Chondrichthyan research in South America: Endocrinology overview and research trends over 50 years (1967–2016) compared to the rest of the world

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ABSTRACT

The endocrine system plays a crucial role in regulating the activity of cells and organs among vertebrates, including the class Chondrichthyes. Accordingly, Chondrichthyan endocrinology publications have been steadily increasing in the global literature. However, while interest in South American Chondrichthyan research has been growing over the last 50 years, the field of endocrinology related to Chondrichthyans has been limited. Understanding the trajectory of a scientific discipline assists researchers and stakeholders in making decisions regarding which research areas require further attention. Further, visualisation techniques based on bibliometric analysis of scientific publications assist in understanding fluctuations in the trends of specific research fields over time. In this study, Chondrichthyan research publications over time were analysed by creating visualisation maps using VOSviewer bibliometric software. Trends in South America Chondrichthyan research with an emphasis on endocrinology were explored over a 50-year period (1967–2016). These trends were compared with Chondrichthyans research worldwide for the more recent 15-year period (2002–2016). The number of South America Chondrichthyan scientific publications increased from six during the 1967–1981 period to 112 in 2016. However, only eight papers were found published in the area of Chondrichthyan endocrinology research. Fisheries, reproduction and taxonomy were the dominate research areas in South America over the 50 years. For the more recent 15 years, South American publications comprised 11% of the total literature published globally. While South America research outputs fluctuated closely with global research trends, differences appeared when comparing areas of growth. This study describes the trends in Chondrichthyan research literature globally and more specifically in South America. Although South American countries may never contribute to the same scale as the wider international scientific community, the future of Chondrichthyans would strongly benefit from the contributions of the many diverse research groups around the world.

1. Introduction

Chondrichthyans comprise approximately 1000 living species of cartilaginous fishes grouped into two main lineages, the elasmobranchs (sharks, rays and skates) and the holocephalans (chimaeras), which diverged over 450 million years ago (Sansom et al., 1996). The vast majority of living chondrichthyans are elasmobranchs, whilst the holocephalans are represented by about 40 extant species (Didier et al., 2012).

Worldwide research interest in Chondrichthyans has been growing steadily over the last 50 years, with the number of publications on Chondrichthyan research increasing approximately 12 times from 1967 to 2016 (Scopus, January 2018). However, due to conservation and sustainable management policies, a significant merging of Chondrichthyan research has been clearly identified in the last 10–15 years (Last and Stevens, 2009). Furthermore, studies on Chondrichthyans as models to provide insights into vertebrate evolution have become more noteworthy over the last 10 years and are likely to be as a result of the whole-genome analysis of the Holocephali *Callorhinchus milii*, one of the first cartilaginous fish whole-genomes to be sequenced (Venkatesh et al., 2007; Venkatesh et al., 2014).

As was recognised 40 years ago (Gilbert, 1977), Chondrichthyans (in particular sharks and skates) have long been used as laboratory animal models in biomedical and physiological investigations. However, despite of the crucial role the endocrine system plays in regulating the activity of cells and organs in vertebrates, and with research in this

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area related to Chondrichthyans increasing, the field remains relatively unexplored. To the best of our knowledge, over the past 50 years, only two one-day International Symposiums focusing exclusively on Chondrichthyan endocrinology have been held. The first in 1997 as part of the American Elasmobranch Society Conference (AES) (see Journal of Experimental Zoology 1999, Volume 284 Issue 5), and the second in 2012 as part of the 7th International Symposium on Fish Endocrinology (ISFE) (see General and Comparative Endocrinology 2013, Volume 192).

South American waters are an important habitat for an extensive biodiversity of Chondrichthyan species (Compagno et al., 2005). The importance of Chondrichthyans for the region may be understood by the adoption and implementation of the National Plan of Action for Conservation and Management of Sharks (NPOA-Sharks) (FAO, 2012) by the majority of South American countries. Furthermore, there has been an increase in the number of South American Chondrichthyan learned societies that have been established with some holding their own national conferences. The Brazilian Society for Elasmobranch Studies was founded in 1997 (SBEEL, Sociedade Brasileira para o Estudo de Elasmobrânquios) and the Colombian Foundation for Research and Conservation of Sharks and Rays was founded in 2002 (SQUALUS, Fundación Colombiana para la Investigación y Conservación de Tiburones y Rayas). However, despite the growing importance and understanding of South American Chondrichthyans, the extent of the development and progress of Chondrichthyan research areas, and in particular as related to the field of endocrinology, currently remains limited.

Understanding the development of a specific scientific discipline with an associated understanding of the profile of its current and potential future so-called 'hot topics' assists researchers and stakeholders in making strategic decisions regarding which research areas require further attention and potential funding investment. However, apart from a publication exploring the evolution of Chondrichthyan research through three international conferences between 1991 and 2014 (Huveneers et al., 2015), there is a lack of information capturing how Chondrichthyan research has evolved over time, both worldwide and more specifically in South America.

Undertaking bibliometric studies of scientific publications assists identifying and understanding trends in specific research fields (Baldock, 2017; De Groot et al., 2015; Rizzi et al., 2014). Visualisation techniques based on bibliometric analysis of publication data are often used to generate so-called term maps to assist in the exploration of the structure and evolution of research areas over time. A term map is a two-dimensional representation of a research area in which strongly related terms are located spatially close to each other and less strongly related terms are located further away from each other with the term map providing an indication of the overall structure of a research area (Van Eck and Waltman, 2014).

In the current study, term maps were created using VOSviewer Software to evaluate Chondrichthyan research undertaken in South America over a 50-year period (1967–2016) and worldwide during a 15-year period (2002–2016). The terms maps were used to explore trends and active growth areas with an emphasis on endocrinology-specific Chondrichthyan research in South America and compare it with more general South America and worldwide Chondrichthyan scientific research during for the most recent 15-year period.

2. Methodology

A bibliometric analysis of Chondrichthyan scientific publications was undertaken (i) for all worldwide publications for the 15-year period from 2002 to 2016, and (ii) more specifically for all South America publications for the 50-year period from 1967 to 2016. The Scopus bibliographic database (http://www.scopus.com) was used as a platform to identify relevant publications related to Chondrichthyan research (scientific papers, reviews and conference papers). English

language publications were searched for each year from 1967 to 2016 using the following search terms in their titles, keywords and abstracts: 'shark', 'skate', 'stingray', 'elasmobranch*' 'holocephal*' and 'chondrichthy*'. The '*' was used to replace multiple characters found anywhere in the term (e.g. the term 'elasmobranch*' included 'elasmobranchs' and 'Elasmobranchii'). The term 'ray' was not used in the search as it resulted in the inclusion of thousands of scientific publications associated with medical fields (e.g. 'X-ray'). By including the term 'stingray' together with the term 'elasmobranch*' the search could be refined to include only Chondrichthyan associated ray publications. Scientific publications having the term 'shark' in their title, abstract or keyword but not related to shark research were excluded (e.g. the use of the term 'shark-skin' as a model for designing engineering applications, the use of the term 'shark' to denominate computer and mathematical algorithms or programs, and use of the term 'shark' when describing and referring to certain characters within the fields of finance, legal and sporting areas). As the Scopus database subdivides search results into subject areas, to further delete any unwanted scientific publication, the subject areas of 'Engineering', 'Physics and Astronomy', 'Arts and Humanities', 'Business, Management and Accounting', and 'Economics, Econometrics and Finances' and 'Psychology' were excluded from the search results. The accuracy of the search outcomes was checked by reviewing the title, abstract and keyword of each scientific publication found. Of all the publications identified in the search, 77% corresponded to Chondrichthyan global research that were subsequently selected for the bibliometric analysis.

For the South American bibliometric analysis, the Chondrichthyan publications obtained in the global search were limited to include solely South American countries.

Finally, to exclusively obtain papers in the field of Chondrichthyan endocrinology, the list of Chondrichthyan research publications obtained both globally and for South America were redefined using the search terms 'endocrine*', 'hormone' and 'peptide'.

The bibliometric analysis was undertaken with VOSviewer, a computer program used for creating and visualising bibliometric maps of science (Van Eck and Waltman, 2010) and freely available at www.vosviewer.com. VOSviewer enables the exploration of research topics from different journals and the citation impact of these topics. The software generates term maps based on terms that have been identified and selected from the titles and abstracts of scientific publications and made available to VOSviewer. A term map reveals the relationships between terms located 2-dimensionally in such a way that the distance between two terms can be interpreted as an indication of the relatedness of the terms. In general, the smaller the distance between two terms, the stronger the terms are related to each other. The relatedness of terms is determined based on the co-occurrences of terms in the titles and abstracts of two or more scientific publications.

To generate the term maps, VOSviewer excludes terms with a small number of occurrences to avoid including in the map general terms that provide little or no useful information (e.g. 'conclusion', 'results', 'biological effects'). To exclude general terms, the software determines for each term a relevance score. Terms with a high relevance score tend to represent specific topics covered by the text data, while terms with a low relevance score tend to be general and not illustrative of any specific topic. By excluding terms with a low relevance score, general terms are filtered out with the map focusing on more specific and more informative terms (Van Eck and Waltman, 2014).

In the current work, term maps were created based on a corpus of publications in the field of Chondrichthyan research with each term that occurred at least five times in the titles or abstracts of scientific publications. Each term is represented by an individual circle (node) on the map. The size of the circle indicates its frequency of occurrence with more publications containing the term resulting in a larger circle. Circles are positioned in a 2D plot in which their relative positions are determined by their co-occurrence with other terms in titles or abstracts included in the analysis. The closer the terms, the more often they tend

(caption on next page)

Fig. 1. Network and density visualisation term maps based on 5039 terms of Chondrichthyan research undertaken globally from 2002 to 2016. (a) Network visualisation map showing related terms grouped in eight clusters. Cluster 1 (red): fisheries, management, marine protected areas (MPAs), conservation, population dynamics, life history, movement patterns and spatial ecology; cluster 2 (green): fossils, paleoecology and paleobiogeography, morphological and molecular tax-onomy, phylogenetics and phylogeny; cluster 3 (blue): genetics, anatomy and physiology, including also the use of these three disciplines in an evolutionary context; cluster 4 (yellow): diet and trophic ecology, marine pollution, and the use of Chondrichthyans in medicine (e.g. shark liver oil, cancer); cluster 5 (violet): parasitology and the use of parasites for taxonomic identifications; cluster 6 (pink): metabolism and osmoregulation; cluster 7 (orange): genomics; cluster 8 (black): functional morphology of the reproductive system in both sexes. (b) Zoomed in view of cluster 1. (c) Density visualisation term map with terms mainly concentrated in one high-density red region on the top right corner of the map (corresponding to cluster 1). Two smaller and less dense yellow-orange regions visible on the right side of the map (zoomed in (d)) one corresponding to phylogenetics and phylogeny and the other on parasitology. A few lesser dense regions at the bottom and along the left side of the density map corresponding to fossil studies, genetics, metabolism and osmoregulation.
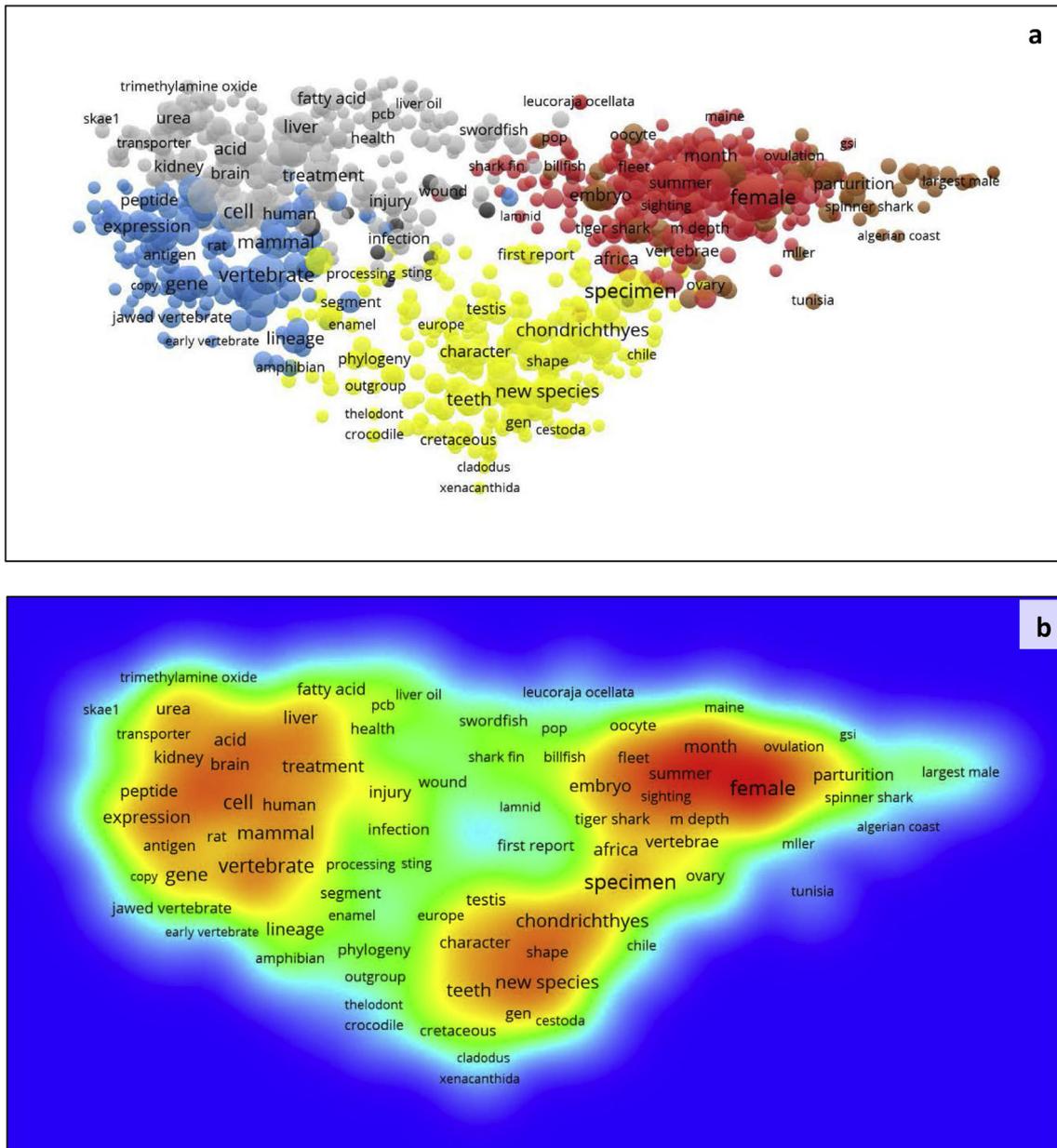

Fig. 2. Network and density visualisation term maps based on 1038 terms of Chondrichthyan research undertaken globally from 2002 to 2006. (a) Six clusters are distinguished on the network visualisation map concerning areas related to (red): fisheries, movement patterns, spatial ecology, population dynamics; (brown): life history; (black): functional morphology of male reproductive system; (bright yellow): fossils, paleoecology and paleobiogeography, morphological and molecular taxonomy, phylogenetics and phylogeny, general parasitology and the use of parasites for taxonomic identifications; (grey): diet and food web interactions, marine pollution, the use of Chondrichthyans in medicine, parasitology, metabolism and osmoregulation; (blue): genetics, anatomy and physiology, including also the use of these three disciplines in an evolutionary context. (b) Density visualisation term map shows the areas of research divided in two broader regions. The right region is linked to non-physiology disciplines, highlighting the areas of taxonomy, fossils, fisheries, sustainability, and life history. The left region comprises physiology disciplines.
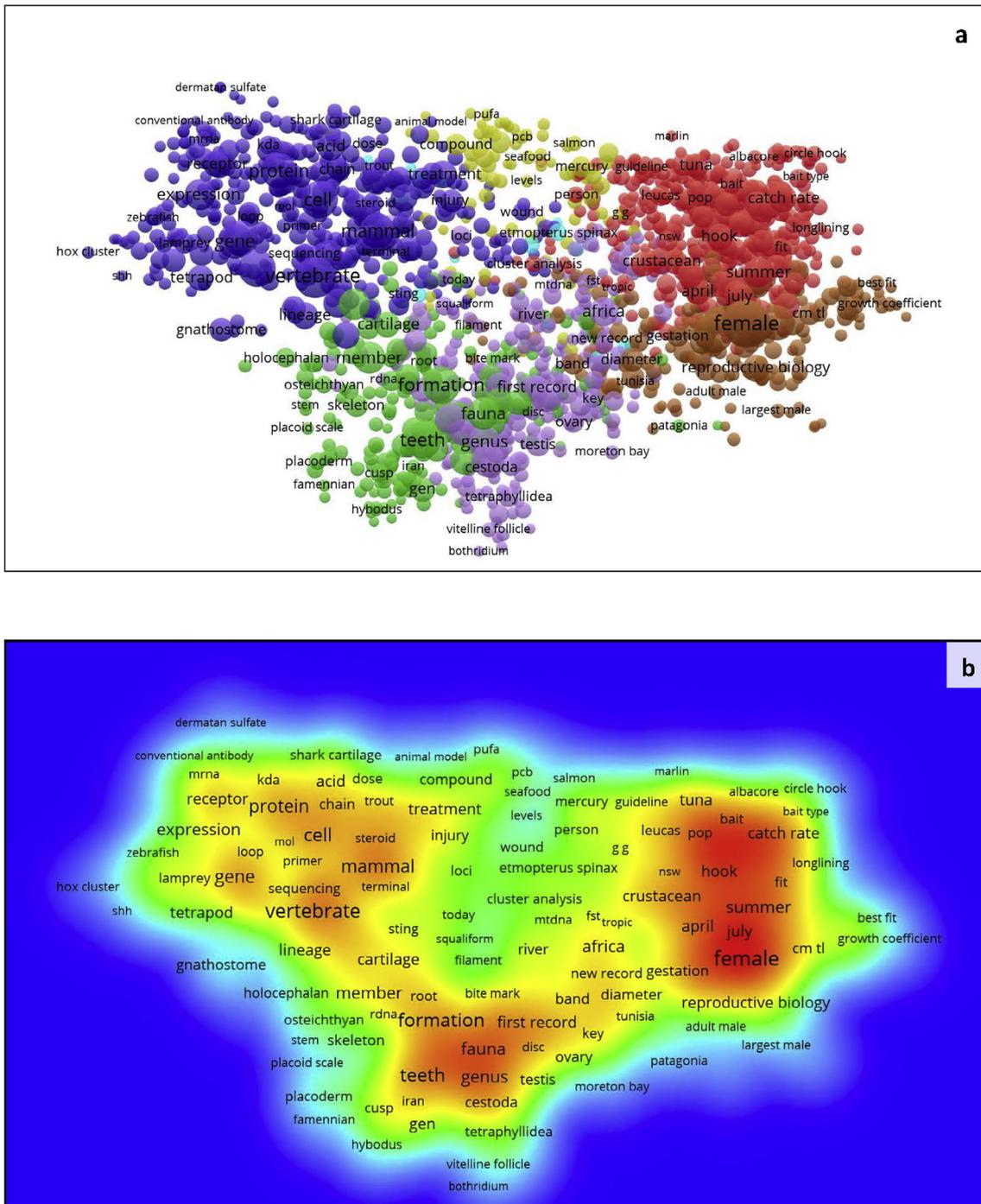
Fig. 3. Network and density visualisation term maps based on 1726 terms of Chondrichthyan research undertaken globally from 2007 to 2011. (a) Seven clusters are represented on the network visualisation map. Red and brown clusters kept the same research themes as seen in Fig. 2a. Three clusters, yellow, green and violet, previously observed in Fig. 1a are again represented on the current network visualisation map. A new big purple cluster is formed by terms previously belonging to different clusters, comprising the areas of: Chondrichthyans in medicine, metabolism and osmoregulation, genetics, anatomy and physiology, including also the use of these three disciplines in an evolutionary context. A new small cluster linked to bioluminescence investigations is distinguished in light blue. (b) Similar to 2002–2006 period the density visualisation map shows the right area filled by high concentration of terms related to fisheries, sustainability, and life history. However, the area of taxonomy and fossils and paleobiodiversity is further separated towards a down central position. The left region of the map still comprises physiological related disciplines, however the area is less marked than in the 2002–2006 period.

to co-occur. Finally, terms are grouped and coloured into clusters of terms that tend to broadly co-occur. A default value of one was chosen to determine the resolution parameter (level of detail) of the clustering produced by the software.

3. Results

3.1. Global Chondrichthyan research from 2002 to 2016

The network visualisation term map for Chondrichthyan research undertaken globally over the 15-year period from 2002 to 2016 is shown in Fig. 1a. The map is characterised by circles and labels

representing each of the terms. The size of the circle and label is determined by the relative weight of the term and is an indication of the number of publications that the corresponding term occurs in either the title or abstract of the publication. A term with a higher weight is considered to be more significant and shown more distinct than a term with a lower weight. In the term map (Fig. 1a) eight thematic research areas or clusters can be distinguished consisting of 5039 co-occurring terms categorising the Chondrichthyan research field: cluster 1 (red): fisheries, management, marine protected areas (MPAs), conservation, population dynamics, life history, movement patterns and spatial ecology (a zoomed-in example of cluster 1 illustrates further detail in Fig. 1b); cluster 2 (green): fossils, paleoecology and paleobiogeography, morphological and molecular taxonomy, phylogenetics and phylogeny; cluster 3 (blue): genetics, anatomy and physiology, including also the use of these three disciplines in an evolutionary context; cluster 4 (yellow): diet and trophic ecology, marine pollution, and the use of Chondrichthyans in medicine (e.g. shark liver oil, cancer); cluster 5 (violet): general parasitology and the use of parasites for taxonomic identifications; cluster 6 (pink): metabolism and osmoregulation; cluster 7 (orange): genomics; cluster 8 (black): functional morphology of the reproductive system in both sexes.

The density visualisation term map in Fig. 1c illustrates the overall Chondrichthyan research field during the 2002–2016 period. The colours in the map are determined by the density of terms with the number of terms in the neighbourhood and the weight of the each term determining the density of the terms. The higher the density of terms, the higher the colour value (by default colours ranged from blue to green to red). The larger the number of terms in the neighbourhood and the higher the weight of the terms, the closer the colour of the area is to red. Conversely, the smaller the number of terms in the neighbourhood and the lower the weight of terms, the closer the colour of the area is to blue (Van Eck and Waltman, 2010, 2014). In Fig. 1c, the map shows terms mainly concentrated in a higher dense region in the top right corner of the map, corresponding to cluster 1 (fisheries, management, MPAs, conservation, population dynamics, life history, movement patterns and spatial ecology) in Fig. 1a. Two smaller and less dense yellow-orange regions are also visible on the right side of the map corresponding to phylogenetics and phylogeny (part of cluster 2) and parasitology (part of cluster 5) in Fig. 1a (a zoomed-in example illustrating further detail can be seen in Fig. 1d.). A few conspicuously reduced dense regions can be distinguished at the bottom and along the left side of the density visualisation term map associated with fossil studies, genetics, metabolism and osmoregulation.

By dividing the 15-year period of global Chondrichthyan research into three discrete five-year periods, it was possible to further explore evolving research areas and trends over time. The 2002–2006 network visualisation term map shows six thematic research areas or clusters comprising 1038 co-occurring terms categorising the Chondrichthyan research field for that period (Fig. 2a). Similar to the 2002–2016 global network visualisation map (Fig. 1a), the red cluster for the 2002–2006 period (Fig. 2a) comprises research involving fisheries, movements, spatial ecology and population dynamics. However, no terms associated with management, conservation and MPAs were visible in this cluster for 2002–2006. Furthermore, life history terms associated with age and growth and reproduction are no longer found within the red cluster but in a new brown cluster. As for the 2002–2016 period, the black cluster (outcomes on functional morphology of the reproductive system), although more focused on males (e.g. sperm, seminal vesicle, spermatogenesis) during the 2002–2006 period, and the blue cluster (genetics, anatomy and physiology, including also the use of these three disciplines in an evolutionary context) were also represented in the 2002–2006 period. Cluster 2 (fossils, paleoecology and paleobiogeography, morphological and molecular taxonomy, phylogenetics and phylogeny) and cluster 5 (general parasitology and the use of parasites for taxonomic identifications) for the 2002–2016 period were grouped into one bright yellow cluster for the 2002–2006 period. Similarly,

cluster 4 (diet and trophic ecology, marine pollution, and the use of Chondrichthyans in medicine) and cluster 6 (metabolism and osmoregulation) were grouped into one grey cluster for the 2002–2006 period.

The density visualisation term map for 2002–2006 is broadly divided into two regions (Fig. 2b). The right region is associated with non-functional physiology disciplines and can be further subdivided into two closely related areas involving taxonomy and fossils (top) and fisheries, sustainability, and life history (bottom), with the bottom left region comprising functional physiology areas.

The next five-year period, 2007–2011, shows an increase in the number of clusters in the network visualisation term map (Fig. 3a). Seven clusters can be distinguished consisting of 1726 co-occurring terms. Two clusters, red and brown, retained the same thematic research areas (and colours) of the 2002–2006 period. However, terms related to management and MPAs begin to appear within the red cluster. Compared with the 2002–2006 period, clusters 4 and 6 are no longer grouped within a unique cluster. Cluster 4 comprising diet and trophic ecology and marine pollution form one cluster (yellow). Conversely, the remainder of cluster 4 (Chondrichthyans in medicine), cluster 6 (metabolism and osmoregulation) and the blue cluster 3 (genetics, anatomy and physiology) all form one bigger cluster (purple). The bright yellow cluster (clusters 2 and 5) observed during the previous five years 2002–2006 (Fig. 2a) has been divided into the green (fossils, paleoecology and paleobiogeography, morphological and molecular taxonomy, phylogenetics and phylogeny) and violet (general parasitology and the use of parasites for taxonomic identifications) clusters as previously seen in Fig. 1a for the 2002–2016 period. The cluster on functional morphology of the reproductive system no longer exists due to an insufficient number of co-occurring terms to form a single cluster. However, a new light blue cluster appears comprising a small group formed by terms linked to research based on bioluminescence investigations (these terms are within cluster 3 in the 2002–2016 period). Similar to the 2002–2006 period, the non-physiological fields of fisheries, management, MPAs, life history and spatial ecology are the more research intensive ones in the 2007–2011 period, followed by a smaller area linked to fossils, taxonomy, and paleobiogeography (Fig. 3b).

For the last five-year period, 2012–2016, the network visualisation term map is based on 1102 co-occurring terms distinguishing six clusters (Fig. 4a). Similar to the previous periods (2002–2006 and 2007–2011), the red and brown clusters remain. The terms referring to conservation began to appear within the red cluster. Similar to the 2007–2011 period, the yellow cluster (diet and trophic ecology and marine pollution) and purple cluster (Chondrichthyans in medicine, metabolism and osmoregulation, genetics, anatomy and physiology) are present in this later 2012–2016 five-year period. Similar to the 2002–2006 period, the green cluster 2 (fossils, paleoecology and paleobiogeography, morphological and molecular taxonomy, phylogenetics and phylogeny) and the violet cluster 5 (general parasitology and the use of parasites for taxonomic identifications) were once again grouped into one single bright yellow cluster in this 2012–2016 period. The light blue cluster (bioluminescence) represented in the previous 2007–2011 period does not appear in a separate group in this 2012–2016 period, likely due to a low number of terms related to bioluminescence in comparison to other terms. However, a new orange cluster appeared related to genomic research. Following the trend observed in the previous five-year periods (2002–2006 and 2007–2011), the area of fisheries, management, conservation, spatial ecology, population dynamics and life history is where the majority of the research remains concentrated in this later period, 2012–2016 (Fig. 4b).

Of the total number of publications in Chondrichthyan research in the global literature for the 2002–2016 period, 3.51% corresponded to endocrine-related research. The endocrine research network visualisation map for 2002–2016 shows five clusters of 215 terms categorising the endocrine thematic research areas (Fig. 5a). The biggest cluster
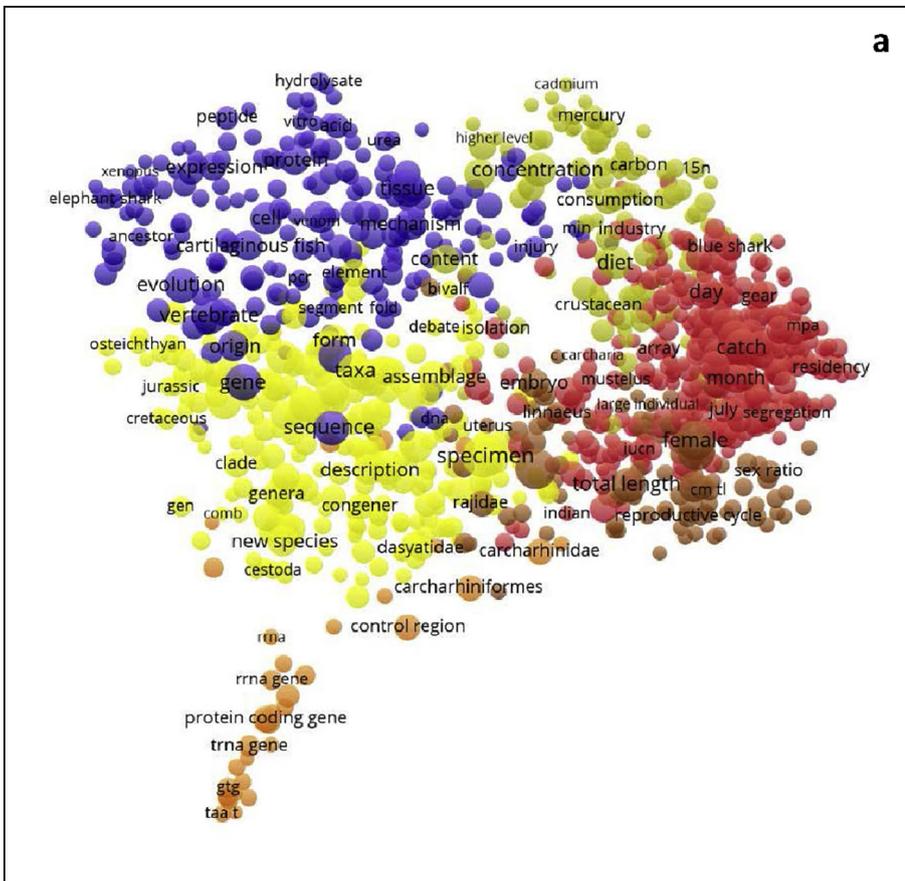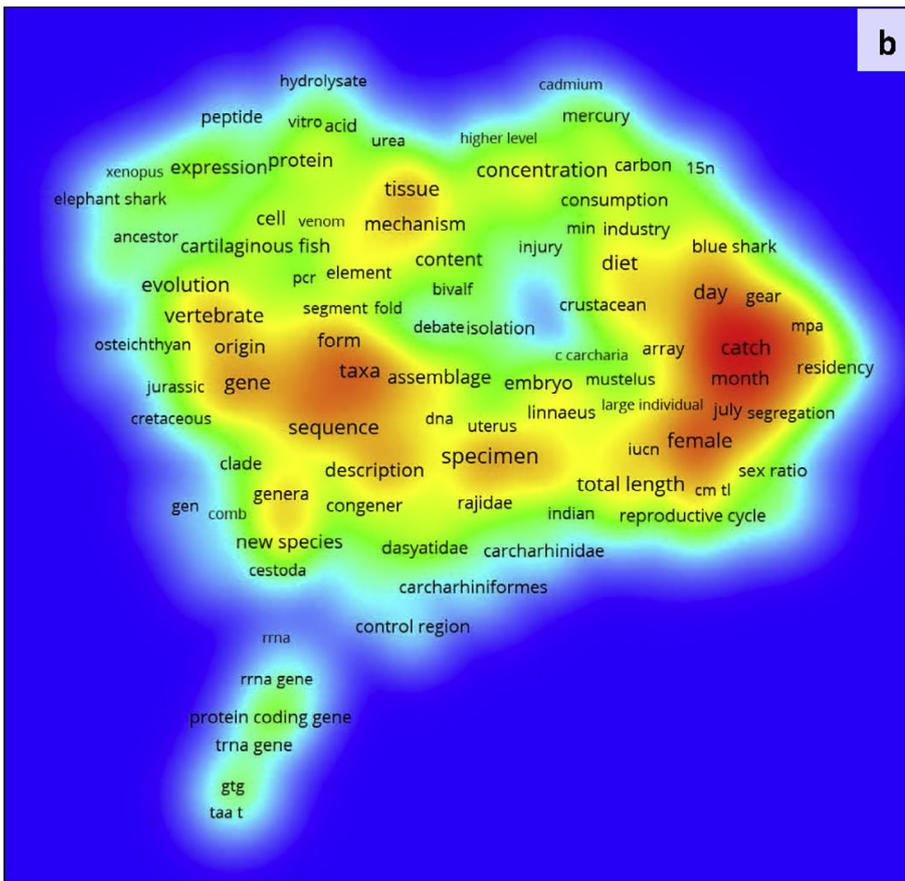
Fig. 4. Network and density visualisation term maps based on 1102 terms of Chondrichthyan research undertaken globally from 2012 to 2016. (a) Six clusters are distinguished on the network visualisation map. As previous seen in Fig. 3a, the red, brown, yellow and purple clusters are distinguished on this map. However, the area of Chondrichthyan in medicine does not have enough number of terms to be shown within the purple cluster. The big bright yellow cluster firstly formed by the merge of violet and green clusters (Fig. 2a) is also present in this map. There is a new orange cluster related to genomic research terms. (b) The density visualisation map shows two areas where the research is mainly concentrated. The main area (on the right) is related to fisheries, management, conservation, spatial ecology, population dynamics and life history, while the left area represent a less intense research field linked to fossils, taxonomy, and paleobiogeography.
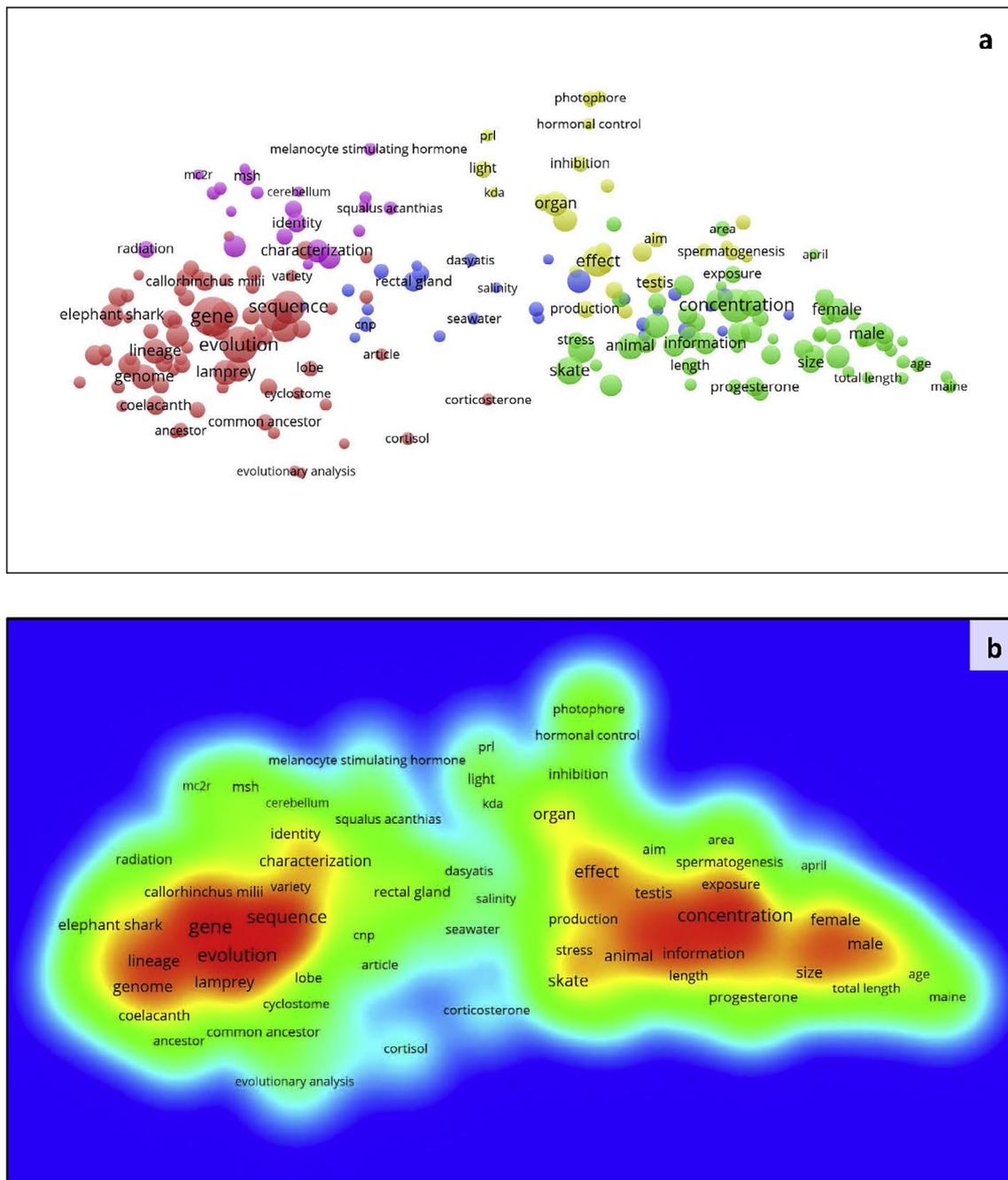
Fig. 5. Network and density visualisation term maps of endocrine research thematic areas based on 215 terms of Chondrichthyan research undertaken globally from 2002 to 2016. (a) Five clusters are distinguished on the network visualisation map. The red cluster is formed by terms linked to the role of Chondrichthyan hormones in understanding the endocrine system evolution. The green cluster encompass the field of reproductive endocrinology. The three smaller clusters involve the areas of melanocortins (pink), hormonal control of osmoregulation (yellow), and hormonal control of bioluminescence and testicular steroidogenesis (blue). (b) The density visualisation map shows two main areas of research associated with the reproduction and with the endocrine system evolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(red) comprises terms mainly associated with the role played by Chondrichthyan hormones in understanding the evolution of the endocrine system. The next largest cluster (green) is formed by research into endocrine reproduction, which includes publications on the correlation between reproductive hormone levels and gonadal development as well as the use of hormones as a non-lethal methodology to understand Chondrichthyan reproduction. The three smaller clusters involve research mostly into melanocortins (pink), hormonal control of osmoregulation (yellow), and terms linked to hormonal control of bioluminescence and testicular steroidogenesis (blue). The density visualisation term map shows two main regions comprising two main areas of endocrine research, linked to the red and green clusters (Fig. 5b).

3.2. South American Chondrichthyan research

Of the total global Chondrichthyan literature produced during the 2002–2016 period, 11% corresponded to research undertaken by South American-affiliated authors (Fig. 6).

By exploring the scientific literature co-authored between South American-affiliated authors and non-South American-affiliated authors, trends in international research collaboration could be determined for
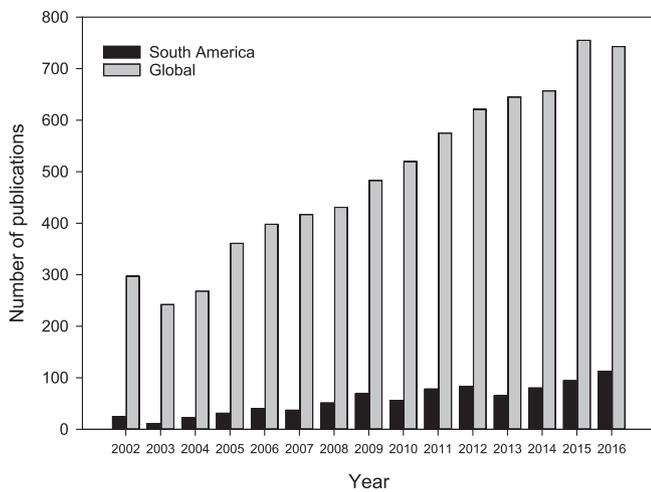
Fig. 6. Total number of Chondrichthyan literature published globally and specifically from South America. Based on Scopus data base (www.Scopus.com. downloaded January 2018).

South American Chondrichthyan-related research. A map representing co-authorship by countries indicated four clusters (Fig. 7). Clusters are formed by the frequency of co-occurring terms representing each country, the more often the terms tend to co-occur they get coloured into clusters. The yellow cluster shows numerous collaborative links between the largest circles of Brazil and the United States representing authors affiliated to these countries. Brazil is associated with Portugal, for presumably reasons of a common language, and to a lesser extent other countries (recognised by the numerous lines radiating from the Brazilian circle). Similar to Brazil, the green cluster shows Argentina having the strong research collaborations with Canada and three

European nations and Peru. The blue cluster is dominated by Chile with collaborative association mainly with Australia, the United Kingdom and South Africa, and in much lesser extent with the territory of the Islas Malvinas (Falkland Islands), New Zealand and Brazil. The lack of apparent collaboration between Argentinean authors and those affiliated to the Islas Malvinas is perhaps unsurprising. The Guerra de las Malvinas (Falklands War) took place in 1982 between Argentina and the United Kingdom over the sovereignty of the Islas Malvinas, and unresolved political issues between both countries may have influenced the lack of productive scientific collaboration between both nations. The red cluster is mainly formed by small South and Central American countries collaborating with each other with Colombia leading the research collaborations. Interestingly, there are significantly limited collaborations between Chile (blue), Argentina and Peru (green), and the other South American countries (red). Furthermore, although strong and sustained research collaborations have been formed between Argentina and Brazil in several areas (Chittó-Stumpf et al., 2017; Leta and Chaimovich, 2002; Malacalza, 2016), research associations involving Chondrichthyans remain limited.

The network visualisation term map for South American Chondrichthyan research for the 15-year period, 2002–2016 (Fig. 8a) categorised the thematic research areas into six clusters based on 670 co-occurring terms (Fig. 8a). Similar to the Chondrichthyan research literature published globally, the red cluster mainly comprises research related to the areas of fisheries, management, MPAs, conservation, population dynamics and life history. However, different to the global trends, the cluster does not include studies on spatial ecology and terms specifically related to reproductive biology are grouped within one individual brown cluster. Terms related to trophic ecology and diet are clustered in the dark yellow cluster, and those focusing on taxonomy, phylogenetics and phylogeny, parasitology and the use of parasites for taxonomic identifications are clustered in the violet cluster. This violet cluster also displays terms on the family Potamotrygonidae, a family
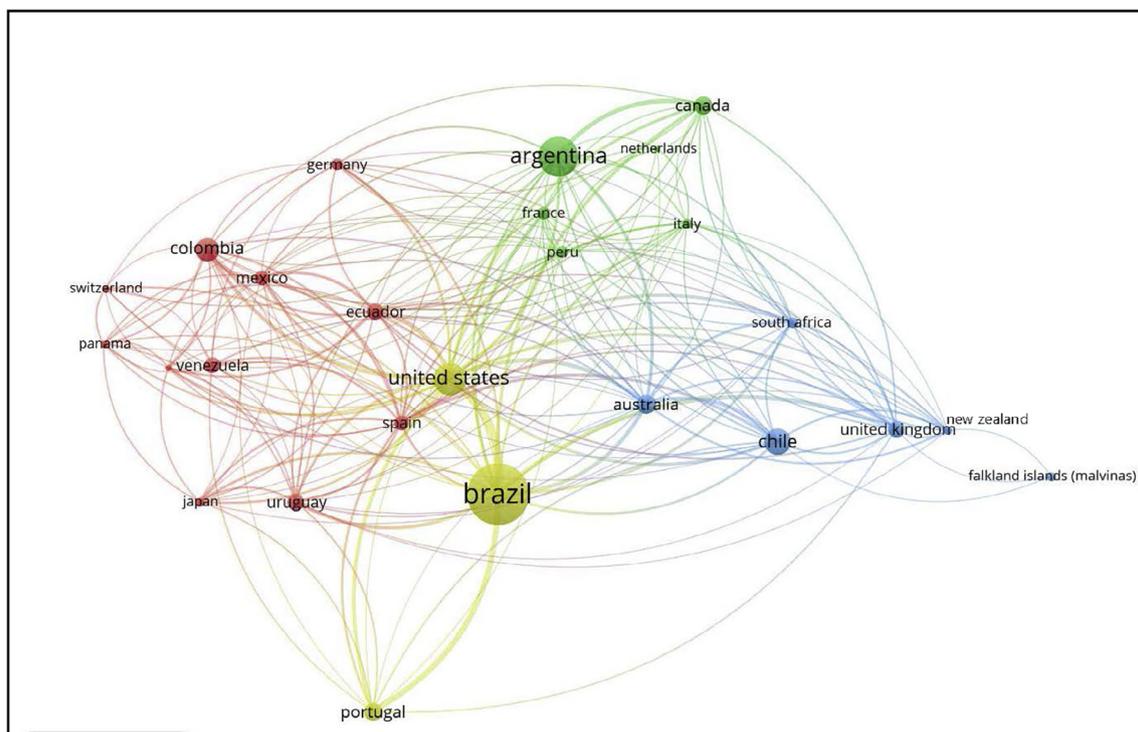

Fig. 7. South American Chondrichthyan research collaborations for the 2002–2016 period. Twenty-six countries are distinguished on the network visualisation term map. The countries are grouped into four different clusters formed by the frequency of co-occurring terms representing each country. The yellow cluster mainly comprise Brazil and United States and smaller node corresponding to Portugal. Argentina, Peru, Canada and some European Nations shaped the blue cluster. The green cluster is formed by Chile collaborating to others Southern hemisphere countries and United Kingdom. Small South American countries associated to Central America countries form the red cluster. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
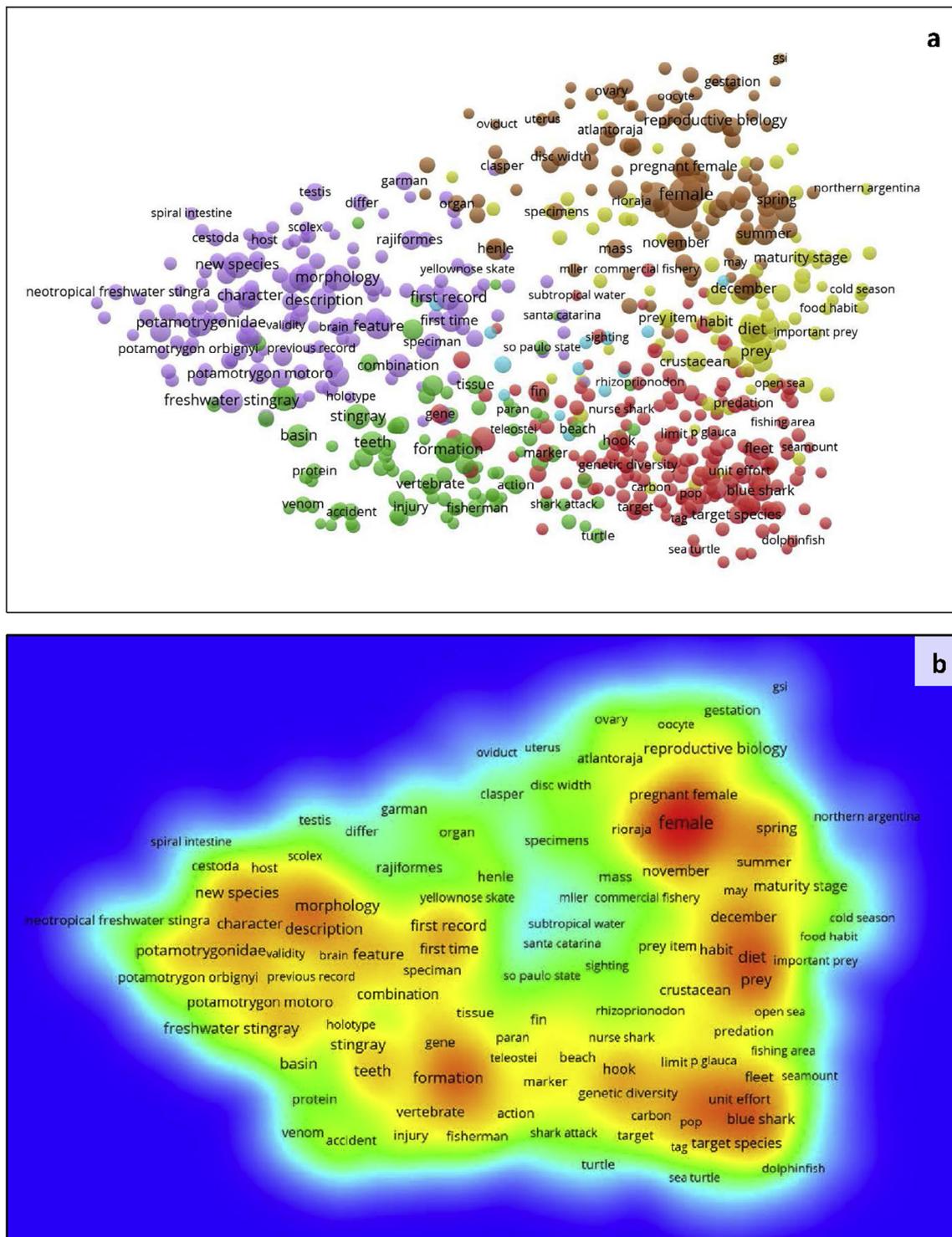
Fig. 8. Network and density visualisation term maps based on 670 terms of Chondrichthyan research undertaken in South America from 2002 to 2016. (a) Six clusters are distinguished in the network visualisation map containing areas related to: (red): fisheries, management, MPAs, conservation, population dynamics, and life history; (dark yellow): diet and trophic ecology; (brown): reproductive biology, (violet): morphological and molecular taxonomy, phylogenetics and phylogeny, parasitology and the use of parasites for taxonomic identifications; (green): fossils, shark attacks, stingray venom; (light blue): Whale sharks, Manta and Devil rays. (b) The density visualisation map shows reproductive biology as the hottest area of research, followed by the areas of fisheries, diet and trophic ecology. The fields of taxonomy, phylogenetics, phylogeny and fossils are less marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

representing species native to freshwater environment of South America. The green cluster comprises two different research areas, fossils and human injuries cause either by shark attacks or by stingray venom. Finally, a small light blue cluster refers to studies linked mostly to whale sharks, *Rhincodon typus*, and species from the Mobulidae and

Myliobatidae families (Manta and Devil rays). The density term map (Fig. 8b) shows higher concentration of research within the field of reproductive biology, followed by the areas of fisheries, diet and trophic ecology, and in a lesser extent, taxonomy, phylogenetics, phylogeny and fossil investigations.
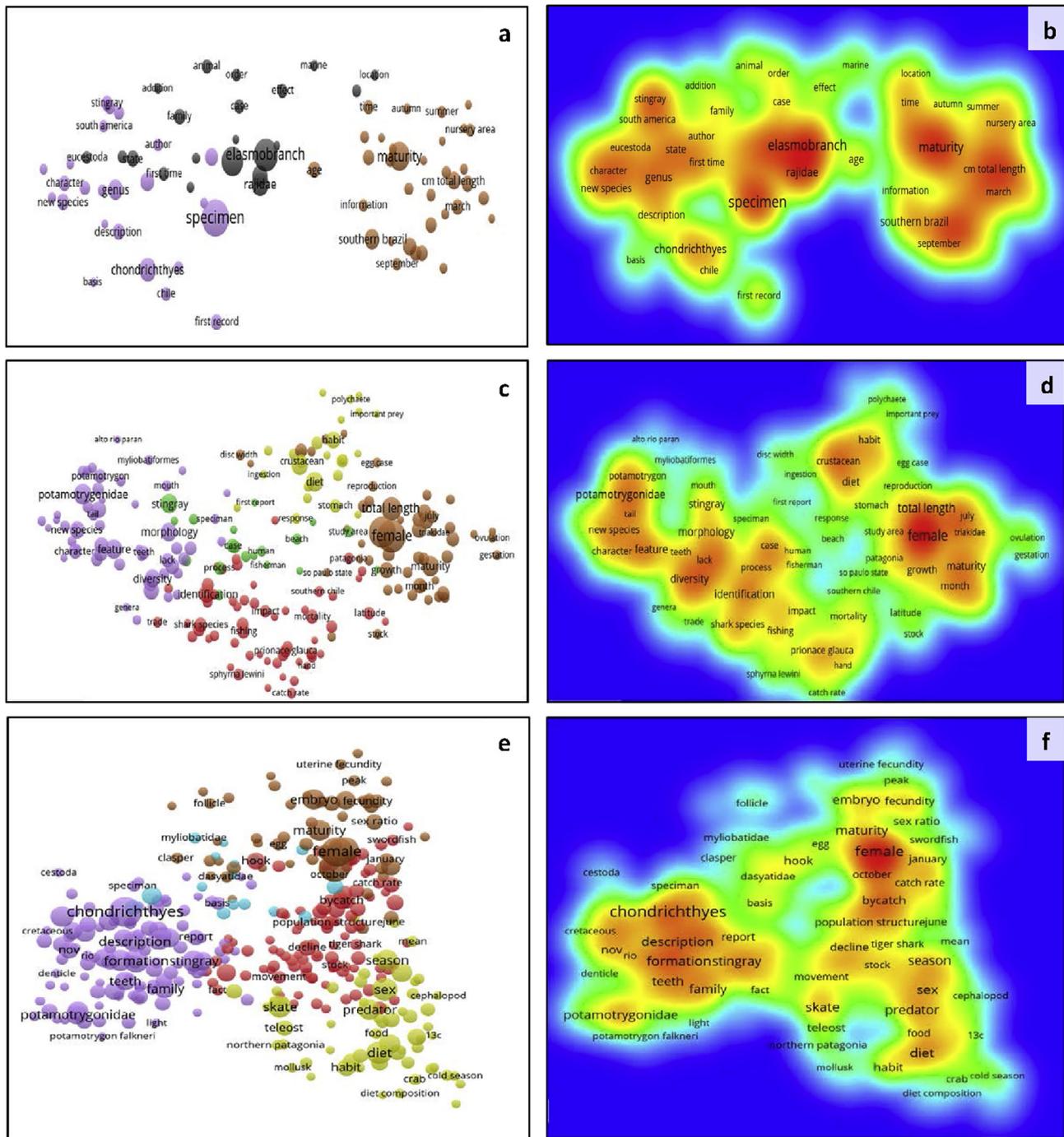
Fig. 9. Network and density visualisation term maps based on South American Chondrichthyan research. Network (a) and density (b) visualisation maps based on 79 terms from 2002 to 2006. Three broader and research-intensive areas are distinguished: reproductive biology (brown cluster), taxonomy and parasitology (violet cluster), publications focused on the Rajidae family (black cluster). Network (c) and density (d) visualisation maps based on 208 terms from 2007 to 2011. The network map reveals five clusters, four (red, violet, dark yellow, brown) represent similar research themes as those display in Fig. 8a. A green cluster comprise terms associated to stingray venom. The density visualisation map shows the research concentrated mainly in the field of reproductive biology, closely followed by taxonomy and phylogenetics. Network (e) and density (f) visualisation maps based on 343 terms from 2012 to 2016. As in previous years, the red, violet, dark yellow and brown clusters are represented on the network visualisation map. Likewise, the light blue cluster is formed by terms associated with whale sharks, Manta and Devil rays. The density visualisation map shows reproductive biology as the hottest research theme, followed by taxonomy, phylogenetics and by trophic ecology and diet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similar to the Global analysis, to further explore the South American research trends from 2002 to 2016, the 15-year period was divided into three discrete five-year periods. The 2002–2006 period resulted in low number of terms (79 terms grouped in three clusters), and was therefore difficult to specifically identify the themes of each cluster (Fig. 9a). However, an indication of the specific research areas can be still

distinguished. The brown cluster represents research mainly on reproduction and to a lesser extent with age and growth. The violet cluster comprises the areas of phylogenetics, taxonomy and parasitology, while the black cluster comprises research concentrated mainly related to the Rajidae family, a family well represented in both marine and freshwater South American waters. A significant proportion

of the literature published on the Rajidae family focuses on phylogenetics and conservation. Although comparable research outputs are distinguished for all thematic areas during the 2002–2006 period, publications comprising life history (age and growth, reproductive biology) and those concerning the Rajidae family were hot topics (Fig. 9b).

The research themes over the next five-year period, 2007–2011, begin to resemble the overall 15-year period. Based on 208 terms, five clusters are identified (9c). Four clusters (red, brown, violet, dark yellow) are similar to the ones represented during the 15-year period (Fig. 8a). However, although the green cluster comprises publications on human injuries caused by stingray venom (as the 2002–2016 period), terms related specifically to fossils and human injuries caused by shark attacks do not occur sufficiently to be shown within the cluster. The black cluster focused on the Rajidae family during the previous 2002–2006 period lost significance (Fig. 9a). The density visualisation map (Fig. 9d) reveals the area of reproductive biology to be research intensive, followed by taxonomy and phylogenetics.

The exploration of the last five-year period, 2012–2016, reveals five clusters based on 343 terms (Fig. 9e). The larger four clusters (red, brown, violet, dark yellow) remain similar as previously observed in the network visualisation map during the overall 15-year period (Fig. 8a) and earlier 2007–2012 period (Fig. 9c). Furthermore, the light blue cluster linked to research on whale sharks and on Manta and Devil rays was formed during this last five-year period. However, the green cluster (Fig. 9c) comprising themes on fossils and human injuries (caused either by shark attacks or by stingray venom) is not observed during 2012–2016. Terms related to fossils appear within the violet cluster, and those related to shark attacks appear within the red cluster. No terms on injuries caused by stingray venom appear in this period. Similar to previous periods, the overall distribution of research efforts fall within the reproductive biology theme, closely followed by taxonomy and phylogenetics and less intense by trophic ecology and diet (Fig. 9f).

From 1967 to 2001, 134 papers were published on Chondrichthyans research in South America. Throughout this period, the number of Chondrichthyan terms used to create and visualise the term maps was very small (51). Thus, it was difficult to determine accurately the research themes. However, further exploration looking into publication titles and the network visualisation map, revealed a patchy map containing three broad clusters covering diet and reproduction (brown), taxonomy and phylogenetics (green), physiology and biochemistry (blue) (Fig. 10a). Although patchy, these research themes were of similar research intensity (Fig. 10b).

Chondrichthyan endocrinology research undertaken in South America during the 2002–2016 period was very small with only five corresponding publications identified in the literature. Two publications from Brazil were related to research on Potamotrygon species, one on stress and hormonal response (in 2012) and the other on thyroid hormones (in 2015). The remaining three publications were from a researcher co-affiliated with both Argentinean and Australian research institutes (one in 2013 and two in 2014). For the remaining 35 years, 1967–2001, three scientific papers were published on Chondrichthyan endocrinology. These publications are associated to the renin-angiotensin system (in 1983), the neurophysins, carrier proteins (secreted by the preoptic area) involve in transporting oxytocin and vasopressin to the neural lobe of the pituitary gland (in 1996), and the hormonal regulation of skin colour change in elasmobranchs (in 1999).

4. Discussion

4.1. Global Chondrichthyan research

The bibliometric analysis on Chondrichthyan publications in the global literature during the 2002–2016 period has revealed overall trends in the different thematic research areas.

The areas of fisheries and population dynamics have been a constant hot topic during the entire 15-year period, strongly related to the field of life history (e.g. growth rates, reproduction, maximum body length and mass, natural mortality). Although the area of reproduction also involved anatomo-histological studies of the reproductive system, this topic has never received a strong research focus. The reproductive area mainly concentrated on addressing the size and age at onset of sexual maturity followed by studies on reproductive cycles. This is not surprising as addressing onset at maturity is fundamental for the sustainable management and conservation of any species to ensure their capacity to reproduce and contribute to future generations. However, it was not until 2006 when the terms 'conservation' and 'management' began to strongly and increasingly appear in the scientific literature (Davidson et al., 2015; Dulvy et al., 2008; Ellis et al., 2005; Simpfendorfer et al., 2011), likely linked to the growing number of Chondrichthyan species listed as endangered or threatened in the International Union for the Conservation of Nature (IUCN, 2018). Furthermore, the term 'extinction' denoting the possibility of a species going extinct became frequently used in many scientific publications (Dulvy et al., 2014; Dulvy et al., 2003; McClenachan et al., 2016). In parallel with the growth in the number of publications related to conservation issues, publications linked to a better understanding of the implementation of management strategies have increased. The implementation MPAs for Chondrichthyan species (Blyth-Skyrme et al., 2006; Davidson and Dulvy, 2017; McAllister et al., 2015) and the importance of incorporating information on Chondrichthyan movement behaviours and habitat utilisation into population dynamic models, have been recognised as multidisciplinary aspects for management and conservation programmes (Barnett et al., 2011; Heupel et al., 2005; Simpfendorfer and Heupel, 2004). Furthermore, historically, established fisheries-dependent population surveys were used to assess Chondrichthyan population structures to develop management strategies. However, in the past 10 years baited remote underwater video (BRUV) and underwater visual census (UVC) (Brooks et al., 2011; Juhel et al., 2018), and more recently environmental DNA (eDNA) (Bakker et al., 2017; Simpfendorfer et al., 2016) have been increasingly used as non-invasive methods for monitoring Chondrichthyan biodiversity and abundance. Although eDNA was not distinguished in the term maps due to the first papers published in 2016, the area clearly is emerging.

Following closely to the growth of the Chondrichthyan conservation thematic area, two other broader related areas, trophic ecology and human-chondrichthyan interactions, are developing and growing.

Although studies focusing on Chondrichthyan diet composition have been commonly published, an assessment of the publication trends in recent years revealed a change in the analysis and interpretation of the diet data. Studies on Chondrichthyan diets have stopped focusing merely on prey composition to shift into the field of trophic ecology, which includes food web structures and prey-predator interactions. The trophic ecology thematic field has been increasingly linked to aquatic conservation, highlighting the importance of Chondrichthyans in regulating biodiversity in aquatic ecosystems (Barnett and Semmens, 2012; Hammerschlag et al., 2018; Heithaus et al., 2012).

In the most recent years, increasing numbers of social and scientific publications focusing on human-chondrichthyan interactions (e.g. the effects of tourism activities on Chondrichthyan conservation) have emerged (Macdonald et al., 2017; Trave et al., 2017). However, although this research field has not as of yet been distinguished in the term maps, likely due to the lack of sufficient publications and subsequent terms to be incorporated into the maps (in comparison with other research areas), the area is significantly growing and will probable appear in future analysis. A similar situation is expected for the field of public perceptions and education programs on Chondrichthyans (Neff and Hueter, 2013; Neff and Yang, 2013).

Another extensive field of research that has been under constant focus over the 15-year period is the area comprising taxonomy, phylogenetics and phylogeny. Species identification has long been based on morphological features. However, over the past 15 years the emerging
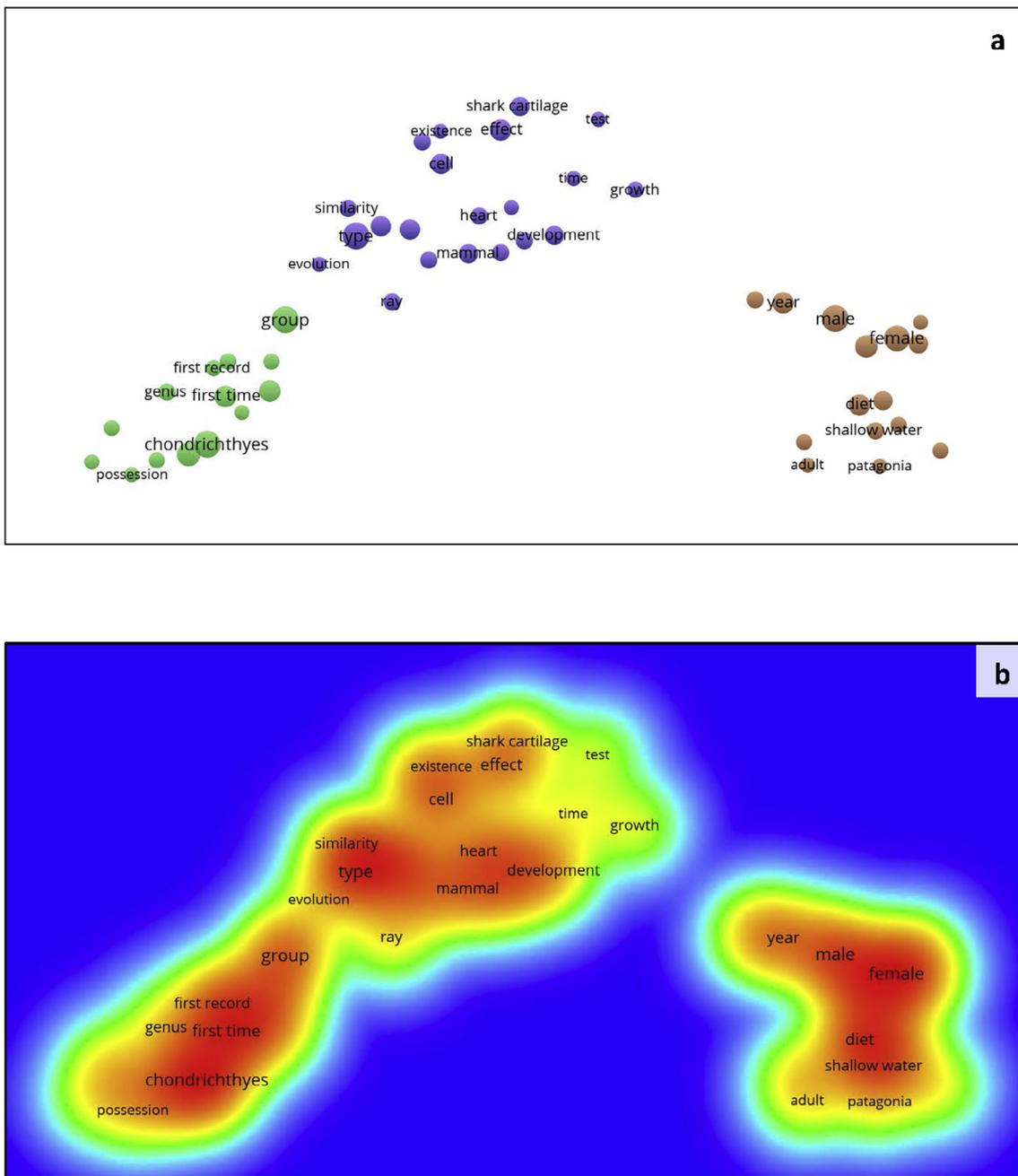
Fig. 10. Network and density visualisation maps based on 51 terms on Chondrichthyan research undertaken in South America from 1967 to 2001. (a) The network visualisation map clustered three research areas linked to diet and reproduction (brown cluster), taxonomy and phylogenetics (green cluster), physiology and biochemistry (blue cluster). (b) The density visualisation map shows similar research effort over the three clustered areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of molecular taxonomy using DNA barcoding methodologies (the use of COI, cytochrome oxidase I, sequences to distinguish species) has gradually evolved to assist with species identification and the improvement of Chondrichthyan biodiversity monitoring programs (Bineesh et al., 2017; Cariani et al., 2017; Feitosa et al., 2018; Ward et al., 2008). This area of DNA barcoding has developed in concert with the area of genomic-based research, including genomics and transcriptomis (Kress and Erickson, 2008). This area has importantly increased in Chondrichthyans, particularly since Elasmobranch and Holocephali genome projects (Venkatesh et al., 2014; Wyffels et al., 2014) were established. This trend is also reflected by the presence of a genomic standalone cluster identified in the 2012–2016 term map. As studies on Chondrichthyan phylogeny, population dynamics, and physiology are

accelerating by genomics, transcriptomic and protein sequence data (Wyffels et al., 2014), this field of research will likely keep expanding.

The field of Chondrichthyan physiology has not received significant attention in comparison with other research areas. However, in the last few years there has been a surge of physiological studies, particularly focusing on Chondrichthyan physiology as a link to understand vertebrate evolution (Payne et al., 2016; Renshaw et al., 2010). Furthermore, following the expansion in Chondrichthyan conservation, there has been a growing trend in integrating physiology to improve management and conservation programs (Brooks et al., 2012; Skomal and Mandelman, 2012; Young et al., 2006).

4.2. South American Chondrichthyan research

One limitation of the current bibliometric analysis is the possibility of have missed some publications, particularly when evaluating South American scientific outputs. This is potentially related to the extent of coverage of the Scopus database resulting in some national journals not indexed in the database. However, this could partially be solved by including multiple databases directed to South American scientific literature (e.g. SciELO, Redalyc) (van Leeuwen et al., 2001; Van Leeuwen et al., 2003). However, for the scope of this study we wanted to compare publication outputs sourced from the same bibliographical database.

By comparing Chondrichthyan publication outputs between South America and the global literature during the overall 2002–2016 period, it is apparent that over time, South America research trends to fluctuate similar, but with delay, to that of the global research endeavours. However, differences are noticed when comparing emerging areas.

By evaluating the more recent 15-year period in South America, three main broad research areas are distinguished: fisheries and life history, diet composition, and taxonomy. Similar to the global trends, the fields of fisheries, population dynamics and life history were hot research topics in South America during the 15-year period. Likewise, terms related to 'conservation' and 'management' have increasingly appeared during the past 10 years, likely linked to the increase of South American Chondrichthyan species being listed on the IUCN red list (Dulvy et al., 2014; Lucifora et al., 2011). Furthermore, studies assessing the use of MPAs (Davidson and Dulvy, 2017; Menni et al., 2009) and the use of movement patterns and habitat utilisation for conservation and management programs are recurrent in South American research (Garla et al., 2006; Hearn et al., 2016). However, the implementation of novel techniques such as BRUV and UVC are yet infrequent and to our knowledge, no papers have been published on eDNA.

The field of diet composition in South America Chondrichthyan research also received significant and constant attention during the 2002–2016 period. However, it was not until the most recent five-year period that the area shifted from publications purely describing Chondrichthyan diet structures to expand to the concept of trophic ecology and its possible role in aquatic conservation (Klarian et al., 2016; Ruiz et al., 2016; Spath et al., 2016). Taxonomy, phylogenetics and phylogeny has also been a constant research focus in South America over the 2002–2016 period, and similar to global research, papers published on DNA barcoding are common (De Astarloa et al., 2008; Ruocco et al., 2012; Serra-Pereira et al., 2011). However, conversely to global research, the field of genomic-based research has not yet evolved in South America.

Finally, the integration of the remaining 35 years (1967–2001) of research in South America confirmed that the areas of reproduction and taxonomy have been long established main fields of research. Interestingly, the area of Chondrichthyan physiology received significant attention during the early years (Araya and Krauskopf, 1976; Dafre and Reischl, 1990; Driedzic and de Almeida-Val, 1996) but not in later years.

4.3. Endocrinology research overview

By looking into the proportion of literature published on Chondrichthyan endocrinology in comparison with other thematic areas, it does become clear that the field of endocrinology does receive the attention of many research groups. Similar as was already reported for the reproductive endocrinology specific area (Awruch, 2013), the lack of research focusing on all aspects of chondrichthyan endocrinology is likely due because this group of fish is of less economic importance than other aquatic vertebrates and because the complexity of maintaining Chondrichthyans in captivity for experimental studies. Nevertheless, the bibliometric exploration of the field of endocrinology

undertaken globally reveals that the area fluctuates comparable to the non-endocrine research trends.

The fields of endocrine reproduction and endocrine vertebrate evolution led the focus of research outputs during the 2002–2016 period. These areas are comparable with the intensive non-endocrine areas of research comprising reproductive studies (Gelsleichter et al., 2002; Hoffmayer et al., 2010; Waltrick et al., 2014) and phylogeny-phylogenetic scientific studies (Adkins-Regan, 2012; Cardoso et al., 2014; Kim et al., 2011). Furthermore, the increase use of hormones as non-lethal tools to assess reproductive parameters are linked with the implementation of Chondrichthyan management and conservation strategies (Awruch et al., 2008; Guida et al., 2017; Hammerschlag and Sulikowski, 2011; Sulikowski et al., 2016). The remaining endocrine fields involving melanocortins (Takahashi et al., 2016), osmoregulation (Yamaguchi et al., 2015), and steroidogenesis (Baker et al., 2015) are consistently small research areas. Moreover, within the steroidogenesis area, studies focusing on the hypothalamus–pituitary–gonadal (HPG) axis are very limited. Thus, although the HPG axis is conserve among vertebrates, the pathways regulating the endocrine control of reproduction in Chondrichthyans remains largely unknown (Awruch, 2013).

When comparing endocrinology research undertaken in South America with the rest of the world, important gaps can be easily identified. From the very low (eight) number of publications in South American during the 50-year period from 1967 to 2016 it may be concluded that endocrinology is not a significant field of research in South America. This result is not surprising, as the field of endocrinology comprises less than 4% of the total research undertaken globally, and of the total number of Chondrichthyan papers published globally, only 11% were originated from South American countries.

5. Conclusions

A key strength of this bibliometric study was an understanding and appreciation of the broader landscape of the Chondrichthyan research literature both globally and more specifically in South America.

South America is formed by developing countries (low and middle income countries) and it has already been shown that there is disparity in the research contribution (measured by scientific publications) from developing countries compared with developed ones (Holmgren and Schnitzer, 2004). Thus, it is unsurprising to observe a delay in the timing of publications undertaken in South America in comparison with global trends mostly influenced by developed countries. The limitation of adequate research funding due to fluctuations in the economic situation and in the investment in scientific research by South American governments and funding agencies, largely affecting the ability and resource to conduct research, is likely to be one of the main explanations regarding this. However, while this is probably part of the problem, it is also important to acknowledge that the majority of publications sourced from South American countries often suffer a lack of visibility within the international mainstream scientific publishing community. This does not necessarily reflect a lack of quality in South American scientific research and subsequent publications, but a symptom of the internationalised publishing system and the dominance of English language journals (Estrada-Mejía and Forero-Pineda, 2010; Vessuri et al., 2014) and highlights some of the challenges that South American and other developing nations face in making research visible to the international scientific community. The international databases (e.g. Scopus, Web of Science by Thomson Reuters) propagate the notion of 'core (or international) journals', journals within a given specialty that are deemed to be the most important and significant ones for that specialty (the most often read and cited). The journals rely on ranking systems based on citation counting such as by the Science Citation Index (SCI) in the 1960s (Beigel et al., 2018). Consequently, journals began to focus on strategies to increase citation patterns and associated metrics. For example, although quality should be the necessary criteria

for inclusion in a peer reviewed journal, it may not be enough for a journal publishing good work from unknown (or lesser known) authors based in unknown institutions as it will not bring prestige to the targeted journal (Vessuri et al., 2014). Further, the so-called Matthew Effect also plays a role whereby eminent scientists get disproportionately greater credit for their scientific contributions when compared with less eminent and relatively unknown scientists, with the latter getting lesser credit for their comparable research contributions (Baldock et al., 2017; Merton, 1968). Thus, independent of the quality of a publication, a high quality publication from developing countries may be passed over. Papers that result from international collaborations have greater impact because they themselves tend to appear in core journals and play a very important role in the worldwide democratisation of knowledge generation in science (Delgado, 2010). However, the limitation in research funding in developing countries also limits the establishment of productive collaboration networks with other countries, particularly with regards to visiting overseas research institutions and attending international conferences This issue is partially evident in Fig. 7, where few international research collaborations were evident for South American authors undertaking Chondrichthyan research. Integrated research programmes and increased support given to established scientists from low-income countries to attend to international conferences would assist in addressing this issue (Huveneers et al., 2015).

Furthermore, it is important to note that English is the international language of science. Many, if not all, South American journals are excluded from international databases, even when such journals are bilingual (published in both the national language and English) (Meneghini and Packer, 2007). As a result, several regional publishing initiatives like Latindex, SciELO, Redalyc have been developed whereby South/Latin American journals are open access and, therefore visible and available to the international community. However, while much can be undertaken to improve access to South American research publications, it will remain of limited value as long as the international scientific community does not embrace the outcomes of such research. Further, scientific endeavours concentrated in developed countries are habitually regarded as excellent (Van Leeuwen et al., 2003). However, excellent science also exists in developing countries and needs to be better integrated with the international community as numerous good quality scientific publications have been invisible due to a lack of accessibility to the international mainstream thereby reinforcing the phenomenon of 'lost or unseen science' in the global literature (Wagner and Wong, 2012).

Although South American countries may never contribute an equitable share to the international scientific community, future Chondrichthyan research and publications would benefit from the contributions of many diverse research groups around the world.

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