a flor do campo, assim ele floresce. Pois o vento passa por ela, e ela se vai, e o seu lugar não mais a conhecerá. Mas a misericórdia do Senhor é de eternidade à eternidade sobre aqueles que o temem, e a sua justiça sobre os filhos dos filhos"

Salmos 103: 14 a 17

**Agradecimentos:**

Começo esta seção agradecendo ao Autor da vida, Soberano Criador dos céus e da terra, Jesus Cristo, o único Deus, em quem eu creio e confio, Aquele que me proporciona o melhor da vida. Em segundo lugar agradeço a meu filho e melhor amigo, um cachorro que nunca foi simplesmente um cachorro, Bartolomeu, que não se encontra mais entre nós desde o último dia 16 (16/08/2022). As alegrias, sorrisos, brincadeiras, todo o afeto e amor verdadeiros que experimentei com você jamais serão substituídos ou esquecidos meu filho, e sei que ainda nos veremos em um lugar infinitamente melhor!

Duas pessoas em especial também merecem agradecimentos em destaque, não só pelo papel crucial que tiveram na conclusão dessa etapa da minha vida, mas por tudo que me proporcionam: Minha esposa Rebecca é indubitavelmente o melhor presente que Deus já me deu, uma companheira ajudadora e sempre fiel que a cada dia eu admiro mais. Minha mãe, Soraia, é simplesmente o meu exemplo de vida, quem me ensinou com as palavras e com os atos como viver uma vida digna. A gratidão que devo a essas duas vai além do que palavras podem expressar! Agradeço grandemente também a meu pai Elpídio e meu irmão André que sempre me incentivaram e me deram todo suporte que puderam.

Agradeço também ao meu orientador Matheus Lima-Ribeiro que precisou ter muita paciência e longanimidade comigo ao longo desses quatro anos e cinco meses e sempre me tratou com uma gentileza muito singela e sincera. Agradeço aos colegas pesquisadores Bruno Ribeiro, Alessandra Bertassoni e Hugo Bampi por toda ajuda em discussões e dicas sobre os artigos que compõem esta tese e também aos meus colegas de turma por todo o companheirismo. Por fim, agradeço à Coordenação de Aperfeiçoamento Pessoal de Nível Superior (CAPES) pela provisão da bolsa, e à Universidade Federal de Goiás e ao Programa de Pós-Graduação em Ecologia e Evolução pela provisão dos suportes físico e intelectual.

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## **Resumo**

No primeiro capítulo desta tese, avaliamos as principais tendências e padrões de pesquisa espaço-temporais associados aos artigos analíticos (artigos em que os pesquisadores realizaram análises de priorização espacial usando dados reais) sobre o Planejamento Sistemático da Conservação. No segundo capítulo desta tese revisamos brevemente o que sabemos sobre alguns padrões, possíveis causas e consequências da extinção de mamíferos nos últimos 126 mil anos. Também discutimos brevemente as deficiências de conhecimento e os desafios metodológicos que enfrentamos ao estudar tais extinções. No terceiro capítulo desta tese, investigamos o equilíbrio entre espécies descritas, extintas e categorizadas como ameaçadas de extinção dentro de Tetrapoda. Nossos dados mostram 519 Tetrápodes extintos em 519 anos e 6673 espécies recebendo status de ameaça em 56 anos (1965-2021) (119,16 spp/ano). Quando contamos o número de espécies que foram extintas antes, no mesmo ano, ou alguns anos após sua descrição (até 20 anos depois) temos 318 espécies. A distribuição dos anos de descrição dessas 318 espécies concentra-se em anos recentes (dos anos 1970 aos anos 2000). Nossos resultados corroboram o que outros pesquisadores têm encontrado: espécies recentemente descritas (e, portanto, espécies não descritas muito provavelmente também) estão em maior risco do que outras espécies. Muitas espécies estão provavelmente se extinguindo sem nunca terem sido descritas. Investir em pesquisas intensivas visando áreas com alta diversidade de espécies não descritas em áreas tropicais pode ser de grande ajuda para proteger espécies com pequenas populações e pequenos tamanhos de distribuição que enfrentam ameaças severas.

Palavras - chave: Conservação da Biodiversidade, Descrição de espécies, Extinção, Mamíferos, Tetrápodes.

### **Abstract**

In the first chapter of this thesis, we evaluated the main trends and patterns of spatio-temporal research associated with analytical articles (articles in which researchers performed spatial prioritization analyzes using real data) on Systematic Conservation Planning. In the second chapter of this thesis we briefly review what we know about some patterns, possible causes and consequences of mammalian extinction over the last 126,000 years. We also briefly discuss the knowledge gaps and methodological challenges we face in studying such extinctions. In the third chapter of this thesis, we investigate the balance between described, extinct and categorized as endangered species within Tetrapoda. Our data show 519 extinct tetrapods in 519 years and 6673 species receiving threatened status in 56 years (1965-2021) (119.16 spp/year). When we count the number of species that went extinct before, in the same year, or a few years after their description (up to 20 years later) we have 318 species. The distribution of years of description of these 318 species is concentrated in recent years (from the 1970s to the 2000s). Our results corroborate what other researchers have found: recently described species (and therefore very likely undescribed species as well) are at greater risk than other species. Many species are likely to become extinct without ever having been described. Investing in intensive research targeting areas with high diversity of undescribed species in tropical areas can be of great help to protect species with small populations and small distribution sizes that face severe threats.

Keywords: Biodiversity Conservation, Species Description, Extinction, Mammals, Tetrapods, Systematic Conservation Planning.

## **Introdução geral:**

Quantas espécies existem? Essa tem sido uma questão de ouro na biologia, e uma série de esforços têm sido aplicados para chegar a essa resposta (Mora et al., 2011; Pimm et al., 2014; Burgin et al., 2018; Moura & Jetz, 2021). As estimativas sugerem que pelo menos um milhão de espécies em todo o mundo ainda não foram descritas (Mora et al., 2011; Costello et al., 2012). Avaliar a riqueza global em nível de espécie é uma tarefa desafiadora, mas fundamental (Costello, May & Stork, 2013). O conhecimento taxonômico por meio da descrição de espécies tem se provado como uma métrica útil para rastrear o progresso científico na exploração da biodiversidade global e categorizar habitats e ecossistemas. As espécies fornecem aos ambientes, ecossistemas e humanos muitos serviços que possibilitam a vida na Terra (Essl et al., 2012; Pimm et al., 2014). Outro motivo para melhorar o conhecimento taxonômico é rastrear quantas espécies estão ameaçadas de extinção e quantas estão sendo extintas (Costello, May & Stork, 2013; IUCN, 2022).

O *Systema Naturae*, desenvolvido por Linnaeus (No século XVIII), foi a tentativa mais significativa de documentar a vida na Terra, nomeando e classificando as espécies (Anderson et al., 2007). Fornecer o reconhecimento científico de uma espécie, avaliando assim a taxonomia do organismo, envolve um processo de descrição (Zamani et al., 2022) que segue diretrizes internacionais (por exemplo, The International Commission on Zoological Nomenclature for Animals). Quando uma espécie é formalmente reconhecida,

abrem-se as portas para levantamentos e avaliações. A partir deste momento, também é possível estimar o risco de extinção da espécie (IUCN 2022). Se determinar a descrição de uma espécie é desafiador, determinar a extinção de uma espécie - o desaparecimento de todos os indivíduos - é ainda mais difícil. (Pimm et al., 2014; Tedesco et al., 2014; Liu et al., 2022).

As taxas atuais de extinção de espécies são alarmantes (Ceballos et al., 2015), e as estimativas sugerem que tais taxas estão mais de 1.000 vezes maiores do que as taxas naturais de fundo (Pereira et al., 2010; Andermann et al., 2020). A União Internacional para a Conservação da Natureza possui um comitê responsável pela Lista Vermelha de Espécies Ameaçadas. Esse comitê possui um banco de dados com curadoria de cientistas e especialistas que fornecem avaliações recorrentes de espécies, incluindo avaliações sobre tendências populacionais, ameaças e risco de extinção (IUCN 2022). Essas avaliações periódicas têm sido cruciais para ajudar governos e organizações em todo o mundo a focar suas estratégias de conservação e priorizar as espécies e ecossistemas nas necessidades mais urgentes (IUCN 2022).

Os números relatados de extinções de espécies podem estar subestimados, considerando que uma alta porcentagem da biodiversidade de espécies ainda não foi descrita (Mora et al., 2011; Costello et al., 2012, Costello, May & Stork, 2013). Além disso, a maioria das espécies descritas recentemente tem distribuição geográfica restrita, o que as torna (e muito provavelmente as espécies ainda desconhecidas também) mais propensas a processos de extinção (Giam et al., 2012). Dessa forma, muitas espécies podem estar desaparecendo antes do reconhecimento científico formal (Niemiller et al., 2013).

Uma classe taxonômica que tem sofrido perdas significativas nos últimos milhares de anos é a classe dos mamíferos, muito conhecida por nós. A diversidade de mamíferos atualmente compreende 5.869 espécies vivas (The International Union for Conservation of Nature, 2021). No entanto, se estivéssemos testemunhando uma taxa natural de extinção de mamíferos nos últimos milhares de anos, esse número poderia ser massivamente maior (Andermann et al., 2020). Estima-se que 348 mamíferos tenham sido extintos nos últimos 126 mil anos (o chamado período “Quaternário Tardio”). Essas extinções, que ocorreram em menos de 130 mil anos, teriam levado 1,75 milhão de anos para acontecer se as taxas de extinção tivessem permanecido inalteradas nos últimos 130 mil anos (Andermann et al., 2020).

Nos últimos cem milênios, estima-se que a biomassa total de mamíferos selvagens tenha diminuído em 85% (Bar-On et al., 2018; Ritchie, 2020). Atualmente, 22,6% das espécies de mamíferos são consideradas ameaçadas de extinção (The International Union for Conservation of Nature, 2021). Estima-se que os animais selvagens representem apenas 4% da biomassa atual de mamíferos em todo o mundo, e os animais de criação representam mais de 60% dessa biomassa total (Bar-On et al., 2018; Ritchie, 2020). Sabe-se que 31,9% das espécies de mamíferos têm populações decrescentes (The International Union for Conservation of Nature, 2021), e muitas espécies perderam mais de 40% de sua área geográfica desde 1900 (Ceballos et al., 2017).

Análises feitas aqui nesta tese revelaram que não só os mamíferos mas também os anfíbios, aves e Répteis (os Tetrápodes) ainda estão sendo descritos em altas taxas mesmo após 261 anos de descrições científicas formais (1758-2019), e ao mesmo tempo estão entrando em processo de extinção (sendo

categorizados como ameaçados) ou sendo completamente extintos em um ritmo assustadoramente acelerado. Nossos dados mostram 519 Tetrápodes extintos em 519 anos (ou seja, estamos perdendo 1 spp/ano de Tetrápodes desde 1500), e 6673 espécies recebendo status de ameaçadas em 56 anos (1965-2021) (119,16 spp/ano) .

Considerando tal cenário crítico não só para os Tetrápodes mas para a biodiversidade no geral, cenário no qual as taxas de extinção estão talvez 1000 vezes maiores do que estariam naturalmente, como fazemos para salvar espécies de terem um fim que não aconteceria naturalmente? Para isso cientistas, organizações e governantes ao redor do mundo tem se empenhado para planejar de forma eficiente ações de conservação que possam ser efetivas. Nesse sentido, surgiu então o Planejamento Sistemático de Conservação.

O Planejamento Sistemático de Conservação (SCP (sigla em inglês)) é um campo preocupado com o uso mais eficaz de recursos limitados para atingir as metas de conservação da biodiversidade (Margules & Pressey 2000; Margules & Sarkar 2007). O ponto de partida do SCP pode ser rastreado até a década de 1980, quando pesquisadores australianos introduziram o princípio da complementaridade para identificar áreas prioritárias de conservação da biodiversidade (Kirkpatrick 1983). A partir daí, o SCP passou por três marcos: o desenvolvimento teórico nos primeiros anos, a definição dos conceitos subjacentes e o desenvolvimento dos primeiros algoritmos usados para a seleção de áreas prioritárias na década de 1990 e, finalmente, o estabelecimento de um processo padronizado e sistemático em anos 2000 (Margules & Pressey 2000). Nas últimas duas décadas, o campo de SCP experimentou um aumento exponencial associado à maior disponibilidade de softwares amigáveis para

realização das análises. Todo esse desenvolvimento teve como objetivo fornecer aos tomadores de decisão elementos concretos visando melhores decisões (Margules & Pressey 2000).

O SCP se estabeleceu como uma área produtiva e influente, com centenas de publicações revisadas por pares e vários exemplos de uso de planejamento regional (DiMarco et al., 2017).

Nesta tese se encontram revisões, descrições e análises feitas sobre o planejamento sistemático de conservação (Capítulo 1), as extinções de mamíferos nos últimos milhares de anos (Capítulo 2), e também sobre as descrições de espécies, extinções, e espécies se tornando ameaçadas nas 4 classes de Tetrápodes (capítulo 3). Os capítulos foram feitos no formato de manuscritos para serem enviados para revistas de publicação científica e por esse motivo se encontram escritos em inglês.

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**PRIMEIRO CAPÍTULO DA TESE:**

## **Systematic conservation planning: A systematic review of the analytical papers**

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## **Abstract**

Systematic Conservation Planning (SCP) provides a strategic framework to locate and design efficient reserve systems. Here, we assess the main spatial-temporal research trends and patterns associated with the analytical papers (articles in which the researchers performed spatial prioritization analyses using real data) on Systematic Conservation Planning. We evaluated a set of 549 papers published from 1984 to 2018 in 23 different scientific journals. Two-thirds of the articles assessed here (66.67%) were published in *Biological Conservation* (31.88% of the articles), *Conservation Biology* (20.40%), and *Biodiversity and Conservation* (14.39%). 82% of the studies were performed using data from only one country (national studies). The biogeographical realms that received most attention were Palearctic (n=161; 29.3%) and Nearctic (n=123; 22.4%). Most SPC exercises were done using data on Communities (n=191; 34.17%), Birds (n=75; 13.42%), Mammals (n=74; 13.24%), and Plants (n=71; 12.7%). The great majority (90%) of the studies considered only the taxonomic dimension of biodiversity; only 3.28% of the analyses considered phylogenetic or functional diversity. Most studies that used data on costs considered the opportunity costs, and the software Marxan and Zonation were more commonly used to support conservation planning. The studies that recommended actions to be taken were only 37.7% of the 549 papers assessed and were mainly concern with the urgency of protecting a given area or set of areas. Besides reinforcing the importance of overcoming these biases for the urgent need of a scientific production more linked to the real practical conservation needs, our study has the advantage of having done a throughout evaluation of many features in the analyses and having evaluated the proportion of papers that give recommendations of actions to be taken and which types of recommendations are those. Living in a time of such a dramatic biodiversity crisis, it is of paramount importance to evaluate how conservation research communicates the urgent needs for those who can take action to guarantee more effective protection of biodiversity and think about solutions on how to improve the communication between conservation research and stakeholders.

**Keywords:** Systematic Conservation Planning; Resource allocation; Scientometrics; Spatial Conservation Prioritization; Zonation; Marxan.

## **Introduction**

Systematic Conservation Planning (SCP) is a field concerned with the most effective use of limited resources to achieve biodiversity conservation goals (Margules & Pressey 2000; Sarkar & Margules 2007). The starting point of SCP can be traced to the 1980s when Australian researchers introduced the complementarity principle to identify priority biodiversity conservation areas (Kirkpatrick 1983). Thenceforth, SCP went through three landmarks: theoretical development in the first years, the definition of the underlying concepts and development of the first algorithms used to select the priority areas in the 1990s, and ultimately, the establishment of a standardized and systematic process in the 2000s (Margules & Pressey 2000). In the last two decades, the field of SCP has experienced an exponential increase associated with a broader availability of user-friendly software to conduct analyses (Ribeiro & Atadeu 2019; DiMarco et al. 2017). All this development aimed to provide stakeholders with concrete elements aiming at a better decision-making process (Adams et al., 2019).

Recently, SCP has been established as a productive and influential area, with hundreds of peer-reviewed publications with several examples of regional planning use (DiMarco et al., 2017; Sinclair et al., 2018). Many reviews have been done on SCP (DiMarco et al. 2017; Clark and May 2002; Fazey et al. 2005; Lawler et al. 2006; Griffiths and Dos Santos 2012), but a review focused on the characteristics of the analytical papers, which are more likely to support on-the-ground conservation actions, is still lacking.

In this study, we assess the main spatial-temporal patterns of the analytical papers on SCP and trends and biases in the analyses being done in the field. The analytical papers applying the SCP approach have a higher impact on guiding the practice of conservation in the real world (Sinclair et al. 2018; McIntosh et al. 2017), and their results and recommendations can help the stakeholders make more efficient decisions when selecting areas to protect biodiversity (Venter et al. 2018; Hoekstra et al., 2005; Joppa & Pfaff 2009; Nori et al. 2015; Pressey et al. 2015; Scott et al. 2001).

## Methods

We retrieved analytical papers applying the SCP approach from *Web of Science Clarivate Analytics ISI* primary collection ([webofknowledge.com](http://webofknowledge.com)) using the following topics (originally from Moilanen et al., 2011a) searched in the title, abstract, and keywords: ("reserve network" OR ("reserve design" AND conservation)) OR "reserve selection" OR "site selection algorithm" OR ((systematic OR spatial OR quantitative) AND "conservation planning") OR "reserve site selection" OR (conservation AND ("spatial optimization" OR "spatial optimization")) OR "conservation prioritization" OR "conservation area prioritization" OR "conservation area selection" OR "protected area network."

We considered as analytical papers those that applied the framework of SCP to set priorities for conservation by using an optimization algorithm or software based on actual data. We read the abstract of the articles and excluded articles not directly related to SPC (e.g., addressing strictly ecological, genetic, or other topics not directly related to SCP), conceptual and methodological studies, papers outside the area of "Biodiversity Conservation" and those not considered as research papers (e.g., editorial material, reviews, letters, and proceeding papers). We selected papers published between 1983-2018, given that the first analytical publication considered as SCP was in 1983 (Kirkpatrick, 1983). Non-English papers were not considered. In the end, we analyzed a set of 549 articles to assess published in 23 different scientific journals (Figure 1).

Following Ribeiro and Atadeu (2019), for each paper, we obtained the following information: 1) Year of publication; 2) Institution of the lead (first and last) authors; 3) Journal of publication; 4) Environmental realm (terrestrial, freshwater, marine); 5) Geographical scale (national, regional or global); 6) Taxonomic group (plants, invertebrates, mammals, birds, fish, amphibians, reptiles, community-based approaches – more than two taxonomic groups -, or others); 7) Biogeographical realm 8) Dimension of biodiversity (taxonomic, functional, or phylogenetic); 9) Software used to perform the SCP analyses (e.g., Consent, C-plan, CPLEX, Marxan, ResNet, Zonation, WORLDMAP); 10) Type of cost considered in the SCP analyses (see below), and 11) Recommendations of practical conservation actions provided by the authors (see below).

When a study considered cost in its SCP analyses, we determined the type of cost according to pre-defined categories as follow: Damage cost (the financial cost of damages to nature caused by human activities); Implementation cost (the financial cost of implementing a given conservation plan); Land cost (the price of the land that would be necessary to be bought for the implementation of the conservation plan); Management cost (the price of implementing a management plan); Opportunity cost (the profit that is missed or given up due to the use of an area to nature conservation); Restoration cost (the financial cost of putting a restoration plan into action); and Monetary cost (studies that included data regarding costs but did not specify the type of cost). Some of the studies had more than one of these types of costs.

The recommendations of practical conservation actions provided by authors were also classified according to pre-defined categories, such as Connect (studies recommending actions to guarantee the connectivity among protected areas); Expand (studies proposing the expansion of an already existing system of protected areas); Gap-analysis (studies that identified the gaps of protection of a given system of protected areas); Manage (studies recommending to implement management actions); Protect (studies that argued an urgency to preserve the areas identified as high priority by their analyses); Real (studies that depict an actual conservation program already put in practice); Restore (studies that propose a restoration plan); Specific (studies performing specific SCP analyses that cannot be generalized, such as recommending conservation actions for a particular local or species). Studies that identified priority areas for conservation but did not recommend practical steps were not categorized.

## **Results**

Most analytical papers on SCP were published in the journals Biological Conservation (31.9%), Conservation Biology (20.4%), and Biodiversity and Conservation (14.4%). Few articles were published in generic journals such as Global Change Biology (1.3%) or ecology journals as Ecography (1.5%). An increasing number of papers were published after the 2000s, the year of

publication of the seminal paper of Margules & Pressey (2000) (Figure 1). We also observed an increase in paper production after the year 2007, likely because of the increasing availability and use of user-friendly supporting tools (i.e., Marxan and Zonation; Ball, Possingham, & Watts, 2009; Moilanen & Ball, 2009). Considering the number of papers by countries (i.e., where the institutions of the first authors of studies were based), the USA (19.5% of the articles) and Australia (17.3%) stand out as global leaders of production in the area, followed by UK (9.8%), South Africa (7.6%), Brazil (6%), Canada (5.5%), China (4.2%) and Finland (4%). Considering collaborations between the institutions in which the first and last authors of the studies were based, most collaboration occurred between American & British institutions (7.2%), followed by partnerships between British & Australian (5.1%) and American & Canadian institutions (4.1%). All countries present in more than 10% of the collaborations are Englishspeaking ones (figure x), but Finland and Germany are also present in almost 10% of associations.

A total of 82% of studies were carried out using data from only one country (national studies) whereas only 2.7% could be categorized as global analysis. Most studies were carried out in Palearctic (n=161; 29.3%) and Nearctic (n=123; 22.4%) biogeographical realms; few studies were performed in the IndoMalay (n=47; 8.6%) and Antarctic (n=1; 0.2%). Most of the analyses used data of Communities (n=191; 34.8%), Birds (n=75; 13.7%), Mammals (n=74; 13.5%), and Plants (n=71; 12.9%). Overall, the taxonomic dimension of biodiversity was the most used in analyses (n=494; 89.9%) whereas 3.3% of the analyses considered phylogenetic or functional diversity. Around 80% of studies were carried out on terrestrial environments (n=431; 78.5%), followed by marine (n=87; 15.8%) and freshwater environments (n=40; 7.3%).

Most studies that used data on costs considered the opportunity costs of establishing a protected area system or a new protected area (n=62; 41.7% of the studies using data on costs). A total of 40.4% of these studies (n=58) considered in the analyses only monetary costs but without specifying among opportunity costs, land price, etc.

Among the studies in which we could identify that the authors recommended specific actions to be taken on the ground (209 out of 549 studies; 38.1%), most recommended the established protected area (n=63; 30.1% of these). Many studies performed gap-analyses and therefore, the recommendation implied was to fill the gaps in a given system of protected areas (n=59; 28.2%). A total of 19.1% of studies (n=40;) pointed out specific recommendations related to a particular context or a local conservation problem. A total of 275 studies (50.1%) used software to identify priority areas, of which 41.8% (n=115) used the software Marxan (Ball, Possingham, & Watts, 2009) and 26.9% (n=74) used the software Zonation (Moilanen & Ball, 2009).

## **Discussion**

In this study, we identified patterns and biases of the analytical papers on SCP. Most articles were produced by researchers sited on USA and Australia and sought to identify priority areas for conservation using based on the taxonomic diversity of many taxa at a national scale and terrestrial environment; Marxan and Zonation were the software most used for identifying priorities areas. Around one-third of the articles considered information on costs and explicitly recommended conservation actions to be taken on the ground.

Ultimately, conservation science aims to improve conservation outcomes (e.g., species protection) on the ground (Knight et al. 2008, Mair et al. 2018, McIntosh et al., 2018). Conceptual and methodological studies on SPC indirectly underlying the definitions of conservation actions on the ground by discussing essential subjects and preparing researchers to use their best resources and skills on practical conservation exercises (Ribeiro & Atadeu 2019). Analytical studies on SPC that use actual data to find the best conservation solution contribute more directly to the real conservation plans being developed and established by governments and organizations worldwide (McIntosh et al., 2018). Therefore, our study brings a new and meaningful perspective on the trends and biases of such critical analytical papers on SPC.

The fact that around one-third of the analytical studies assessed used data on costs or provided explicit recommendations of actions to be implemented on-the-ground show that conservation science still needs to be more connected and engaged to the social, political, and economic issues to produce more relevant research (Adams et al. 2019, Kareksela et al. 2018, Knight et al. 2008, McIntosh et al. 2018). Botts et al. (2019) suggest the South African model of implementing conservation research should be copied by other countries. In South Africa, there have been some good examples of applied conservation science involving government leadership of plans, decreasing the size of planning units, increasing emphasis on end-user products, and scheduled revision of plans (Botts et al., 2019).

The geographical biases in conservation research have been reported since the first reviews in the area (DiMarco et al., 2017). Australia's presence in the third place is explained by the origin of the field, which started in the 1980s with Australian researchers searching for early optimization methods to find priority areas for biodiversity conservation (Kirkpatrick et al. 1983, Purdie et al. 1986, Cocks & Baird 1989). Australian researchers have been pioneering the field ever since (Ribeiro & Atadeu 2019). These conclusions also explain the high percentages of studies conducted in the Palearctic, Nearctic, and Australasia biogeographical regions (29.3%, 22.4%, and 20%, respectively). Geographic biases in conservation analytical science undermine our performance to halt biodiversity loss, mainly when areas with a high number of threatened species are neglected, as is the case of the IndoMalay Biogeographical realm, home of not less than five biodiversity hotspots (the Western Ghats and Sri Lanka, Indo-Burma, Sundaland, Wallacea and Philippines (Myers et al. 2000)) and assessed in only 8.6% of the studies evaluated here. The many collaborations between researchers based in South Africa with researchers from leading countries (mainly with researchers based in the UK) explain the high number of articles assessing the Afrotropics (20.6%).

Biases in conservation analytical research also influence our understanding of how much and how exactly different taxonomic groups are threatened, which affects the allocation of funding to combat various threats (Donaldson et al., 2016). According to the IUCN, 41% of amphibian species are threatened with extinction (IUCN 2020). Among the studies we assessed here, only 3.8% were

focused on amphibians (9.1% if we also consider the studies concentrate on vertebrates in general). Mammals are the most studied taxonomic group in the field. Still, when we remember that 25% of them are threatened with extinction (Bowyer et al. 2019), we have an idea of how much research still lags behind compared to levels of threat.

The difference in the amount of research being conducted in the Terrestrial realm compared to the freshwater and marine ones is also worthy of note (78.5% for terrestrial against 22.8% for freshwater and marine combined). Marine conservation science has been expanding (Alvarez-Romero et al., 2018). Still, such an enormous imbalance among the research conducted in these realms may lead to a lack of funding. Consequently, a lack of capacity to combat specific threats found only in freshwater and marine environments (dos Santos et al. 2020).

Our work might not have included some analytical papers on SPC because of the search terms we used and because we searched exclusively on the ISI Web of Science database. However, we could see congruence among our results and the results of other meaningful reviews in the area (DiMarco et al. 2017, Ribeiro & Atadeu, 2019). Assessing whether the papers give explicit recommendations of actions to be taken is somewhat subjective, but we believe the most significant novelty in our work is having analyzed and quantified the different types of recommendations of the authors' actions. Our conclusion that researchers lack engagement concurs with previous work (McIntosh et al. 2018, McIntosh et al. 2017, Knight et al., 2008), and it is clamant. Urgent action must be taken to make conservation science more connected with the urgency of measures demanded by such a dramatic biodiversity crisis.

In summary, here, we assessed past and present trends and patterns in papers that performed spatial prioritization analyses in the area of Systematic Conservation Planning. By analyzing this category of papers, we could shed light on what should be improved specifically in the analytical articles to achieve a more practical scientific production in such an important area of research.

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## Figures:

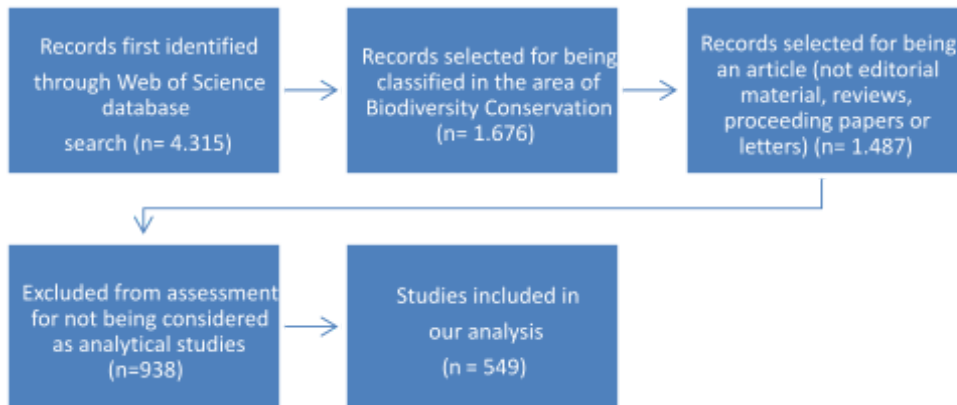
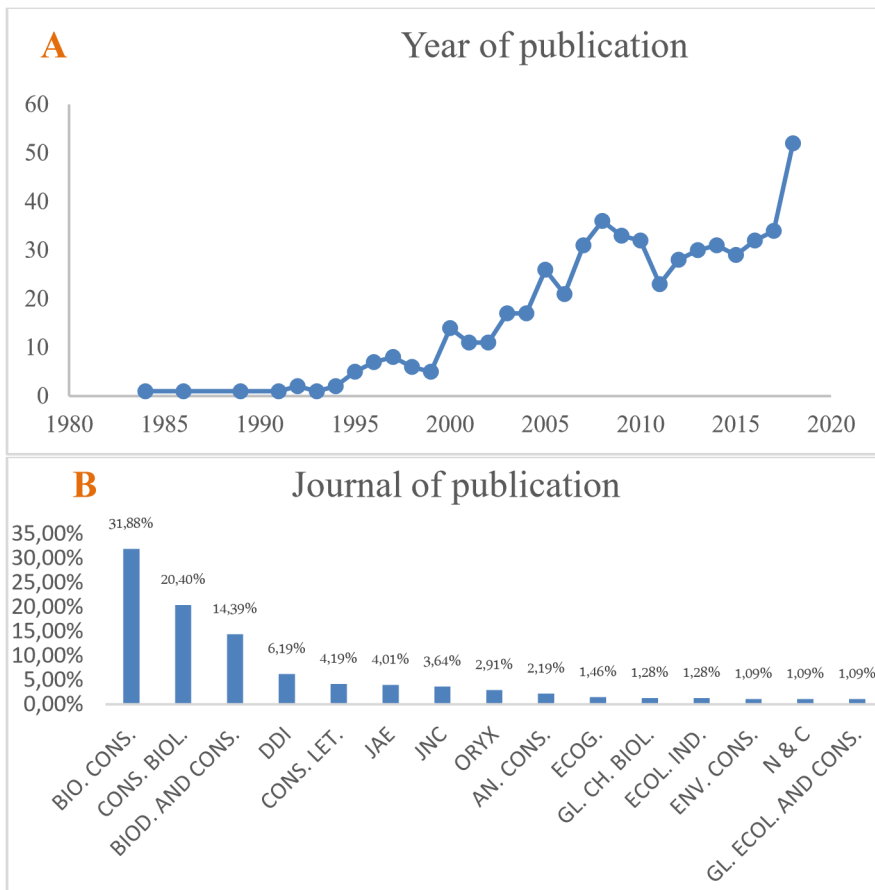
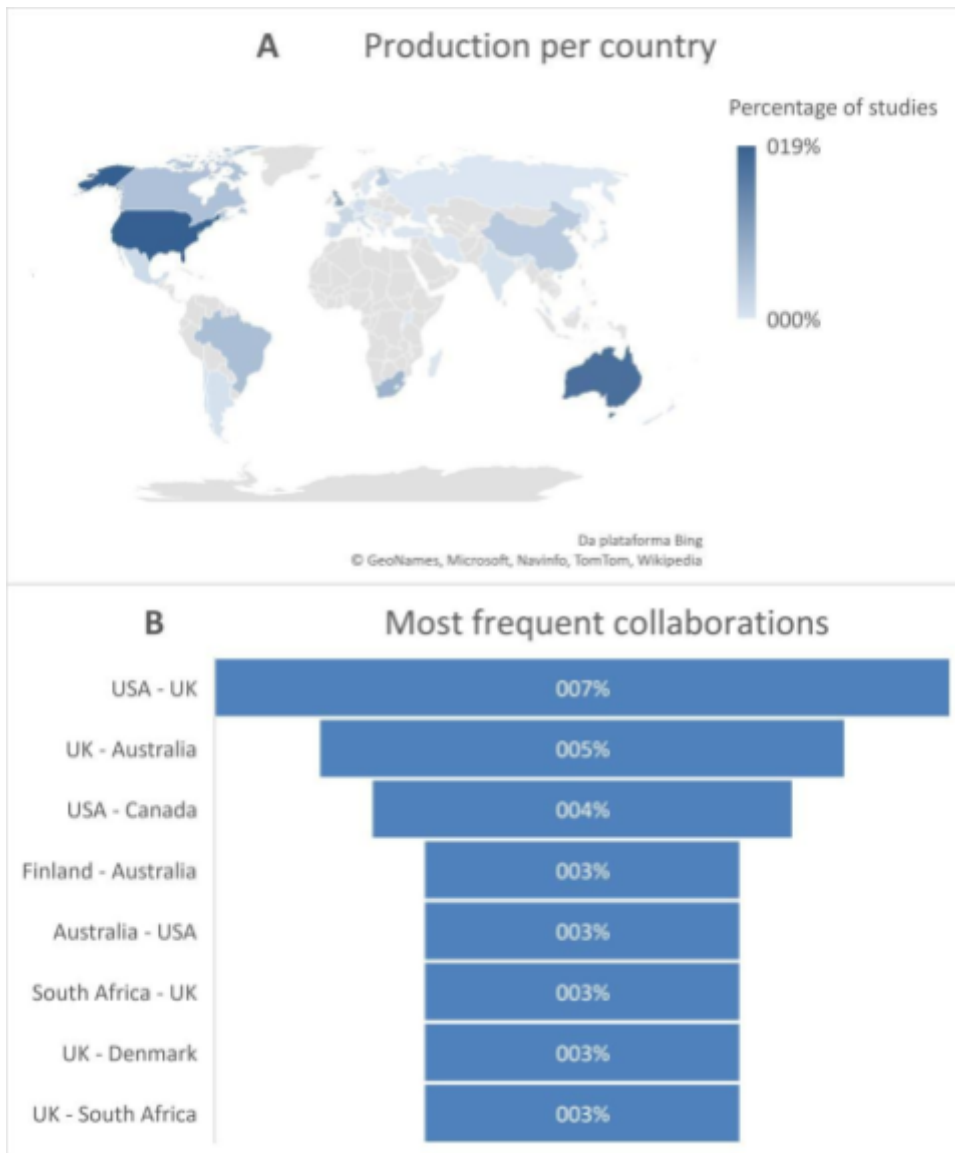


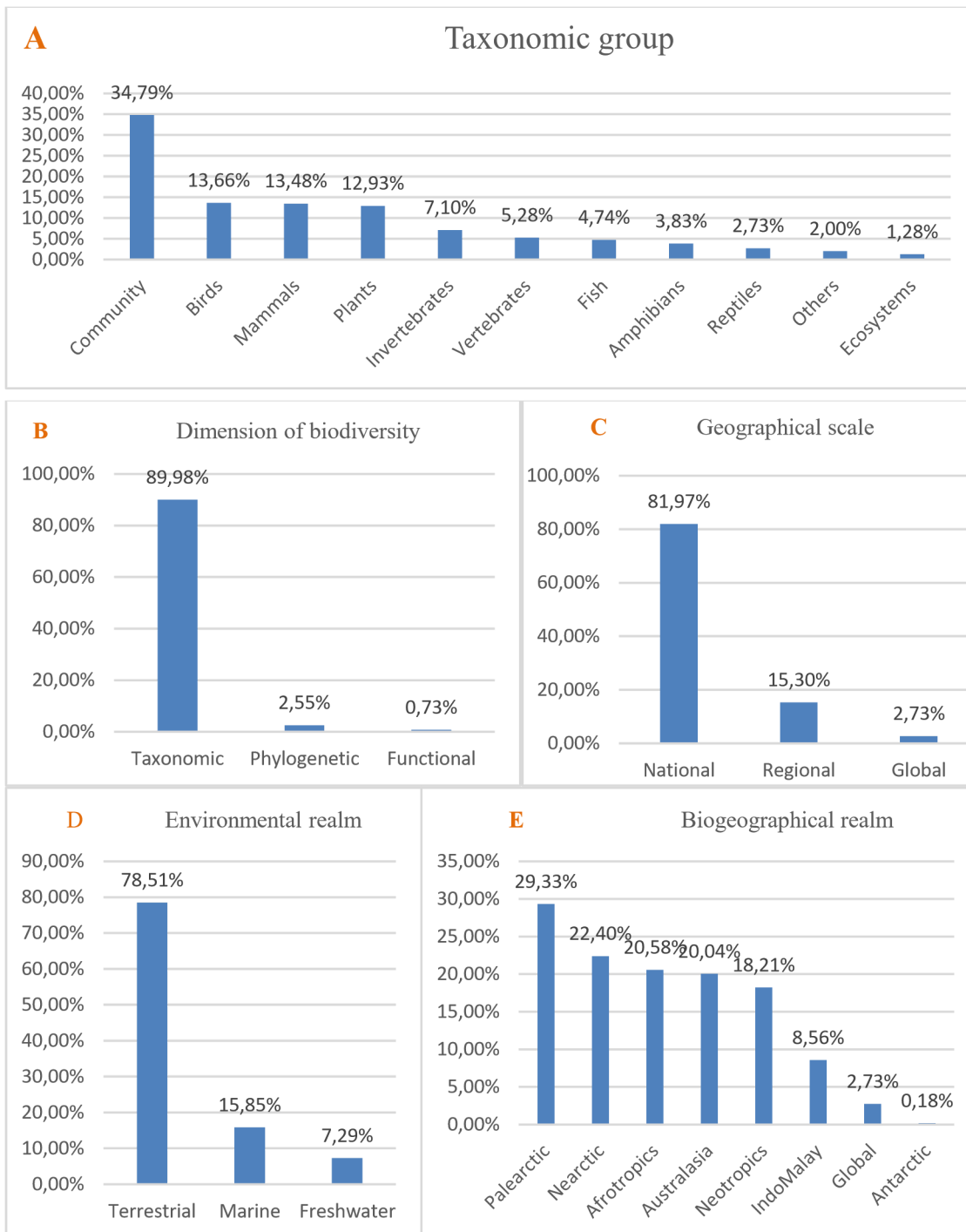
Figure 1. Flow diagram depicting the processes adopted to select the analytical studies on Systematic Conservation Planning.



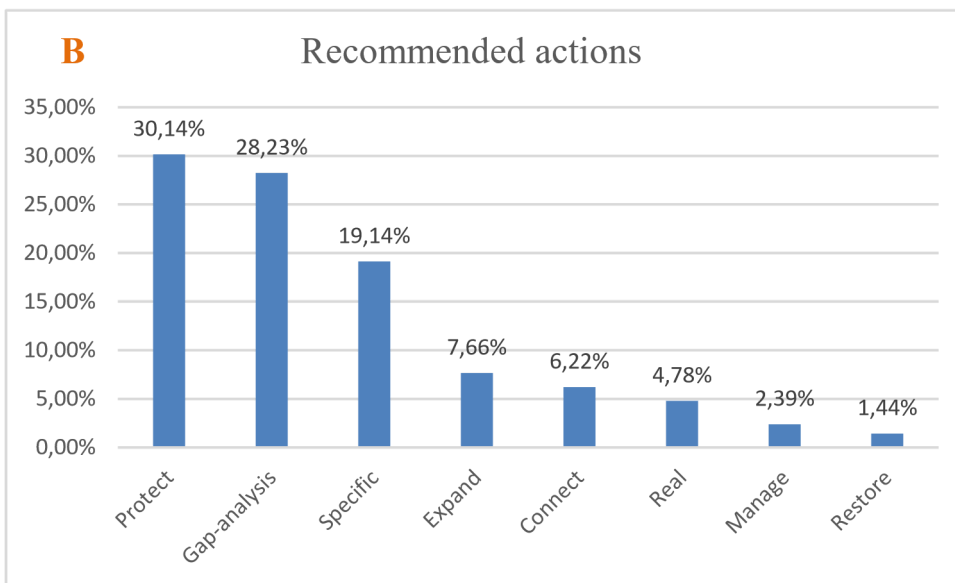
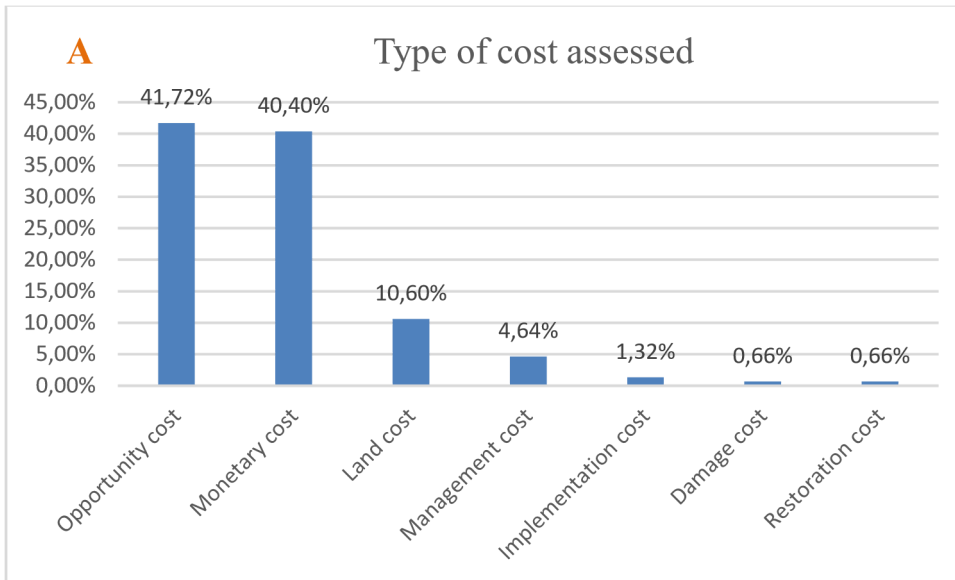
**Figure 2. Scientometric results. A – Year of publication (x) per number of articles published in that year (y). B – Percentage of articles published in each journal (BIO. CONS.= Biological Conservation; CONS. BIOL.= Conservation Biology; BIOD. AND CONS.= Biodiversity and Conservation; DDI= Diversity and Distributions; CONS. LET.= Conservation Letters; JAE= Journal of Applied Ecology; JNC= Journal for Nature Conservation; AN. CONS.= Animal Conservation; ECOG.= Ecography; GL. CH. BIOL= Global Change Biology; ECOL. IND.= Ecological Indicators; ENV. CONS.= Environmental Conservation; N & C= Natureza & Conservação (currently “Perspectives in Ecology and Conservation”); GL. ECOL. AND= Global Ecology and Conservation); Journals that published less than 1% of the papers assessed were not included.**



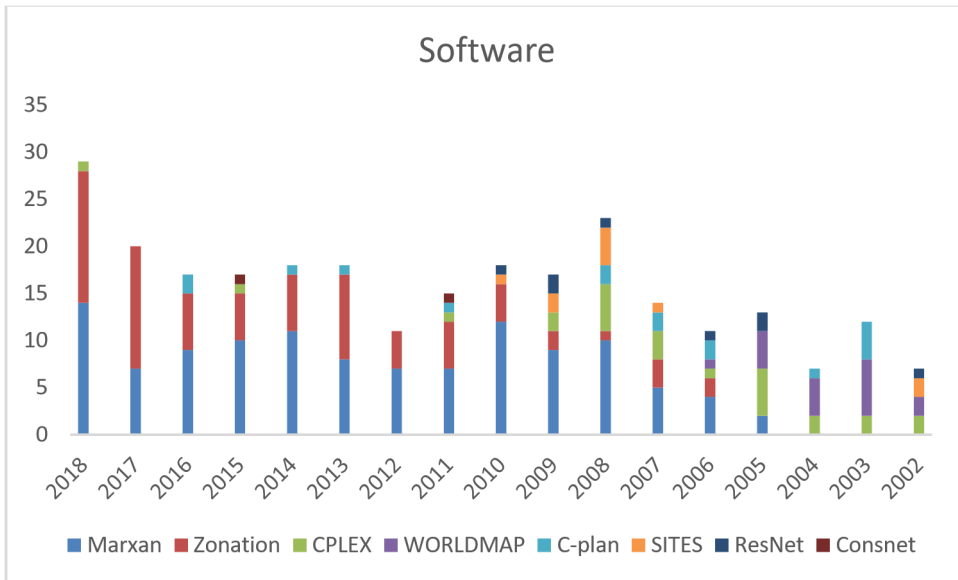
**Figure 3. Most productive countries in the field. A – The different shades of blue in the map represent the percentage of articles published per country (Country in which the main institution that the first author was based in). B – Most frequent collaborations between countries to publish articles (the collaborations were analyzed considering the countries in which the main institutions of the first and the last author were based) Here are shown all the collaborations summing more than three percent of all collaborations.**



**Figure 4. Biological and geographical results.** A) Percentage of studies per taxonomic group. (Community = studies that performed analysis using data from several different taxonomic groups; Ecosystems = Studies that used data from Ecosystems (n=3) or Ecosystem services (n=4) instead of taxa; Others = Fungi, cyanobacteria, lichens, coral or zooplankton; Vertebrates = Studies that used data from various vertebrate groups), some studies used data on more than one of these taxonomic categories. B) Percentage of the analyses considering each dimension of biodiversity, some studies considered more than one dimension. C) Percentage of studies that worked in each of these three geographical scales (Regional = More than one country). D) Percentage of studies considering each of the environmental realms, some studies considered more than one environmental realm. E) Percentage of studies considering each biogeographical realm, some studies assessed more than one biogeographical region, the global studies were accounted both for the global category as well as for each of the biogeographical realms.



**Figure 5. Conservacionist results. A) Percentage of studies using each type of cost (Considering only the studies that used data on costs (25.32% of the studies)), some studies considered more than one type of cost. B) Percentages of recommendations given by the authors categorized in each of the 8 categories of recommendation, some studies made recommendations on more than one category (the percentages were calculated considering only the studies that gave such recommendations (38% of all studies)).**



**Figure 6. The change in the use of software along the years (before 2002 we could not register more than one software being used in the same year).**

# **A brief review on the mammalian extinctions in the Late Quaternary**

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## **Abstract**

Here, I briefly review what we know about some patterns, possible causes, and consequences of the extinction of mammals in the last 126 thousand years. I also briefly discuss the knowledge shortfalls and methodological challenges we face when studying such extinctions. Research regarding Late Quaternary extinctions has been highly focused on the search for a cause of the disappearance of most megafauna in the Terminal Pleistocene and Early Holocene. Much improvement has been achieved in new technologies, which allow for advances in the search for the cause and the consequences of these extinctions. The extinction of most megafauna species in the Pleistocene-Holocene transition brought significant ecological effects to current biodiversity communities, such as changing ecosystems structures and seed dispersal. The expectancy for finding a sole cause that would satisfactorily explain all prehistoric Late Quaternary mammalian extinctions in all the continents has been proven fruitless. Most researchers now agree that the causes vary among continents and species and that our aim should be to unravel the magnitude of anthropogenic and climate change effects for each Late Quaternary scenario. Unraveling the processes by which human overexploitation and climate change together caused many Late Quaternary extinctions is of paramount importance for developing strategies to deal with the current scenario of these same factors leading even a higher number of species to their demise.

**Keywords:** Climate change, Holocene, Late Pleistocene, Megafauna, Overkill, Review.

## **Introduction**

Mammal diversity currently comprises 5,869 living species (The International Union for Conservation of Nature, 2021). However, should we be witnessing a natural rate of mammal extinction in the last thousands of years, this number could be massively higher (Andermann et al., 2020). Three hundred forty-eight mammals are estimated to have been extinct in the last 126 thousand years (the so-called “Late Quaternary” period). These extinctions, which have taken place in less than 130 thousand years, would have taken 1.75 million years to happen if the extinction rates had remained unchanged in the last 130 thousand years (Andermann et al., 2020).

In the last one hundred millennia, the total biomass of wild mammals is estimated to have decreased by 85% (Bar-On et al., 2018; Ritchie, 2020). Currently, 22.6% of mammal species are considered threatened with extinction (The International Union for Conservation of Nature, 2021). It is estimated that wild animals comprise only 4% of the current mammal biomass globally, and livestock animals make up more than 60% of this total biomass (Bar-On et al., 2018; Ritchie, 2020). 31.9% of mammal species are known to have decreasing populations (The International Union for Conservation of Nature, 2021), and many species have lost more than 40% of their geographical range since 1900 (Ceballos et al., 2017).

Eighty-five species of mammals have been reported as extinct since the year 1500 (The International Union for Conservation of Nature, 2021), and 30 more are declared as possibly extinct by the International Union for the Conservation of Nature (The International Union for Conservation of Nature, 2021). Much research has paid attention to these mammalian extinctions reported in recent centuries to discuss human impact over wild mammal populations and formulate strategies to protect the remaining wild biodiversity of mammals (MacPhee & Flemming, 1999; Morrison et al., 2007). However, wild mammalian annihilation has lasted for over 100 thousand years (Stuart, 2015); (Andermann et al., 2020). A closer look at the mammalian losses throughout the late quaternary period (~ the last 126 k years) may yield enlightening conclusions on how to conserve what remains.

Much research has paid attention to the body size selectivity of mammal extinctions in the Late Quaternary (Johnson, 2002; Smith et al., 2018), mostly when the subject is the Terminal Pleistocene and Early Holocene extinctions (approximately from 50 to 8 thousand years ago), which wiped out most gigantic animal forms in the world (Barnosky et al., 2004). Looking at the “average body mass” data from PHYLACINE 1.2, we can see that precisely 50% of the mammals extinct in the last 126 thousand years weighted (in average) 45 kg or more (this is the most common definition of megafauna in the literature (Stuart, 2015). However, looking at the geology, climate, and history, we may distinguish three different periods of extinctions: The Late Pleistocene (From 126 to 11.7 thousand years ago), The precolonial Holocene (from 11.7 thousand years ago to ~500 ago), and the postcolonial Holocene (the last ~500 years).

In the Late Pleistocene, eighty-eight mammals went globally extinct, 78.4% of which could be considered megafauna ( $\geq 45$  kg), 19.32% were large mammals (From 10 to 45 kg (Koch & Barnosky, 2006), and only 2.27% were small mammals (less than 10 kg (Koch & Barnosky, 2006). In the precolonial Holocene, one hundred eighty-five mammal species disappeared (51.35% megafauna, 16.76% large mammals, 31.89% small mammals). Finally, we lost seventy-five mammals from the colonial period until 2020 (13.33% megafauna, 6.7% large, 61.3% small). Johnson (2002) showed that the apparent body-size selectivity of these extinctions was actually due to the slow breeding that characterized megafauna mammals and not really due to their body sizes (Johnson, 2002).

The period which attracts most research is the Terminal Pleistocene and Early Holocene (~ 50 to 8 thousand years ago). During this period, we lost spectacular, impressive, charismatic species such as the woolly mammoth, saber-tooth cats, giant ground sloths, giant marsupials, among others ((Stuart, 2015); see (Andermann et al., 2020) for the species counts considered here). One hundred twenty species vanished during this period; 76.6% weighed 45 kg or more, 18.3% were large mammals, and only 5.1% were small mammals (Calculations made based on the numbers from (Andermann et al., 2020)). These extinctions were contemporary to human populations' spread and growth and severe climatic and environmental changes (Araujo et al., 2017). Such contemporaneity has fueled intense

scientific debates on the causes of this brusque extinction event (mainly of massive mammals) since the 19<sup>th</sup> century (D. k. Grayson, 1984).

Here, I briefly review the patterns, possible causes, and consequences of the mammal extinction across the last 126 thousand years. I also briefly discuss the knowledge shortfalls and methodological challenges we face when studying such extinctions.

## **Causes**

Since the 19<sup>th</sup> century, researchers have been intrigued with the question of what could have caused the disappearance of most gigantic mammalian forms in all continents except Africa in a geologically short time (D. k. Grayson, 1984). In the early 1800s, the three central hypotheses for the cause of these extinctions were: rapid geological change, slow and natural changes across the surface of the earth, and human activities (D. k. Grayson, 1984). In the 1960s, Paul Martin renewed interest in the topic when he vigorously endorsed the “Prehistoric overkill” hypothesis as the cause for North America megafauna extinctions ((Martin, 1967); later, the hypothesis was extended for the other continents (Martin, 1984)). Since then, the scientific debate has been fierce between researchers who advocate anthropogenic causes for these extinctions (Andermann et al., 2020; Araujo et al., 2017; Smith et al., 2018) and those who defend climatic/environmental changes as the explanation (D. K. Grayson & Meltzer, 2003; Meltzer, 1986; Stewart et al., 2021). A third group of researchers has proposed a combination of climatic and environmental natural changes with an unsustainable level of human hunting and environmental alterations as the cause (Barnosky et al., 2004; Koch & Barnosky, 2006; Nikolskiy et al., 2011). These three hypotheses have been the only three explanations that have received support from the community of researchers (Stuart, 2015). Other hypotheses proposed to explain these extinctions, such as hyper disease (MacPhee & Marx, 1997), solar flare (LaViolette, 2011), and extraterrestrial impact (Firestone et al., 2007), all have severe scientific demerits and have all been ruled out by the scientific community in general; therefore, they will not be considered here.

## **Climatic/environmental changes**

It is known that climatic changes provoke environmental changes which intensely affect animal species (Seersholm et al., 2020; Stewart et al., 2021). The Late Quaternary mammalian extinctions concurred, in general, with the last glacial-interglacial transition, which led many researchers to formulate hypotheses centered on environmental changes caused by extreme climatic changes to explain what caused the extinctions (D. K. Grayson & Meltzer, 2003; Meltzer, 1986; Seersholm et al., 2020; Stewart et al., 2021).

In North America and Northern Eurasia, extended areas of mammoth steppe (open vegetation dominated by herbs and grasses) were replaced by forests (mainly conifer forests) (Allen et al., 2010; Huntley et al., 2013). In Alaska/Yukon and Northern Eurasia, there is abundant evidence that many species adapted to mammoth steppes lost their habitats (Allen et al., 2010; Guthrie, 1984; Huntley et al., 2013). The idea that in these two regions, most species went extinct because their habitat disappeared is well accepted in the scientific community (Stuart, 2015). Vegetational changes occurred in most ecosystems throughout the globe (in most of the globe, open vegetation areas were replaced by forests) during the last glacial-interglacial transition. However, outside Eurasia and North America, the outcomes of the climatic, environmental, and vegetation changes are less well known (Stuart, 2015).

Generally, the researchers who propose climate change as the cause for the Late Quaternary extinctions center their explanations on habitat loss (Seersholm et al., 2020; Stewart et al., 2021). They argue that as the climate changed, the adequate areas to maintain megafauna either ceased to exist or became unable to maintain megafauna populations because of the small size of habitat patches and their fragmentation (Ficcarelli et al., 2003; King JE & Saunders JJ, 1984). There are also other environmental hypotheses such as Coevolutionary disequilibrium (rapid glacial-interglacial transition would have disrupted Pleistocene networks of resource partitioning, and this process would have led to extinctions (Graham & Lundelius, 1984) and other ecologically centered hypotheses (see (Koch &

Barnosky, 2006) for a brief summary). However, they have never received great support from many researchers (Koch & Barnosky, 2006).

Evidence shows that, in the last 700 thousand years, numerous climatic changes similar to the last glacial-interglacial transition occurred; still, no extinction event such as the Late Quaternary extinction followed them. The defendants of the climatic change hypothesis argue in response that the last glacial-Holocene cycle (glacial-interglacial transition) featured unique climatic/environmental characteristics (Graham & Lundelius, 1984; Guthrie, 1984), but this has yet to be demonstrated. Another serious shortcoming of the climatic/environmental change hypothesis is the inability to explain the body size selectivity of Late Quaternary mammalian extinctions.

### **Anthropogenic causes**

Evidence shows that in the last millennia, humans colonized new islands and devastated animal species by overhunting, habitat alteration, and introduction of invasive species (Crowley, 2010; Martin & Steadman, 1999; Turvey, 2009). The excessive magnitude with which human colonization, overexploitation, and habitat alteration can affect biodiversity has been clearly shown worldwide in the last centuries (Ceballos et al., 2017). The abundant evidence that humans caused most extinctions of vertebrates in the most recent millennia is almost unequivocal (Turvey, 2009). However, the magnitude of human impact in Late Pleistocene and Early Holocene mammal extinctions is less evident.

Since the 19<sup>th</sup> century, explanations based on human impacts have been proposed as the cause for Late Quaternary extinctions (D. k. Grayson, 1984). However, Paul Martin's formulation of the "Prehistoric overkill" hypothesis was the one to revolutionize this discussion (Martin, 1967, 1984). The overkill hypothesis basically tries to extend the process by which humans caused rapid animal extinctions when colonizing new islands to explain the continental extinctions (Martin, 1967, 1984). The overkill proponents center their arguments on unsustainable human levels of hunting when colonizing a new area with new abundant prey (Martin, 1967, 1984). In recent centuries, the colonization of new islands left evidence of overhunting, causing abrupt vertebrate extinctions

(Crowley, 2010; Martin & Steadman, 1999; Turvey, 2009). For the defendants of overkill, the same process followed in the colonization of enormous continents such as Australia and North and South America (In Africa, megafauna extinctions were minor, and in Eurasia, many researchers agree that climate played a more prominent role).

The most famous version of the overkill model is called blitzkrieg, according to which the demise of the megafauna in these three continents would have been speedy (some authors talk about extinctions in less than 1000 years). The model states that large species were naïve, as they had never had contact with humans before, so they would lack the ability to sense a threat in humans and the evolutive adaptations to flee from human predators. Humans would have selectively targeted the largest species for their abundant meat (the reward for each animal hunted would be more significant). Human geographic expansion and population growth would have been almost exponential, fueled by overhunting of large prey with abundant meat, and this whole process would have caused a brisk disappearance of the megafauna in the Americas and Australia (Koch & Barnosky, 2006; Martin, 1984). Another hypothesis to explain the extinctions is called sitzkrieg; it claims that fire, habitat fragmentation, diseases, and the introduction of alien species also played an essential role in the extinctions besides overhunting (Barnosky et al., 2004). Most current defendants of human impact as the cause of Late Quaternary megafauna extinctions state that extinctions were not necessarily as rapid as previously thought (Andermann et al., 2020; Araujo et al., 2017) and present other models that do not follow blitzkrieg assumptions (Andermann et al., 2020; Araujo et al., 2017; Smith et al., 2018) and are more similar to sitzkrieg.

Overkill proponents still have difficulties explaining how small populations of humans with simple technologies would have decimated many different large species over their entire geographical ranges. Many types of predator-prey models have been used to decipher under which conditions would such a process be possible (See (Barnosky et al., 2004) for a brief summary). A few models found overkill possible if humans could switch their hunt to other more abundant prey as the slow-breeding hunted species would become progressively rarer; also, according to these models,

humans would keep hunting the species even when they became rare (Alroy, 2001; Anderson, 1989; Holdaway & Jacomb, 2000). Many researchers also contest the overkill model, arguing that humans could not have extensively hunted the extinct carnivore species. The argument that carnivores would have been extinct due to the extinction of their prey has not been demonstrated yet.

Currently, most paleontologists and ecologists studying the cause of Late Quaternary extinctions support that, as a whole, humans played a more significant role than the climate in the demise of the megafauna (Andermann et al., 2020; Araujo et al., 2017; Smith et al., 2018; Stuart, 2015), but few researchers support the blitzkrieg hypothesis nowadays (Stuart, 2015). Archeologists, in general, strongly reject the overkill hypothesis arguing that there are too few kill sites with associated human and megafauna material. Paul Martin's claim that the extinction process was so fast as to leave almost no trace in the archaeological record has been considered non-scientific by many (Meltzer, 1986) because lack of evidence cannot be regarded as evidence.

### **Combined human and climatic impacts**

Some authors have proposed a combined hypothesis (Barnosky et al., 2004; Koch & Barnosky, 2006; Lima-Ribeiro et al., 2017; Nikolskiy et al., 2011). Generally, it is argued that megafauna species already severely (the severity would vary according to species ecological traits) affected by stresses in response to climatic, vegetational changes, and habitat fragmentation would be led to extinction by human hunting. Hunting pressure would have become fatal after the reduction of populations and geographical range as a result of climatic changes (Barnosky et al., 2004; Koch & Barnosky, 2006; Nikolskiy et al., 2011).

Lately, most researchers searching for the cause of the Late Quaternary extinction event have accepted that neither climatic/environmental changes nor overkill models alone are able to satisfactorily explain this global extinction event (Stuart, 2015). Both hypotheses present serious shortcomings that could not be resolved even with centuries of research on the topic. That way, it has become difficult to defend each one of these hypotheses as to the sole cause of the Late Quaternary megafauna extinction event (Stuart, 2015). Consequently, much research has focused on disentangling

the magnitude of each of these factors in explaining the extinctions in each continent (Barnosky et al., 2004; Koch & Barnosky, 2006; Lima-Ribeiro & Diniz-Filho, 2013; Nikolskiy et al., 2011).

### **Differences among the continents**

#### **North Eurasia**

In North Eurasia (Europe and north of Asia (Palearctic ecoregion)), researchers can find abundant archaeological, paleontological, and environmental data to study the causes of Late Quaternary extinctions. It is the home of the most significant number of available radiocarbon dates made directly on megafaunal remains, which allows detailed chronologies for both extinct species and the ones that survived (A. M. Lister & Stuart, 2008; Nikolskiy et al., 2011; Pacher & Stuart, 2008; Stuart et al., 2002, 2004; Stuart & Lister, 2007, 2011, 2012, 2014).

Evidence shows a staggered chronology of extinctions during approximately forty thousand years (Stuart & Lister, 2012). Losses were less prominent than in the Americas and Australia but were still substantial. Estimates point out that nine genera of megafauna mammals went regionally extinct (Stuart, 2015).

In North Eurasia, there is ample evidence that climatic and vegetational changes impacted species' ranges (Seersholm et al., 2020; Stuart, 2015). Studies show that each species presented a unique pattern of shifts in their ranges; these different patterns resulted in extinction for some species and survival for others (Seersholm et al., 2020). Clear patterns of human impacts causing the general distributional shifts in the species ranges have not been demonstrated for North Eurasia. Moreover, most extinctions appear to have occurred many millennia after human arrival (A. M. Lister & Stuart, 2008; Nikolskiy et al., 2011; Pacher & Stuart, 2008; Stuart & Lister, 2007, 2011, 2012, 2014).

#### **Sahul (Australia, Tasmania, and New Guinea)**

Australia, Tasmania, and New Guinea formed a single continent called Sahul during the low sea level times in the Pleistocene. Glaciation in Sahul was not extensive; no ice sheets covered large areas as in the north of the globe. Nevertheless, the climate fluctuated, causing increasing aridity (Dodson, 1989).

Evidence points out that most Pleistocene extinctions in Australia occurred beyond radiocarbon dating limits (pre 50 ka), and most researchers believe that by 40 thousand years ago, all extinct megafauna was already gone (G Trueman et al., 2005). Other methods of dating besides radiocarbon still need to be highly improved; therefore, working with a chronology of extinctions older than 50 thousand years ago presents severe difficulties (Stuart, 2015). The debate between overkill proponents and climate change defendants is still fierce in Australia. However, the quality of dating and the archaeological data are insufficient to decipher the chronology of the process.

### **North America**

North America did not face a high extinction rate in the Early Pleistocene; therefore, in the Late Pleistocene, its megafauna diversity was greater than other continents (Stuart, 1991). Estimates suggest that around 69% of megafauna went extinct (Faith et al., 2009; Haynes, 2009, 2013).

North America faced extensive glaciation during the late glacial maximum (Ehlers & Gibbard, 2004). There is a wealth of evidence in the Alaska/Yukon region that intense climatic and environmental changes caused excessive habitat loss to extinct megafauna species (Fox-Dobbs et al., 2008; Guthrie, 2003). Accordingly, many researchers accept that climate change played a more prominent role than human impacts in these extinctions (Stuart, 2015). However, in the other regions of North America, most evidence points out to humans playing a more significant role in causing the extinctions (Stuart, 2015).

Many researchers interpret the evidence in North America (outside Alaska/Yukon), stating that most extinctions occurred within a short period of time, around 12 to 14 thousand years ago (Faith et al., 2009). Much discussion still surrounds the validity of some dates, which would place some of the extinctions before human arrival (16 – 13 ka) (Stuart, 2015).

### **South America**

Unfortunately, data is insufficient in South America to draw any permanent conclusions. However, studies point out that the continent suffered the highest number of megafauna extinctions in

the Late Quaternary; apparently, around 80% of megafauna genera went extinct (Barnosky & Lindsey, 2010; Stuart, 2015).

The discussion about the cause of the extinctions in South America is severely hindered by the lack of a satisfactorily good number of valid dates (Barnosky & Lindsey, 2010; Stuart, 2015). The little evidence seems to indicate greater importance for anthropogenic impacts than climatic factors in explaining the extinctions (Lima-Ribeiro & Diniz-Filho, 2013). Much further research is needed in order to draw a chronological pattern of the extinctions.

### **Other continents**

Africa and Southern Asia suffered a low number of mammalian extinctions in the Late Quaternary (Stuart, 2015). These regions, which have megafauna mammals severely threatened with extinction nowadays (The International Union for Conservation of Nature, 2021), were not a significant part of the almost global megafauna extinction event in the Terminal Pleistocene and Early Holocene. Overkill proponents offer a plausible explanation to explain why Africa was not intensely affected by megafauna extinctions; they defend that as humans evolved in Africa, African megafauna had evolved defensive strategies against humans (Martin, 1967, 1984). The reasons why extinctions in Southern Asia were less numerous have not been demonstrated by researchers so far.

### **Consequences**

The extinction of most megafauna species in the Pleistocene-Holocene Transition brought significant ecological effects to current biodiversity communities, such as changing ecosystems structures and seed dispersal (Doughty et al., 2013; Mahli et al., 2016) showed that these extinctions also resulted in intense and continuing disruptions to terrestrial biogeochemical cycling when we look at continental scales. Moreover, nutrient heterogeneity was increased by megafauna extinctions globally (Doughty et al., 2013). Also, food webs were simplified and went through a significant loss of redundancy, which could be harmful to the stability of communities (Galetti et al., 2018).

Galetti et al. (2018) show how the loss of megafauna disrupted and reshaped ecological interactions. Many parasites, commensals, mutualists, and predators, which created a dependency on

their associations with extinct megafauna, died out (Galetti et al., 2018). Species with high specialization in interactions with megafauna were more likely to be extinct since they had more difficulties adapting to new hosts or prey (Galetti et al., 2018). Some species that probably co-evolved with megafauna established new interactions with humans and their domestic animals, such as the vampire bat (*Desmodus rotundus*), which feeds on a variety of domesticated animals also on a few native species (Galetti et al., 2018).

Interestingly, a few extant species still possess traits that currently are of limited or no use, which provided benefits under Pleistocene- Early Holocene conditions because these traits were evolved to interact with megafauna (Ripple et al., 2015). Good examples to illustrate this are the plants with overbuilt fleshy fruits having no ideal dispersers in the Americas and Australia; some argue these plants only survive due to domestication by humans and secondary seed dispersers (Galetti et al., 2018; Ripple et al., 2015).

Such ecological consequences affecting current biotas led some researchers to propose a “rewilding” approach to be applied in some impoverished ecosystems (Pires, 2017). The rewilding proponents argue that we could resurrect ecosystem processes that were in place in the Pleistocene by adding individuals of species phylogenetically related to the extinct megafauna; these species would have similar ecological niches and play similar ecological roles to the extinct mega mammals (usually megaherbivores) (Pires, 2017).

### **Challenges and future directions**

Research regarding Late Quaternary extinctions has been highly focused on the search for a cause of the disappearance of most megafauna in the Terminal Pleistocene and Early Holocene (Barnosky et al., 2004; Koch & Barnosky, 2006; Stuart, 2015). More work is needed regarding the consequences of Late Quaternary extinctions and the functional and phylogenetical patterns in such extinctions.

Since the 19<sup>th</sup> century, researchers have dwelt upon the rather curious case of the megafauna's demise in a recent and rapid (geologically speaking) period of time (D. k. Grayson, 1984). Since then,

much improvement has been achieved in new technologies, which allow for advances in the search for the cause and the consequences of these extinctions (Barnosky et al., 2004; Koch & Barnosky, 2006; Stuart, 2015).

One of the traditional difficulties in studying these extinctions is the modeling of progressive population-level changes; recently, much advance has been made via the advances in studying ancient DNA (extracted from organic remains), which has helped researchers to disclose the complexities of the dynamic process of extinction (Campos et al., 2010; Lorenzen et al., 2011; Shapiro et al., 2004; Stiller et al., 2014). However, there is a need for further advances in population-level models, which are crucial also for conservationists to compare the dynamics of these extinctions with current dynamics of population decreases in threatened mammals.

The number of radiocarbon dates on megafauna and archaeological remains has increased recently (Stuart, 2015), which has brought some improvement to Pleistocene megafauna analyses. However, the dates currently available are not sufficient in number and quality to enable drawing clear conclusions about the causes of the extinctions. Even in Alaska/Yukon and Northern Eurasia, where radiocarbon dating evidence is superior, the dating scenario is still inadequate.

One of the issues presented when studying megafauna and archaeological dates is the lack of objective criteria for assessing the dates and kill sites (A. Lister & Stuart, 2013). Researchers need to agree on a single universal system that allows rigorous application of objective criteria for submitting and assessing published radiocarbon dates (A. Lister & Stuart, 2013). Moreover, dating must always be done directly on well-identified direct material of the target species; dating made on associated material has proven to be frequently incorrect (A. Lister & Stuart, 2013; Stuart, 2015). When finding unexpected results in dating megafauna remains (for example, the last appearance dates too distant from all the other dates previously found for that species), these dates must be submitted to independent repeated dating (A. Lister & Stuart, 2013).

In Australia, apparently, many extinctions took place previous to 50 thousand years ago (G Trueman et al., 2005), and therefore it is not possible to use radiocarbon dating (the most reliable

dating method in paleontology) to study these extinctions. Advancements in other dating techniques such as Uranium, Electronic spin resonance, Optically simulated luminescence, and Amino acid racemization are crucial to advance the discussion on the causes of megafauna extinctions in Australia (Stuart, 2015). In South America, available radiocarbon dating is seriously deficient, but prospects are good since most extinctions seem to have occurred under radiocarbon dating limits (Barnosky & Lindsey, 2010). In all the continents, a boosting in radiocarbon (in Australia, other methods) dating of megafauna remains is pivotal. However, South America and Australia are the most urgent cases, mainly because the debate regarding the causes is still too contentious in these regions. Africa is also in a precarious situation regarding dating, but apparently, Late Quaternary megafauna extinctions in Africa were very few (Faith, 2014).

Advances in Paleoclimatology are essential to improve our understanding of Pleistocene climates and how they affected the range contraction dynamics of extinct species (Lima-Ribeiro & Diniz-Filho, 2013). Paleoclimatology advances are also necessary to allow researchers to understand better whether the last glacial-interglacial transition was peculiar in Pleistocene history or not. Defendants of climate change as the cause of the extinctions can still not demonstrate how and why the last glacial-interglacial transition would have been unique compared to the various other similar climatic changes in the last 700 thousand years (Stuart, 2015).

Lately, niche modeling has been a handy tool to study Late Quaternary extinctions (Lima-Ribeiro & Diniz-Filho, 2013; Lorenzen et al., 2011; Nogués-Bravo et al., 2008; Nogués-Bravo et al., 2010). Calibrated (with fossil data and paleoclimatic simulations) niche models have been used to estimate the geographic distribution of extinct species and relate these distributions with past climate and vegetation (Lima-Ribeiro & Diniz-Filho, 2013; Lorenzen et al., 2011; Nogués-Bravo et al., 2008; Nogués-Bravo et al., 2010). Coupling niche models and demographic simulations (of human and megafauna populations) have allowed advances in disentangling the magnitude of anthropogenic and climatic/environmental causes on the extinctions (Lima-Ribeiro & Diniz-Filho, 2013).

Improvements in the study of Late Quaternary prehistoric extinctions are vital for conservation biology. The Late Quaternary extinction event has shown how the combination of extreme climatic changes and human overexploitation may cause defaunation. We are still living the Late Quaternary extinction event, and now human overexploitation has reached an even more disastrous level (Ceballos et al., 2017). Paleoecologists need to improve collaboration with conservation researchers in order to enlighten conservation strategies with conclusions from prehistoric extinction processes.

### **Conclusions**

The expectancy for finding a sole cause that would satisfactorily explain all prehistoric Late Quaternary mammalian extinctions in all the continents has been proven fruitless. I believe we may be close to passing the stage of being led to choose a side in the overkill – climate change cause discussion every time we read an article on Late Quaternary megafauna extinctions. Most researchers now agree that the causes vary among continents and species and that our aim should be to unravel the magnitude of anthropogenic and climate change effects for each Late Quaternary scenario.

Stuart (2015) argued that “we require far more high-quality data, not more debate based on imperfect evidence” (Stuart, 2015). Taking a general look at the history and prospects of Late Quaternary studies, I strongly agree. I also believe an improved integration among archaeologists, paleontologists and ecologists would serve the field considerably.

Unraveling the processes by which human overexploitation and climate change together caused many Late Quaternary extinctions is of paramount importance for developing strategies to deal with the current scenario of these same factors leading even a higher number of species to their demise (Ceballos et al., 2017). The sixth mass extinction in earth’s history started more than 100 thousand years ago and treating this whole Quaternary extinction event as one thing might be highly beneficial for conservation planning.

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**TERCEIRO CAPÍTULO DA TESE:**

## **Descriptions, extinctions and threatened species of Tetrapods in the last centuries**

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## **Abstract**

Estimations suggest that at least a million species worldwide are still undescribed. Current species extinction rates are startling, it has been estimated they are more than 1,000 times higher than natural background rates. Here we investigate the balance between species being described, extinct, and categorized as threatened with extinction within Tetrapoda. We attempt to answer the following questions: Over time, at what rate are species being discovered, extinct, and categorized as threatened? How long does it take between the species description and its extinction? How long does it take between the species description and its first entry at a threatened status on IUCN Red List? We collected data on descriptions, extinctions, and threat status from the IUCN Red List. We selected four groups of Chordata: Amphibians, Birds, Mammals, and Reptiles (The Tetrapods). Our data show 519 extinct Tetrapods in 519 years and 6673 species being given a threat status in 56 years (1965-2021) (119.16 spp/year). When we count the number of species that were extinct before, in the same year, or a few years after their description (until 20 years after) we have 318 species. The distribution of the description years of these 318 species is concentrated in recent years (From the 1970s to the 2000s). Two thousand six Tetrapods took only from 0 to 20 years from their description to being categorized as threatened with extinction One thousand three-hundred fifty-eight of these took only from 0 to 10 years from formal description to being categorized as threatened. Our results corroborate what other researchers have been finding: recently described (and therefore undescribed species much likely too) are in bigger risk than other species. Research has shown recently described (and much likely the undescribed also) species generally have small range sizes and populations, characteristics related to a higher probability of extinction. Many species are likely becoming extinct without ever having been described. Investing in intensive surveys targeting areas with high diversity of undescribed species in tropical areas might be of great aid towards protecting species with small populations and range sizes facing severe threats.

Keywords: Undescribed species, Extinctions, Tetrapods, Threat status, Description rates, Unknown extinctions

## **Introduction**

How many species are there? That has been a gold question in ecology, and an array of efforts have been applied to reach that answer (Burgin et al., 2018; Mora et al., 2011; Moura & Jetz, 2021; Pimm et al., 2014). Estimations suggest that at least a million species worldwide are still undescribed (Costello et al., 2012; Mora et al., 2011). Assessing global richness at a species level is a challenging but fundamental task (Costello et al., 2013). Species knowledge has proven to be a helpful metric for tracking scientific progress in global biodiversity exploration and categorizing habitats and ecosystems. Species supply the environments, ecosystems, and humans with many services enabling life on Earth (Essl et al., 2013; Pimm et al., 2014). Another basis for improving taxonomic knowledge is tracking how many species have been threatened with extinction and how many are becoming extinct (Costello et al., 2013; International Union for Conservation of Nature and Natural Resources (IUCN), 2022).

The *Systema Naturae*, developed by Linnaeus (1758), four centuries ago for naming and classifying species, was the most significant attempt to document Earth's life (Anderson et al., 2007). Providing a species' scientific recognition, thus assessing the organism's taxonomy, involves a description process (Zamani et al., 2022) that follows international guidelines. When a species is formally recognized, doors are open to surveys and assessments, giving that species its role in the Earth's species composition. From this moment on, estimating the species' extinction risk is also possible (International Union for Conservation of Nature and Natural Resources (IUCN), 2022). If determining a species description is challenging, settling species extinctions - the disappearance of all

the individuals - is even more difficult. This evaluation is another "gold matter," and many scientists are putting strength into answering it (Liu et al., 2022; Pimm et al., 2014; Tedesco et al., 2014).

Current species extinction rates are startling (Ceballos et al., 2015), and estimations suggest they are more than 1,000 times higher than natural background rates (Andermann et al., 2020; Pereira et al., 2010). The International Union for Conservation of Nature carries a committee responsible for the Red List of Threatened Species. Such a committee holds a database curated by scientists and experts who provide recurrent species assessments, including population trends, threats, and extinction risk (International Union for Conservation of Nature and Natural Resources (IUCN), 2022). Such periodic assessments have been crucial to aid governments and organizations worldwide in focusing their conservation strategies and prioritizing the species and ecosystems in the most urgent need (International Union for Conservation of Nature and Natural Resources (IUCN), 2022).

Reported numbers of species extinctions may be underestimated considering that a high percentage of species biodiversity has yet not been described (Costello et al., 2012, 2013; Mora et al., 2011). Moreover, most species being described have restricted ranges, which make them (and much likely the species still unknown) more prone to extinction processes (Giam et al., 2012). Therefore, many species might be disappearing before formal scientific recognition (Niemiller et al., 2013). Much scientific research has paid attention to the issue of extinct undescribed species and how much that hampers conservation efforts worldwide (Costello et al., 2013; Liu et al., 2022; Niemiller et al., 2013; Tedesco et al., 2014). Recent studies have attempted to estimate how many species are becoming extinct without ever being described (Liu et al., 2022; Tedesco et al., 2014). However, we still lack an exploration of the balance between the numbers of species descriptions, species extinctions, and species being categorized as threatened with extinction. Such exploration may help us relate description rates to how many of these described species are becoming threatened with extinction and how many of them are going extinct, and also how long does it take for a species from their description to become threatened or extinct.

Bearing this scenario in mind, we investigate the balance between species being described, extinct, and categorized as threatened with extinction within Tetrapoda. We attempt to answer the following questions: Over time, at what rate are species being discovered, extinct, and categorized as threatened? How long does it take between the species description and its extinction? How long does it take between the species description and its first entry at a threatened status on IUCN Red List?

## **Methods**

We collected data on descriptions, extinctions, and threat status from the IUCN Red List (<https://iucnredlist.org/>). We selected four groups of Chordata: Amphibians, Birds, Mammals, and Reptiles (The Tetrapods). We focused on these groups because they are well known, and their categories of threat status have been broadly assessed through the last decades. The data we gathered included species' scientific name, year of formal scientific description, year last seen (considered here as extinction date), and threat category (including the year in which each threatened species was first categorized as threatened).

Our data on descriptions of species comprehended 32,793 Tetrapoda species described from 1758 to 2019 (7,203 Amphibians; 11,158 Birds; 5,940 Mammals; and 8,492 Reptiles). Our extinction data included 519 species extinct from 1500 to 2019 (178 Amphibians; 181 Birds; 92 Mammals; and 68 Reptiles). Amphibian extinctions date back to 1853 on the IUCN database, while for the other three classes, IUCN data date back to the 16th century (Mammals: 1500; reptiles: 1544 and Birds: 1550). Two hundred thirty-three of these 519 species that we considered as extinct were actually categorized as "possibly extinct" by the IUCN (species which have not been seen for a long time but have not attended all criteria to be classified as extinct yet). We decided to consider these species as extinct in our analyses, given that they have not been seen for many years despite extensive surveys of their natural environments. According to the IUCN red list, the tag 'Possibly Extinct' has been developed to identify Critically Endangered species that are likely to be already extinct (or extinct in the wild), but for which confirmation is required (<https://www.iucnredlist.org/resources/summary-statistics>). Species

categorized as "extinct in the wild" were not considered extinct in our analyses as there are still living individuals of such species, at least in captivity.

Data on "year last seen" were not available for all extinct and possibly extinct species; in some cases, there were only observations made by IUCN researchers about when that species might have been seen for the last time. Based on such observations, we calculated a random extinction date for each of these species. For example, if IUCN observations about year last seen said: "19th century" we calculated a random number between 1800 and 1899. If IUCN observations about year last seen said "1950s" we calculated a random number between 1950 and 1959. If no observation was provided on when the species may last have been seen, such species were excluded from the analyses (that was the case for 36 species).

We acquired data on 309 Tetrapods categorized as extinct by the IUCN, of which we excluded 23 species because we could not find information to calculate a possible extinction date for these species. Of the other 286 species, 234 present a definite year last seen provided by IUCN, and for other 39 species we calculated an extinction year. We acquired data on 246 Tetrapodes categorized as "possibly extinct" by the IUCN, of which we excluded 13 species because we could not find information to calculate a possible extinction date for these species. Of the other 233 species, 210 presented a definite year last seen provided by IUCN, and for other 23 species we calculated an extinction year. So, in total we gathered data on 555 extinct and possibly extinct species, and 36 were excluded (23 extinct and 13 possibly extinct) and we worked with 519 species that we considered as extinct.

Our data on threat status comprised 6673 threatened Tetrapodes (2441 Amphibians, 1424 Birds, 1325 Mammals, and 1483 Reptiles). For each of these 6673 species, we surveyed the year when the species was first categorized as threatened in order to assess the time between the species being described and entering a threat status (entering an extinction process). Our threat status data were collected later than our description and extinction data. The analyses which include only descriptions and extinctions were performed with data on descriptions and extinctions of tetrapods until 2019

(species described or extinct later than 2019 did not enter these analyses). However, the analyses which include threat status data include species categorized as threatened in 2020 and 2021, including 5 Amphibians described in 2020 (the only 5 species described after 2019 in the whole study) because the data for these analyses were collected later than the data for the other analyses.

To determine the averages of description and extinction per year (or rates of description and extinction) for each of the four groups, we subdivided time from 1758 to 2019 by decades (1758-1767, 1768-1777, and so on), the only exception was the last subdivision, which encompassed the years from 2008 to 2019. In these analyses, we did not consider the extinctions which took place from 1500 to 1757 because there were no formal scientific descriptions of species during these years. We calculated then for each time subdivision the average of extinctions and the average of descriptions per year. From 1965 to 2019, we also calculated the average of species being categorized as threatened per year (1965 was when the IUCN assessed threat status of species for the first time).

To determine the balance between descriptions and extinctions for each year, we calculated the number of descriptions minus the number of extinctions. We calculated such balance for Tetrapods in general and each of the four classes. In this calculation, we did not consider the extinctions which took place from 1500 to 1757 because there were no formal scientific descriptions of species during these years.

To assess how long it took for each extinct species to go extinct after their formal description, we used the description and extinction dates we acquired from the IUCN and performed the calculations. To evaluate how long it took for each threatened species to be categorized as threatened after their formal description, we used the description and threat status categorization dates we acquired from the IUCN and performed the calculations. All the calculations and graphics in this study were made using Microsoft Excel 365 (Microsoft Corporation, 2018), Google spreadsheets, or basic functions on R (R Development Core Team, 2011).

## Results

Our analyses revealed that Tetrapods are still being described at high rates even after 261 years of formal scientific linnean descriptions (1758-2019), and at the same time they are entering an extinction process (being categorized as threatened) or going completely extinct at a worryingly fast pace. Our data show 519 extinct Tetrapods in 519 years (In other words, we have been losing 1 spp/year of Tetrapods since 1500), and 6673 species being given a threat status in 56 years (1965-2021) (119.16 spp/year).

We found that Amphibian description rates (Figure 1) have been the highest amongst Tetrapods since the middle of the twentieth century, followed by Reptilian rates. These two classes have recently shown rates of species description significantly higher than Mammalian and Avian description rates. In 1758, when Linnean descriptions of Tetrapods started, Birds and Mammals presented the highest description rates. Reptilian taxonomic knowledge started to grow at the beginning of the nineteenth century before Amphibian rates of species discovery, which have shown high numbers since 1918 and are now at 78.9 species described per year (2008 - 2019) (Figure 1).

Avian description rates peaked at 124.8 species discovered per year between 1838 and 1847. The second highest peak in our description data is for Amphibians; 108.6 Amphibian species were discovered yearly (on average) at the onset of the twenty-first century (1998 - 2007). Mammalian and Reptilian description peaks also reached large numbers (Mammals: 63.9 spp per year (1898-1907); Reptiles: 74.3 spp per year (1998-2007)). From 2008 to 2019 (the most recent period), we found an average of 42.3 spp described per year considering Tetrapodes in general.

Evaluating extinctions since 1500, we found that from 1500 to 1757, only 6 Reptiles, 11 Mammals, and no Amphibian species went extinct. However, that same calculation for Birds reached 35 extinct species before scientific descriptions started (1758) (Figure 1). Amphibian average of extinctions per year peaked at a staggering rate of 5.2 per year recently (between 1988 and 1997), the second highest peak took place with birds at the onset of the twentieth century (2.1 species per year

(1898 - 1907)). Mammalian and Reptilian extinction peaks were milder (Mammals: 1.2 spp per year (1928-1937); Reptiles: 0.9 spp per year (1958-1967)).

We found that the balance between descriptions and extinctions (a simple calculation: the number of descriptions minus the number of extinctions per year) has been close to the number of descriptions throughout the period assessed. The number of extinctions per year has shown to be low compared to the high number of descriptions per year in these four classes (Figure 2). We found 32,793 Tetrapoda species described from 1758 to 2019 (7,203 Amphibians; 11,158 Birds; 5,940 Mammals; and 8,492 Reptiles). Of these, 519 went extinct from 1500 to 2019 (178 Amphibians; 181 Birds; 92 Mammals; and 68 Reptiles).

One hundred ninety-nine extinct Tetrapods were described after their extinction (32 Amphibians; 55 Birds; 33 Mammals; and 32 Reptiles), which resulted in negative numbers when we calculated TBDE (Time between description and extinction). These 199 extinct species were described on average 104.8 years after their extinction (Averages (in years) for each class were: Amphibians = 33.66; Birds = 180.98; Mammals = 125.69; Reptiles = 100.34) . Thirty-one species were described in the same year they were declared extinct (20 Amphibians, 1 Bird, 4 Mammals, 6 Reptiles), and 289 were declared extinct after their formal scientific description. These 289 species went extinct on average 53.65 years after having been discovered (Figure 3). One-hundred nineteen Tetrapods took 0 to 20 years from their description to their extinction (69 Amphibians, 23 Birds, 14 Mammals, 13 Reptiles). Eighty-three of these took only from 0 to 10 years from formal description to extinction (49 Amphibians, 13 Birds, 11 Mammals, and 10 Reptiles). When we count the number of species that were extinct before, in the same year, or a few years after their description (until 20 years after) we have 318 species. Figure 5 shows that the distribution of the description years of these 318 species is concentrated in recent years (From the 1970s to the 2000s (Figure 5)).

We found that 30 (26 Amphibians & 4 Reptiles) species were categorized as threatened with extinction before their formal description. That was because these species were known before as being part of another species (cryptic species) already considered threatened with extinction. However, then

they were discovered as a distinct species and maintained their recognition as threatened. Thirty-three species were categorized as threatened in the same year they were scientifically described (13 Amphibians, 4 Birds, 8 Mammals, and 8 Reptiles), and 6,610 species were categorized as threatened after their formal description (2,402 Amphibians; 1,420 Birds; 1,317 Mammals; and 1,471 Reptiles). These 6610 threatened species were categorized as threatened on average 74.25 years after their description (Averages (in years) for each class were: Amphibians = 88.55; Birds = 121.98; Mammals = 96.82; Reptiles = 68.61).

Two thousand six Tetrapods took only from 0 to 20 years from their description to being categorized as threatened with extinction (1180 Amphibians, 87 Birds, 280 Mammals, 459 Reptiles). One thousand three-hundred fifty-eight of these took only from 0 to 10 years from formal description to being categorized as threatened (814 Amphibians, 72 Birds, 195 Mammals, 277 Reptiles).

## **Discussion**

Our analyses revealed that Tetrapods have been currently, at the same time, highly researched by taxonomists, highly threatened with extinction (we found 20.35% of Tetrapods categorized as threatened) and lost 1.58% of their species (519 out of 32,793 spp). Humanity has been (mainly) causing large quantities of Tetrapods to enter extinction processes at the same time that we are still discovering many new Tetrapods (and other taxonomic groups). Much research has shown that the patterns and processes of Tetrapod species extinction (and biodiversity more widely (Barnosky et al., 2011)) demonstrate consistently the role of humans in the rapid modern mass extinction (Barnosky et al., 2011; Ceballos et al., 2015; Dirzo et al., 2014). Analyzing how description, threat and extinction processes have operated through the last centuries is quite relevant in order to propose strategies to improve and accelerate our capacity of discovering new species while it is still time to work effectively against their extinction.

It is interesting to note that formal scientific Linnean descriptions of Tetrapods commenced in 1758 and an acceleration in the extinction rates (except for amphibians) took place in 1798 (Figure 1), only 40 years later. These two processes were concomitant with the first decades of the industrial

revolution, which changed dramatically how humans impact ecosystems and biodiversity globally (Newbold et al., 2015; Pincheira-Donoso et al., 2022). The industrial era changed the scale of anthropogenic impact in nature, exacerbating impacts of processes such as: human population growth, deforestation, CO<sub>2</sub> emissions, and exploitation of natural resources (Garrett et al., 2020; Ripple et al., 2020; Steffen et al., 2015). Curiously, the same process (industrial revolution) which brought economic development, enhancing natural sciences responsible for describing new species, also brought anthropogenic alteration of natural habitats to another level (Garrett et al., 2020; Newbold et al., 2015; Ripple et al., 2020) which highly augmented extinction processes and rates (Dirzo et al., 2014).

The existence of a taxonomic impediment (lack of taxonomic expertise) has been discussed in literature (Costello et al., 2013). Our results indicate that Tetrapods have been currently intensively studied by taxonomists, in fact an increasing number of taxonomists have been working on large-sized taxa (Joppa et al., 2011), which may be a reflection of an increase of taxonomists in developing countries (Costello et al., 2013) where most species yet to be described reside (Pimm et al., 2014; Scheffers et al., 2012). The recent high numbers in description rates we found (except for birds), can be partially explained by the effect that recent molecular methods have had in the identification of cryptic species (species apparently phenotypically identical but incapable of interbreeding (Biju et al., 2014; Grismer et al., 2013; Shirley et al., 2018). Herpetologists have found several cryptic species in Amphibians and Reptiles in recent decades, which have boosted these classes' description numbers (Biju et al., 2014; Grismer et al., 2013; Shirley et al., 2018). Even larger-sized groups such as Mammals are highly involved in such a process, Ceballos & Elrich (2009) found that about 60% of mammals described since 1990 are cryptic species (Ceballos & Ehrlich, 2009). In fact, taxonomic issues like cryptic species and synonyms (one singular biological species with more than one formal scientific name) complicate the accuracy of species description numbers (Costello et al., 2013).

We found many Tetrapods extinct before, in the same year, or a few years after their description and also many others categorized as threatened before, in the same year or a few years

after their description (Figures 3 to 5). That corroborates what other researchers have been finding: recently described (and therefore undescribed species much likely too) are in bigger risk than other species (Liu et al., 2022; Tedesco et al., 2014). Our data are in accordance with this hypothesis as they show how most of the 318 species extinct before, in the same year, or a few years after their description were described recently (Figure 5). Research has shown recently described (and much likely the undescribed also) species generally have small range sizes and populations (Ceballos & Ehrlich, 2009; Pimm et al., 2014; Scheffers et al., 2012), characteristics related to a higher probability of extinction (Sloan et al., 2018). In other words, the species facing higher extinction risk are probably the least known to science and conservation planners; consequently, many species are likely becoming extinct without ever having been described (Liu et al., 2022; Tedesco et al., 2014). Our results are probably underestimated considering it usually takes years from the first collection of a species to its description (Fontaine et al., 2012), further time is required to determine that a species is threatened (Tapley et al., 2018) and even longer is taken to declare a species as possibly extinct or extinct (International Union for Conservation of Nature and Natural Resources (IUCN), 2022). Considering all of that, estimatives of extinction rates based on known species only are likely underestimated (Liu et al., 2022; Scheffers et al., 2012).

What to do in face of such a dramatic scenario? Urgent actions are needed towards protecting recently described and undescribed species, which are in bigger risk of extinction. Biodiversity hotspots and tropical areas hold many recently described species and are likely to hold high numbers of undescribed species (Joppa et al., 2011; Moura & Jetz, 2021). Moreover, species are suffering higher human pressure in these areas (Pimm et al., 2014). Considering all these factors, investing in intensive surveys targeting areas with high diversity of undescribed species in tropical areas might be of great aid towards protecting species with small populations and range sizes facing severe threats. Protecting recently described species and advocating for the protection of undescribed biodiversity is not simple, solid research is necessary on the populations of recently described species, and also in their habitats and threats; and the protection of places which likely harbor great undescribed

biodiversity is urgent (Betts et al., 2019). However, many recent successful conservation programs around the world show how possible it is to achieve great conservation results with adequate planning (Bolam et al., 2021).

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Figures:

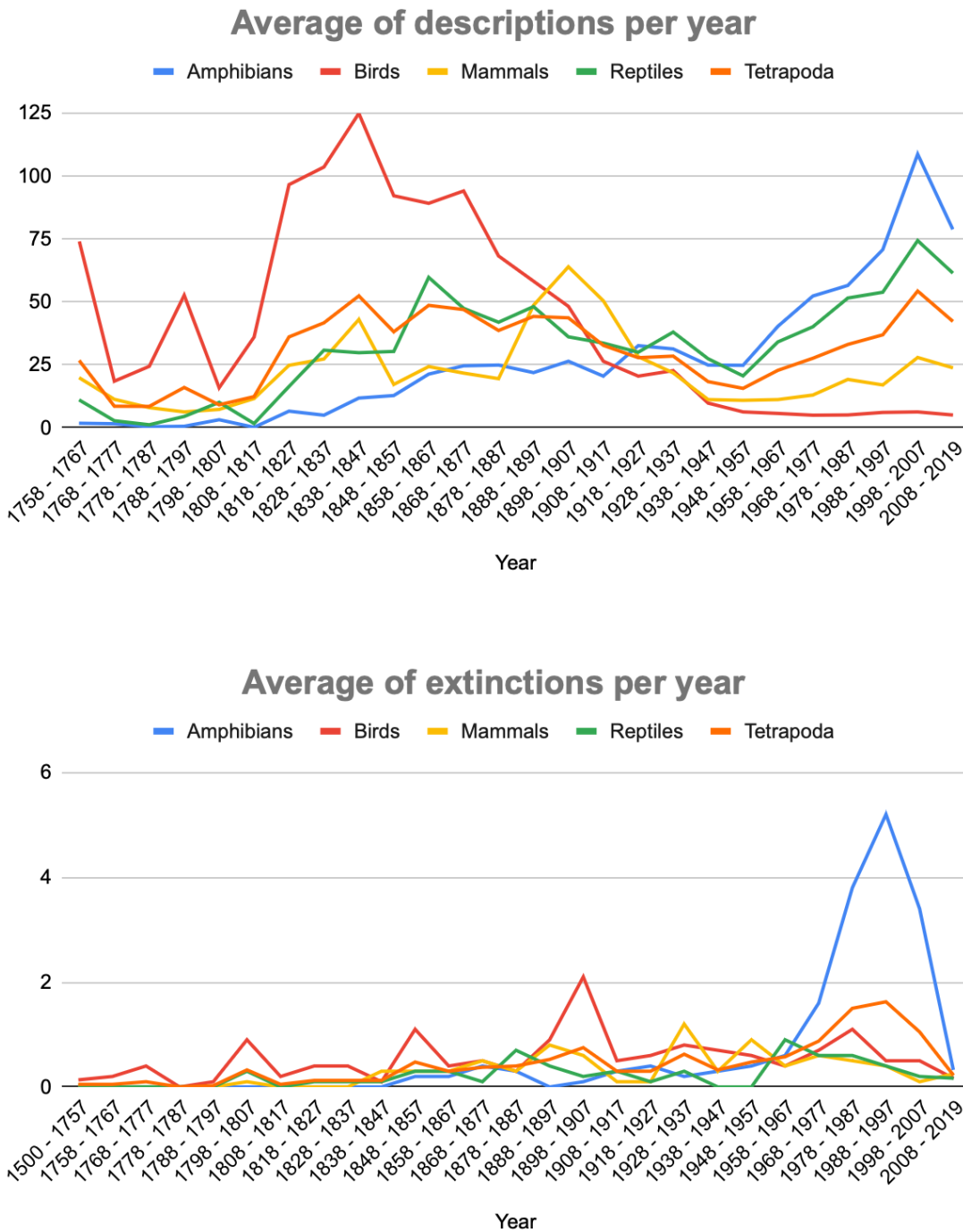


Figure 1: Averages of description and extinction of species (both per year, binned by time intervals of approximately 10 years in most cases) for each class of Tetrapoda and also for Tetrapoda in general (orange lines). For descriptions the figure shows the trajectory since 1758 (Linnaeus' *Systema Naturae*); for extinctions, since 1500 (IUCN data limit). Obs: Species categorized as possibly extinct by IUCN are considered as extinct here.

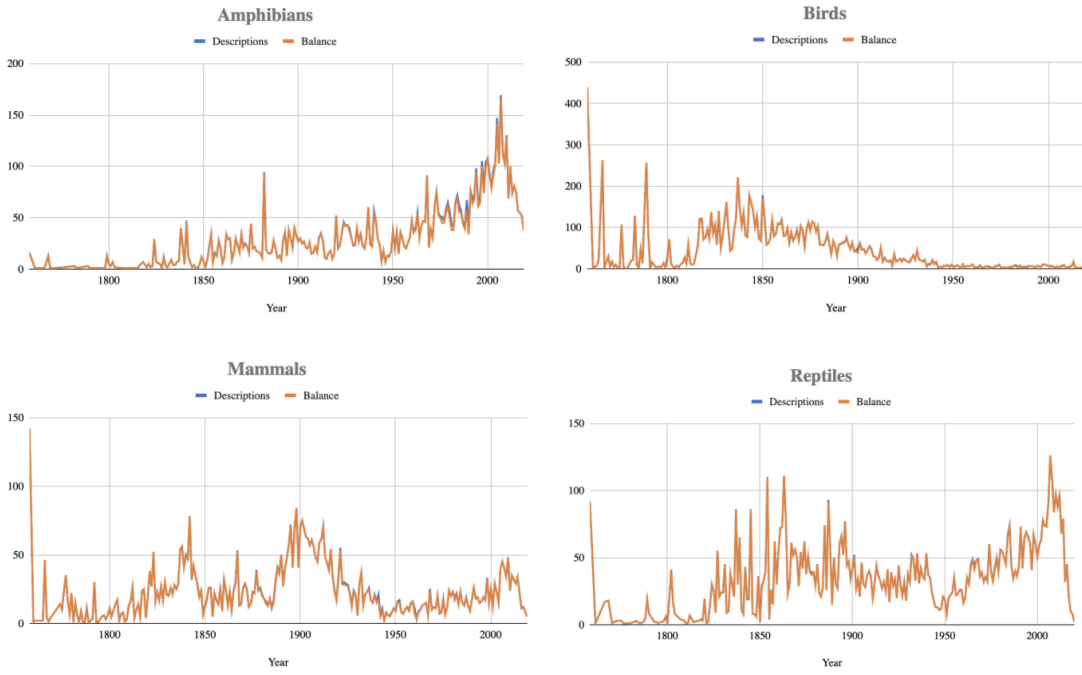


Figure 2: The balance between descriptions and extinctions (number of descriptions - number of extinctions) and the number of descriptions for each class of Tetrapoda, from 1758 (Linnaeus' *Systema Naturae*) to 2019 (Species categorized as possibly extinct by IUCN are considered as extinct here).

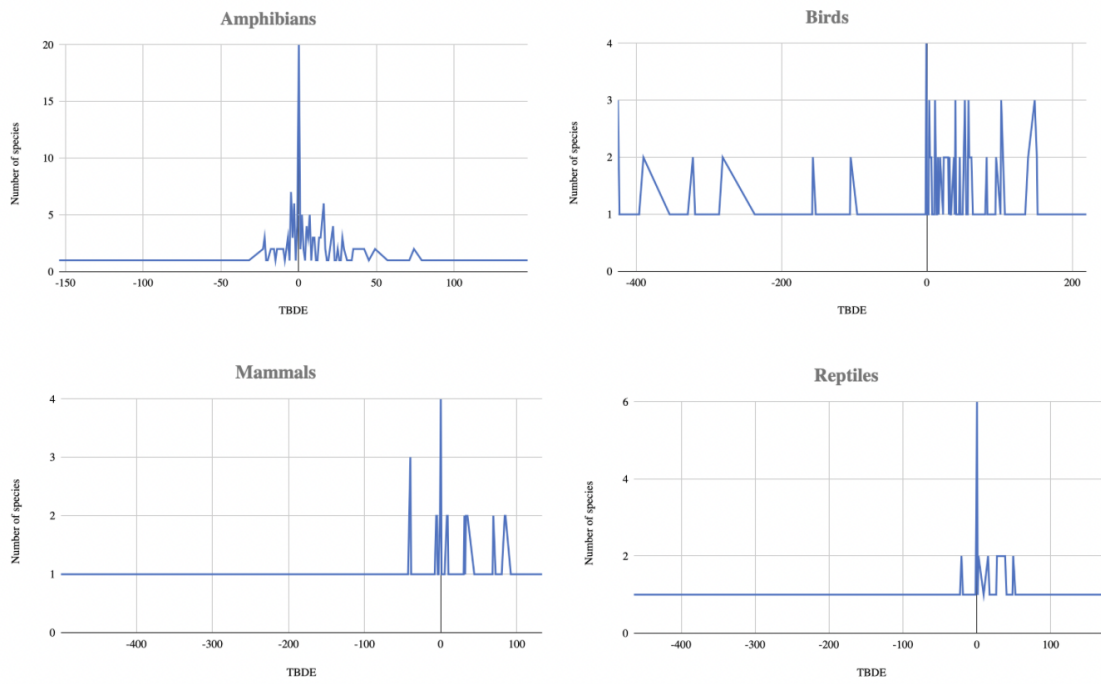


Figure 3: The time interval (in years) between description and extinction (TBDE) (Species categorized as possibly extinct by IUCN are considered as extinct here). Negative numbers of TBDE mean the description of the species took place after its extinction.

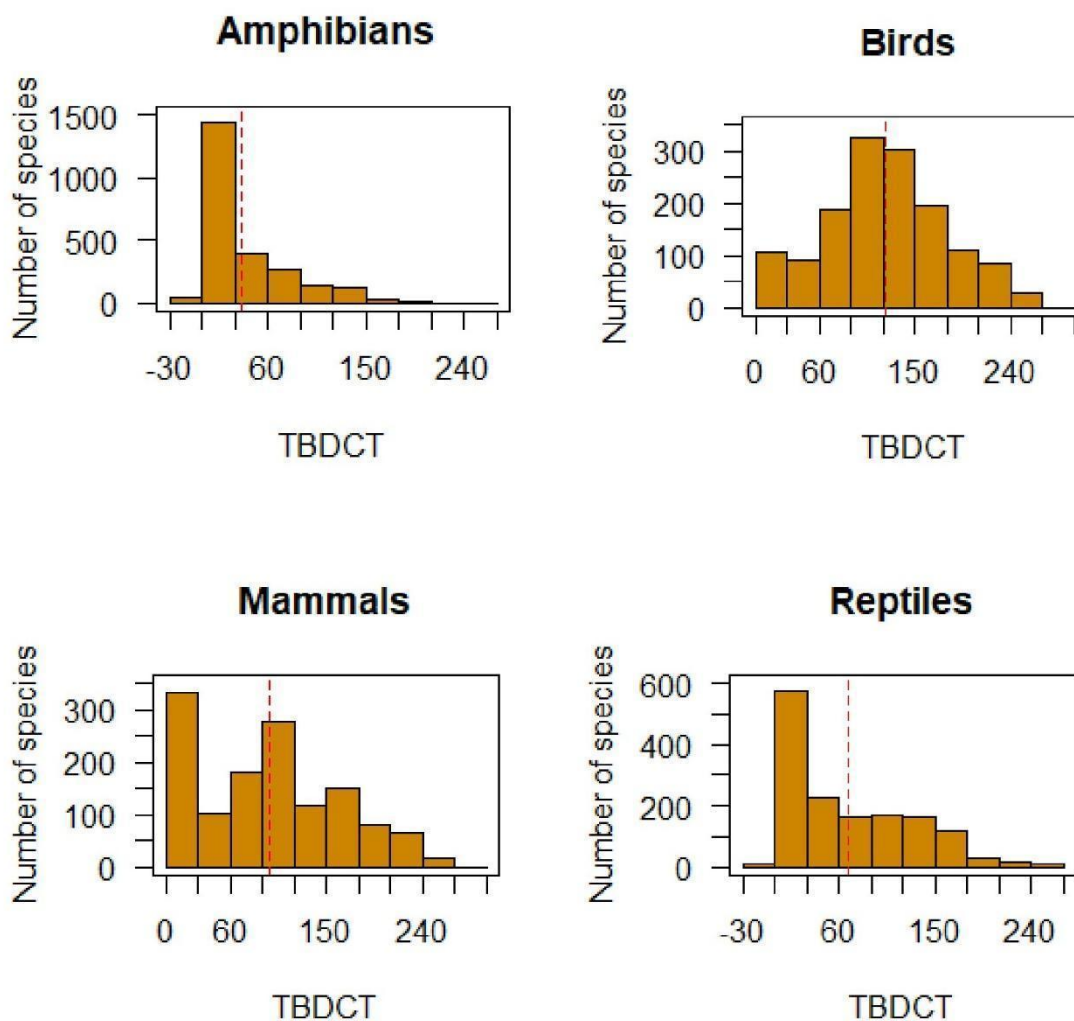


Figure 4: The time interval (in years) between description and categorization as threatened (TBDCT) considering each threatened species. Currently non-threatened or extinct species did not enter this analysis. The red dotted line shows the mean time interval (in years) between description and categorization as threatened for each Tetrapoda group (Amphibians: 36.49 years, Birds: 121.63 years, Mammals: 96.23 years, Reptiles: 68.04 years).

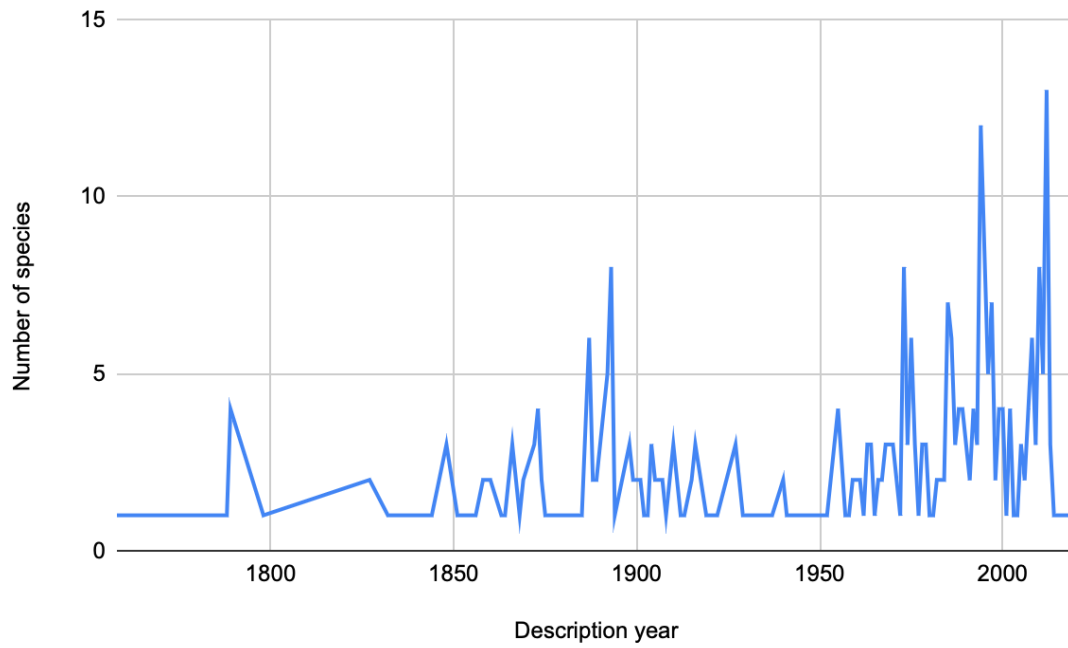


Figure 5: The distribution of the description years of the 318 species which had negative numbers of TBDE or low numbers (0 to 20) years between their description and their extinction.

Table 1: Sums and averages of descriptions, extinctions, and species entering a threatened status from 1965 (When the first Tetrapoda species were categorized as threatened) to 2019, considering all Tetrapoda.

Time interval	Descriptions (sum)	Descriptions (average)	Extinctions (sum)	Extinctions (average)	Threat level spp. (sum)	Threat level spp. (average)
1965 - 1974	1117	27.93	22	0.55	35	3.5
1975 - 1984	1255	31.38	57	1.42	95	9.5
1985 - 1994	1372	34.3	62	1.55	1284	128.4
1995 - 2004	1803	45.1	50	1.25	1936	193.6
2005 - 2014	2425	60.63	20	0.5	1426	142.6
2015 - 2019	458	22.9	0	0	1252	250.4

## **Conclusão**

Pelo fato de cada um dos três capítulos que compõem esta tese tratar um tema diferente, decidi separar a conclusão do trabalho em três partes, uma conclusão para cada capítulo:

### **Conclusão do primeiro capítulo:**

No primeiro capítulo, identificamos padrões e vieses nos artigos analíticos sobre Planejamento Sistemático de Conservação. A maioria dos artigos foi produzida por pesquisadores sediados nos EUA e Austrália e buscaram identificar áreas prioritárias para uso de conservação com base na diversidade taxonômica de muitos táxons em escala nacional e ambiente terrestre; Marxan e Zonation foram os softwares mais utilizados para identificar áreas prioritárias. Cerca de um terço dos artigos consideraram informações sobre custos e recomendaram explicitamente ações de conservação a serem tomadas na prática.

Em última análise, a ciência da conservação visa melhorar os resultados da conservação (por exemplo, proteção de espécies) na prática. Estudos conceituais e metodológicos sobre Planejamento Sistemático de Conservação subsidiam indiretamente as definições de ações de conservação na prática, discutindo assuntos essenciais e preparando pesquisadores para usar seus melhores recursos e habilidades em exercícios práticos de conservação. Estudos analíticos sobre Planejamento Sistemático de Conservação que usam dados reais para encontrar a melhor solução de conservação contribuem mais diretamente para os planos reais de conservação que estão sendo desenvolvidos e estabelecidos por governos e organizações em todo o mundo. Portanto, nosso estudo traz uma nova e significativa perspectiva sobre as tendências e vieses de tais trabalhos analíticos críticos sobre Planejamento Sistemático de Conservação.

### **Conclusão do segundo capítulo:**

A expectativa de encontrar uma causa única que explicaria satisfatoriamente todas as extinções de mamíferos pré-históricos do Quaternário Tardio em todos os continentes provou ser infrutífera. Acredito que podemos estar perto de passar do estágio de acreditar que precisamos escolher um lado (sobre-matança ou mudanças climáticas) toda vez que lemos um artigo sobre as extinções da

megafauna do final do Quaternário. A maioria dos pesquisadores agora concorda que as causas variam entre continentes e espécies e que nosso objetivo deve ser desvendar a magnitude dos efeitos antropogênicos e das mudanças climáticas para cada cenário do final do quaternário.

Precisamos adquirir muito mais dados de alta qualidade, e não ficar insistindo demais em debates baseados em evidências imperfeitas. Também acredito que uma melhor integração entre arqueólogos, paleontólogos e ecólogos serviria consideravelmente a essa área de estudo.

Desvendar os processos pelos quais a superexploração humana e as mudanças climáticas causaram muitas extinções no final do Quaternário é de suma importância para o desenvolvimento de estratégias para lidar com o cenário atual desses mesmos fatores que levam um número ainda maior de espécies ao seu desaparecimento. A sexta extinção em massa na história da Terra começou há mais de 100 mil anos e tratar todo esse evento de extinção no quaternário como uma coisa só pode ser altamente benéfico para o planejamento da conservação.

### **Conclusão do terceiro capítulo:**

Nossas análises revelaram que os Tetrápodes têm sido atualmente, ao mesmo tempo, altamente pesquisados por taxonomistas, altamente ameaçados de extinção (encontramos 20,35% dos Tetrápodes classificados como ameaçados) e perderam 1,58% de suas espécies (519 de 32.793 spp). A humanidade vem fazendo com que grandes quantidades de Tetrápodes entrem em processos de extinção ao mesmo tempo em que ainda estamos descobrindo muitos novos Tetrápodes (e outros grupos taxonômicos). Muitas pesquisas têm mostrado que os padrões e processos de extinção de espécies de tetrápodes (e da biodiversidade no geral) demonstram consistentemente o papel dos humanos na rápida extinção em massa moderna. Analisar como os processos de descrição, ameaça e extinção operaram ao longo dos últimos séculos é bastante relevante para propor estratégias para melhorar e acelerar nossa capacidade de descobrir novas espécies enquanto ainda é tempo de trabalhar efetivamente contra a extinção delas.

São necessárias ações urgentes para proteger espécies recentemente descritas e as ainda não descritas, que correm maior risco de extinção. Os hotspots de biodiversidade e as áreas tropicais

abrigam muitas espécies recentemente descritas e provavelmente abrigam um alto número de espécies não descritas. Além disso, as espécies estão sofrendo maior pressão humana nessas áreas. Considerando todos esses fatores, investir em pesquisas intensivas visando áreas com alta diversidade de espécies não descritas em áreas tropicais pode ser de grande ajuda para proteger espécies com pequenas populações e tamanhos de distribuição pequenos que enfrentam ameaças severas. Proteger as espécies recentemente descritas e defender a proteção da biodiversidade ainda não descrita não é simples, são necessárias pesquisas sólidas sobre as populações de espécies recentemente descritas, e também sobre seus habitats e ameaças; e a proteção de locais que provavelmente abrigam grande biodiversidade não descrita é urgente. No entanto, muitos programas recentes de conservação bem-sucedidos em todo o mundo mostram como é possível alcançar ótimos resultados de conservação com planejamento adequado.

