Trends in
Parasitology

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Opinion

Evolution of parasitological knowledge: can the past inform the future?

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The growth of scientific knowledge is often likened to the evolution and diversification of life: new disciplines branch off older ones, and subsequently prosper or decline in a manner reminiscent of the expansion or extinction of diverse lineages of organisms. Based on a parallel between evolutionary diversification and knowledge growth, I examine the expansion of subdisciplines within 'ecological and evolutionary parasitology'. Bibliometric data are used to map the rise and fall of subdisciplines over time, capturing historical trends over the past several decades. This historical overview is followed by a critical consideration of its practical applications for decision-making, ranging from rational funding allocation among subdisciplines to whether the collective planning of future research directions is a desirable option.

Highlights

The growth of scientific knowledge and the diversification of research directions over time show striking similarities with the evolutionary history of living organisms.

The rise and fall of subdisciplines within ecological and evolutionary parasitology capture the temporal changes in their respective success, with some subdisciplines appearing headed toward extinction.

Relationships among subdisciplines within ecological and evolutionary parasitology can be mapped as a phylogenetic tree, illustrating the branching diversification of the field in the past few decades.

The historical analysis of the growth of research in this broad area of parasitology leads to reflections about its future, and how the past can inform choices of optimal strategies for the continued expansion of our knowledge.

Knowledge growth as an evolutionary process

Human knowledge is growing at an exponential rate and is now estimated to double every few weeks or months, if not faster[i]. Scientific knowledge is nearly keeping pace [1]. Beyond the accelerating speed at which it is accumulating, much has been written about the growth of scientific knowledge [2–6]. Philosophers of science have often drawn parallels between the growth of scientific knowledge and the evolution of life [7,8], a theory known as evolutionary **epistemology** (see Glossary). The similarities arise from the ways in which both knowledge and biological diversity grow over time via a branching pattern, with different branches related to each other through a shared genealogy, each expanding at its own rate over time, and some dying out (Box 1).

Beyond the philosophical and epistemological arguments in support of or against the parallel between the growth of knowledge and organismal evolution, the notion at least suggests approaches to map the temporal expansion of research directions within particular disciplines as a window into the history of those disciplines. For instance, significant new lines of inquiry can be connected by descent from a common ancestral subdiscipline. The **epistemic** relatedness or divergence among subdisciplines can be quantified, just as the genetic relatedness between lineages of organisms. The expanding number of new questions being investigated that originate from the same ancestral subdiscipline (number of branching events), or the relative research effort devoted to these questions, can provide a measure of the success of each new subdiscipline.

Here, I argue that the pattern of growth in our parasitological knowledge follows that of organic evolution. Subdisciplines rise and fall over time in a process akin to **speciation** and extinction of lineages in the tree of life. First, I use bibliometric data on studies broadly falling under the umbrella of 'ecological and evolutionary parasitology' to illustrate the historical patterns of research and knowledge growth in this field. In broad terms, ecological and evolutionary parasitology includes subdisciplines that study interactions between parasites, between parasites and hosts, and between parasites and the nonliving environment which determine the abundance and diversity of parasites at all spatial and temporal scales. The history of research in this broad area has

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Box 1. Evolving scientific knowledge

For the sake of brevity, the following parallel between the evolution of life and the growth of scientific knowledge is a greatly simplified sketch; for a comprehensive account, the reader is referred to classical philosophical discussions on the topic ranging from Kuhn [2] to Haufe [6].

Knowledge expands through time in a branching pattern similar to the phylogenetic diversification of taxa [6], and is occasionally punctuated by scientific revolutions: breakthroughs, game-changing ideas or new and rapidly accepted practices leading to paradigm shifts, which are somewhat reminiscent of key innovations, adaptive radiations and associated extinctions in macroevolutionary history [2]. New subdisciplines arise regularly through a speciation-like process, whereas major new disciplines generally emerge only during paradigm shifts. Overall, science tends to move inexorably toward greater specialization, that is, an increasing number of subdisciplines and/or phenomena under investigation, comparable to the diversification of clades within the tree of life into multiple species with narrow niches [6].

On short time scales, new research directions either flourish or perish through a process of selection akin to Darwinian natural selection. Research subdisciplines that attract more researchers and funding because of their power to generate results or because of their relevance to current social or cultural trends, tend to grow faster than other subdisciplines, just as genotypes that are best suited to current environmental conditions leave more descendants. In particular, funding is a key limiting resource in the competitive research ecosystem, and acquisition of funding determines which subdisciplines prosper [44]. The exchange of ideas across subdisciplines (interdisciplinary research) is more likely to lead to fruitful advances than the flow of genes across hybrid zones [45]. However, exchange of ideas can be limited by isolating mechanisms between subdisciplines, such as researchers attending conferences and reading journals only within their specific areas, just as allopatric divergence resulting from barriers to gene flow occurs during speciation. Also, scientists within subdisciplines generally adhere to certain views and norms that can maintain the subdiscipline's cross-generation stability (passing from mentors to protégés). Indeed, once achieved, scientific consensus and approved practices, just like the fixation of beneficial alleles in natural populations, tend to transmit unchanged down generations of scientists. Yet the topical questions driving research do change over time, and thus modified practices that are adaptive, i.e. that work better at solving current problems, can be 'selected for' and propagated from one generation to the next [6].

been reviewed qualitatively before [9]; here it is examined quantitatively. I then propose how tracking the evolutionary trajectories of research subdisciplines can have practical applications for decision-making and the future growth of the field.

The rise and fall of parasitological subdisciplines

Whether or not it follows a process akin to the evolution of life, scientific knowledge grows and diversifies over time. As one of its most concrete and measurable outputs, peer-reviewed scientific publications provide a means to track its overall growth as well as the temporal changes in the popularity of particular research topics and/or productivity of various disciplines [10]. Indeed, annual numbers of publications are often used as a measure of the past temporal dynamics of research activity and progress in any given field [11]. As a parallel with evolutionary biology, this is akin to using genomic data [12] or paleontological evidence [13] to infer the historical demography or ecological success of particular lineages over time, as past population expansions and bottlenecks are captured by fossils and genes.

Using a search of the parasitological literature (see the supplemental information online), we can use publication data to track the rise and fall of different subdisciplines within ecological and evolutionary parasitology since 1980 (Figure 1), a time when research in this field really took off [9]. There has been a general rise in the number of publications over the four decades covered here, in line with the recent exponential increase in scientific productivity. Here I assume that the information content of individual articles has remained the same over time, such that their annual numbers capture knowledge growth. The different subdisciplines did not all arise at the same time, and they achieved their peak popularity or productivity at different times. In some cases, the underlying reasons for the temporal dynamics are unclear. For example, research in parasite taxonomy is possibly the oldest of subdisciplines in all of parasitology. Its output has increased in the early 2000s and remained mostly high ever since. This is wonderful but also surprising given the evidence that funding opportunities for taxonomical research are dwindling [14] and that

Glossary

AlphaFold: artificial intelligence model, developed by Google DeepMind and currently in its third version, using deep learning to predict the three-dimensional structure of, and interactions among, proteins and other macromolecules.
Artificial intelligence: ability of computer systems to perform tasks normally requiring human intelligence (e.g., speech recognition, visual perception, decision-making) at speeds and on scales vastly exceeding human capabilities.
CRISPR/Cas9: clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR-associated protein 9 (Cas9), a gene-editing technology adapted from a naturally occurring immune defence that bacteria use against viruses; it consists of a piece of RNA guiding an endonuclease to cut the double-stranded DNA at a specific location in the genome so that bits of DNA can be added or removed.
Epistemic: relating to knowledge.
Epistemology: the theory of human knowledge, encompassing its nature, origin, methods, validity, and scope.
Infracommunity: assemblage of all parasite individuals of different species infecting the same individual host.
Infrapopulation: all individuals of the same parasite species infecting the same individual host.
Intelligent design: pseudoscientific argument for the existence of a divine designer guiding the evolution of complex organisms.
Phylogeny: reconstruction of the evolutionary history and relationships between lineages of organisms, typically illustrated as a branching tree.
Sister species: species most closely related to each other, issued from a recent common ancestor.
Speciation: the formation of new species through genetic divergence in the course of evolution, depicted as a branching event in a phylogenetic tree.
Topology: the branching structure of a phylogenetic tree from its root to the tip of its branches, capturing the evolutionary relatedness among lineages and species.

Figure 1. Waxing and waning of subdisciplines over time. Temporal rise and fall in research activity within different subdisciplines of ecological and evolutionary parasitology. The data represent percentages of the total number of articles published in a particular subdiscipline that appeared in each 5-year period, providing relative estimates of growth or decline in research accounting for differences in the overall volume of research published among subdisciplines. For definitions of the subdisciplines and details of the literature search, see the supplemental information online.

taxonomic expertise is disappearing as the most prolific researchers in this area are mostly all in their late career [15]. The lack of continued growth in this area may indicate, as an analogy to natural systems, that it has reached the carrying capacity of the current scientific environment. The same may apply to other subdisciplines, such as research into host–parasite coevolution and virulence. In other cases, the temporal dynamics of subdisciplines follows the pattern we might expect. For instance, the rise in research on parasite phylogeography and phylogenetics followed the widespread adoption of molecular methods combined with a drop in their cost [16]. Similarly, the expansion of research into host–parasite cophylogeny, although tracing its origins over a century ago [17], was spurred by the advent of simple computational tools allowing objective testing [18,19]. In other cases, global concerns shared by the entire scientific community and society at large in the past couple of decades, such as the impacts of climate change and biological invasions on natural ecosystems, have fuelled research on these topics by ecological parasitologists.

At the same time, this look at temporal dynamics based on publication data reveals some subdisciplines that seem headed toward extinction (Figure 1). In nature, extinction is forever; when a species dies out, its ecological activities cease and its unique genetic information goes out of circulation. When scientific subdisciplines die out, however, the knowledge they have produced remains stored in the literature and is thus retrievable in future as a foundation for further research. Investigations on the population biology of parasites and on the within-host interactions between parasites that determine the abundance of **infrapopulations** or the diversity of **infracommunities**, once thriving research areas [20,21], seem to be slowly dying out. This may simply reflect a recent drop in their popularity as subjects for research projects among parasitologists, because it is unlikely that all questions in these subdisciplines have been satisfactorily answered. Most likely, the appeal of new questions arising from methodological advances, such as the advent of cheap molecular tools, is the reason why traditional lines of enquiry have been set aside. The drivers underlying the rise and fall in productivity among subdisciplines are therefore varied, ranging from the development of new technologies to possible bandwagon effects started by genuine societal concerns.

Epistemic relatedness among subdisciplines

The subdisciplines in Figure 1 are not independent of each other: they are related to some degree with one another. Among living organisms, we have long identified **sister species** and determined the level of relatedness between any pair of species by quantifying the number of DNA base pair differences in their gene sequences [22,23], as these differences accumulate over time by random mutations following the species' initial divergence. Similarly, articles that crop up when keywords associated with two different subdisciplines are combined and used for a literature search are those that touch upon both subdisciplines (see the supplemental information online). The greater the number of such articles relative to the total obtained when the two subdisciplines are considered separately, the greater the shared conceptual basis and thus the relatedness of these subdisciplines.

The degree of overlap, or relatedness, between pairs of subdisciplines based on this bibliometric data is generally low (Figure 2). Nevertheless, some obvious and unsurprising patterns emerge from this exercise. In particular, subdisciplines of a more evolutionary nature, which address questions best resolved using molecular data and processes occurring over longer time scales, tend to show higher levels of overlap. Similarly, subdisciplines of a more ecological nature generally show greater overlap with each other. Although the use of bibliometric data confirms what we already knew, it does provide a quantitative basis to reconstruct an evolutionary history of the growth of research and knowledge in this large branch of parasitology.

A phylogenetic tree of ecological parasitology

There have been attempts to build historical connections among scientists, or genealogies, organised as evolutionary trees[ii], and how a genealogy of mentorship can explain the success of individual researchers [24]. Here, I instead attempt to produce a **phylogeny** of parasitological subdisciplines, in which new subdisciplines arise from older ones in a process akin to speciation to produce a branching tree that captures the diversification of research questions over time.

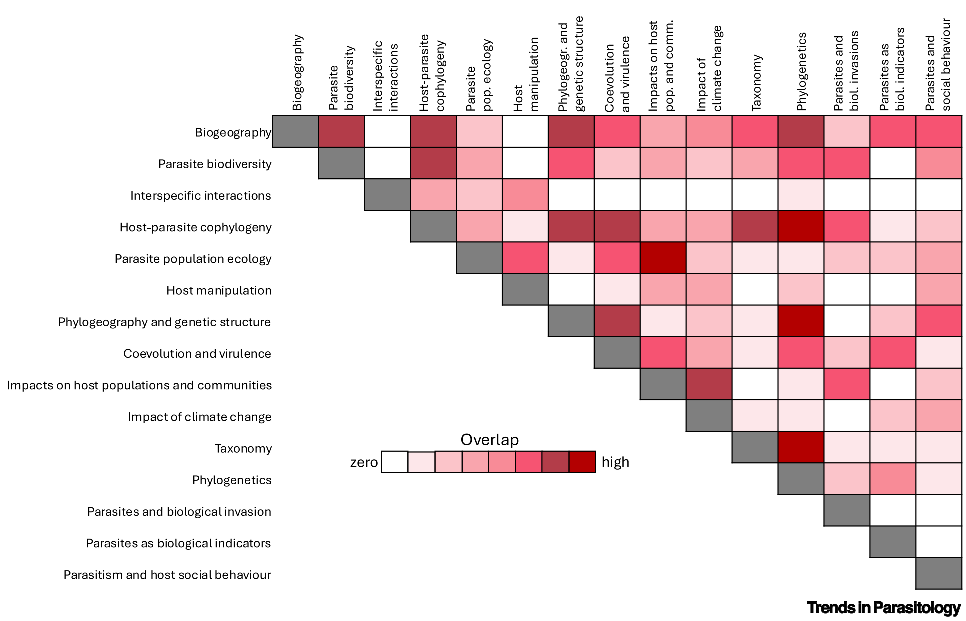

Figure 2. Relatedness among subdisciplines. Pairwise 'epistemic' distances among subdisciplines of ecological and evolutionary parasitology. The data represent overlap between subdisciplines, measured as the percentage of articles shared between two subdisciplines across the entire 1980–2024 period. For details of how search strings were combined for the literature search see the supplemental information online.

Phylogenies of living organisms have a **topology** based on genetic similarities among lineages with the timing of branching events ideally calibrated with dated fossil remains. By extension, similarities between subdisciplines and historical data on their date of emergence can be used to construct a phylogeny of parasitological research. Using information from Figure 1 showing when each subdiscipline became well-established, data from Figure 2 on the conceptual (epistemic) relatedness of subdisciplines, and a solid dose of personal judgement, a rough phylogeny of research in ecological and evolutionary parasitology can be proposed (Figure 3, Key figure). Although this phylogeny should be seen as a hypothesis, it suggests unequal diversification over time, with more subdisciplines arising in the 1990s than in other decades. Some branches may disappear in coming years, as some subdisciplines, such as the study of interspecific interactions among parasites (as defined in the supplemental information online), have been in decline in recent years.

In science generally, the birth of new subdisciplines from a parent subdiscipline becomes more likely over time, as the number of unsolved problems or unexplored exciting ideas in the parent subdiscipline decreases exponentially over time, causing an exodus of researchers with a general skillset toward completely new research areas [6]. After arising by branching or fission of older ones, new subdisciplines then evolve as independent entities and tend to achieve their highest growth rates in their early stages [25]. In the past few years, for instance, booming research into parasite conservation biology [26,27] and parasite microbiomes [28,29] suggests that these are in the process of branching out as distinct new subdisciplines.

Key figure

Phylogeny of ecological parasitology

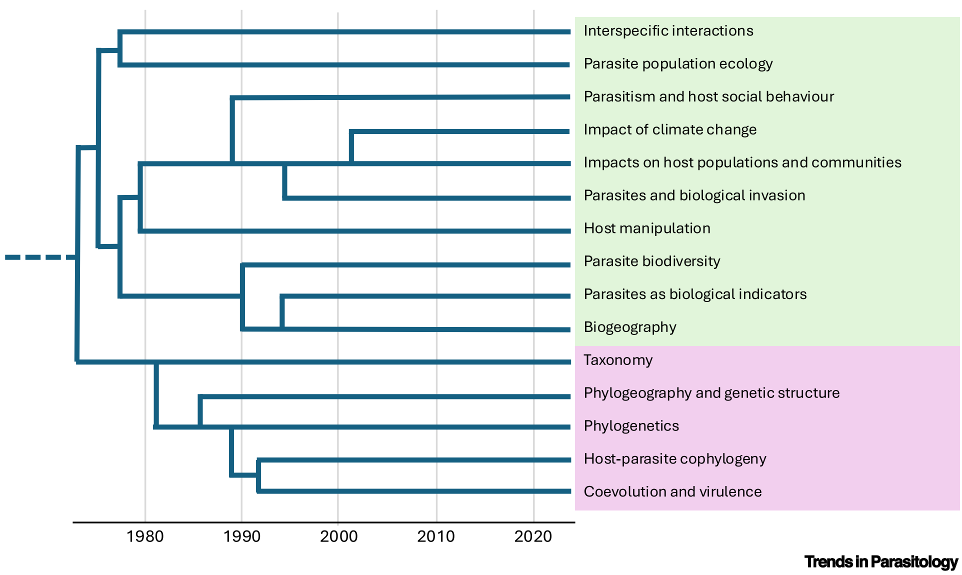

Figure 3. Growth of research in ecological and evolutionary parasitology shown as a branching tree of diversifying subdisciplines. Branching topology roughly reflects the similarity between topics (based on Figure 2), whereas the timing of branching reflects the approximate first increase in research activity of the 'youngest' of two related subdisciplines (based on Figure 1). Pre-1980 branching patterns based on the author's personal interpretation. Ecological subdisciplines (green shading) and evolutionary subdisciplines (pink shading) are highlighted.

Different kinds of factors can trigger branching events. Major new research directions sometimes arise following the publication of 'disruptive' ideas that revolutionise earlier theoretical frameworks, though these new ideas may take years to make their impact [30], and the proportion of publications proposing disruptive ideas has declined in recent years [31,32]. New discoveries and technologies coming out of left field can also spur research in particular subdisciplines; they can even open up new niches and promote the rise of new subdisciplines, that is, by providing new tools to address novel questions [33]. This can be seen in the impact of **CRISPR/Cas9** on genetic engineering and biotechnology [34], **AlphaFold** on structural biology [35], and **artificial intelligence** on integrative, multi-disciplinary biological research [36]. It is therefore difficult to anticipate the future diversification and advances in any field of research.

Concluding remarks

Here I proposed that the growth of parasitological knowledge follows a pattern akin to organic evolution, with the distinction that, unlike the genes of extinct species, the knowledge produced by deceased subdisciplines remains accessible through libraries and online repositories. This essay is based on bibliometric data assumed to capture the rise and fall of various subdisciplines of ecological and evolutionary parasitology, and thus the temporal dynamics of their success. But what is a successful research area, really? There are several ways of defining success for research disciplines [37,38], some with a clear biological equivalent. For instance, a successful discipline can be one that persists as an active research area for a long time, just as successful biological lineages have extended evolutionary longevity. A successful discipline can be one that spawns many new subdisciplines, similar to diversification rate being used as a measure of the success of different plant and animal lineages. Or the number of researchers working in a particular subdiscipline can be used as a measure of its success, just as successful species have large global population sizes. The true measure of a scientific subdiscipline's success, however, should be the number of key questions it answers and its contribution to knowledge advance. The use of publication numbers to quantify the growth and success of various subdisciplines in the previous sections is therefore not ideal: more publications does not always mean more knowledge, as not all publications have the same information content. This was chosen as a compromise between data availability and the likelihood that these numbers capture some of the better metrics mentioned above.

It is challenging to identify distinct disciplines within a broader field; other researchers studying evolutionary and ecological parasitology would no doubt subdivide the field differently than the way I have done here. Nevertheless, the main conclusions would be the same: (i) the broader discipline branches out over time into many subdisciplines, filling new niches as they appear; (ii) just as evolutionary lineages prosper and eventually go extinct, the output of different disciplines rises and falls over time; (iii) conceptual relatedness among subdisciplines links the timing of their rise; and (iv) the diversification of scientific research and the success of each branch show parallels with the evolutionary history of organic life.

The study of the historical growth of scientific concepts and knowledge, and what it can teach us, have generally been the domain of philosophers [6,39,40]. Historical reconstructions of the growth of scientific research and the expansion of our knowledge can raise as many questions as they answer (see Outstanding questions). Yet there are practical applications coming from an examination of how scientific disciplines have grown, diversified and sometimes declined over time, applications of immediate concerns for practitioners of science. It is an opportunity to take stock of the state of the entire field, using the recent past to plan the future. An analysis such as the one presented here can identify research areas that have fallen into neglect, at least as indicated by publication output. One could argue that, in an ideal world, allocation of

Outstanding questions

When subdisciplines are dying out, that is, when the publication output in a branch of research shows a drop, how much is this due to the retirement of one or a few influential researchers?

When subdisciplines are expanding, that is, showing an increase in the volume of research published, how much is this due to a few influential or charismatic researchers attracting a disproportionate amount of funding and/or students? How much is this skewing research effort in directions which may not be objectively the best for knowledge growth?

How much does the volume of publications in a discipline truly capture the actual quantity of real knowledge they contribute? How do we quantify knowledge itself?

Should the research community come to a collective agreement about which research directions are the most fruitful to pursue, and which should be abandoned after having yielded all the knowledge they had to give? Or should these decisions be left to individuals?

How can we best ensure that knowledge survives, that is, remains relevant, understandable, inspirational, and accessible for future generations of researchers, even if a subdiscipline heads toward extinction?

Should future research be primarily method-driven (shifting to take advantage of novel technological breakthroughs as they appear) or concept-driven (remaining focused on answering 'big' questions rather than applying the latest research tool to answer secondary questions)?

funding and resources should be optimised such that more are directed toward promising research directions, to maximise the generation of new knowledge. In the same vein, graduate students and early-career researchers could be encouraged to pursue research aligned with the most (at the time) promising research subdisciplines. However, research areas that have fallen into neglect may not yet have provided answers to fundamental questions, and underfunding them may not be beneficial to progress. As a case in point, the enthusiastic adoption of molecular methods by parasitologists has resulted in some classical research areas being put aside [41], a situation that we may come to regret.

In the evolution of life, natural selection favours individuals that are better at leaving descendants, and higher-level selection favours lineages that are better at persisting and diversifying over time. There is no forward planning, selection acts without foresight. If the growth of science parallels organic evolution, then this would translate into the scientific community favouring subdisciplines that are successful in terms of active researchers, total funding received, and publications. Indeed, in some scientific fields, evidence shows that researchers stick to conservative, traditional research choices that perpetuate the success of already successful subdisciplines, without leading to ground-breaking advances [42,43]. This is not necessarily the best approach for knowledge growth in parasitology or any other field. Perhaps some branches of the scientific research tree are prevented from going extinct well past their use-by date, whereas others that are on the brink of extinction should receive more support if an objective assessment indicates they have more to offer. We have to ask ourselves whether it is desirable to exert some level of 'control' (just a little) over the future directions of research, based on objective guiding principles, or let this happen organically and a little haphazardly, as it has often in the past. I would suggest that general discussions at major international conferences and/or open online forums may be the best way for the research community to seek a consensus regarding where we should most productively invest time, efforts and money. In the evolution of life, **intelligent design** makes no sense whatsoever, however in the evolution of scientific knowledge a modest dose of its equivalent would perhaps not be completely unreasonable.

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Declaration of interests

The author has no conflict of interest to declare.

Resources

[i]www.industrytap.com/knowledge-doubling-every-12-months-soon-to-be-every-12-hours/3950

[ii]https://academictree.org/

Supplemental information

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