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This new section of the ***Bulletin*** will include articles about the practice of ecology: conceptual approaches, new methods and techniques, recent advances in related disciplines. Please contact the ***Bulletin*** Editor with your ideas for future articles.

The use of hypotheses in ecology

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Scientists ask, and then try to answer research questions aimed at furthering science - "that branch of knowledge conducted on objective principles involving the systematised observation of, and experimentation with, phenomena" (Pearsall & Trumble, 1996). The term 'science' encompasses a wide range of disciplines, and implies that there must be some common conceptual framework underlying the full range of activities from the physical through to the ecological sciences.

Charles Darwin is reputed once to have been asked whether he thought natural historians should go out and collect data without the prejudice of a preformed hypothesis, or whether they should observe nature with a particular theory in mind (Hurst, 2003). Darwin was unusually emphatic in his reply. If they did not have a hypothesis, he wrote to his friend the economist Henry Fawcett, they may as well "go into a gravel-pit and count the pebbles and describe the colours" (Darwin, 1903).

The empirical testing of hypotheses is considered by some as the 'criterion of demarcation' that distinguishes science from other forms of knowledge (Ayala, 1994). A hypothesis is a "supposition made as a starting point for further investigation from known facts" (Pearsall & Trumble, 1996). Since a hypothesis is aimed at generating new scientific knowledge, it should be novel and contain a testable prediction. In the field of ecology, there is considerable debate about the relevance and importance of hypotheses in the generation of new knowledge. In particular, several ecologists suggest that hypothesis-driven research is currently constraining the essential integration necessary to develop major new understanding and higher-level theory in ecology (Pickett *et al.*, 1994; Shrader-Frechette & McCoy, 1993). Others argue that ecology is a 'weak science' precisely because it has failed to adopt consistently a predictive, hypothesis-driven research method (Peters, 1991). This debate notwithstanding, many empirical ecologists recognise that hypotheses are at least implicit within their research questions. In some cases, however, their research proceeds without going through the process of clearly *articulating* those hypotheses. Furthermore, in many cases authors do not explicitly state their hypotheses in their research outputs – their publications. Here, I argue that the use of *explicit* hypotheses in the development and publication of ecological research is a means of maximising the effectiveness of that research.

The hypothesis-driven research process

The use of explicit hypotheses in scientific research compels the scientist to articulate a precise description of the research question he or she is focussed on addressing. Initial hypothesis generation is the most creative and imaginative element within research (Ayala, 1994), relying on intuition as well as a thorough review of the knowledge base within the topic area. An essential criterion of a good research hypothesis is that testing it will lead to new knowledge, and therefore its development usually requires a deep understanding of the existing relevant knowledge base. Even if the generated hypothesis represents a strikingly novel 'paradigm shift' (Kuhn, 1962), it is unlikely to arise without a sound background knowledge of the research topic in question, and an analysis of the anomalies contained within that knowledge.

Development and refinement of the precise wording of the hypothesis is often necessary as the researcher contemplates its logic and associated assumptions, as well as the resources, appropriate statistical design and methodological practicalities associated with testing it. In particular, recognition and evaluation of inherent assumptions or 'methodological value judgements' (Shrader-Frechette & McCoy, 1993) is absolutely critical to the quality of hypothesis-driven research. The process of initial hypothesis generation, literature review, methodological considerations, and further refinement (or even replacement) of the hypothesis is iterative (Fig. 1), and may pass through several cycles before a valid and precise focussed hypothesis is reached. This thinking stage is perhaps the most difficult phase, and certainly the one with which graduate students (and many scientists including myself) struggle with most. Nevertheless, the more thought and effort invested at this initial stage, the more effective the experiment or other test of that hypothesis is likely to be.

Once an innovative and testable hypothesis has been developed, the processes of experimentation (or other approaches to testing such as modelling or surveying) and subsequent data analyses and write-up can take place (Fig. 1). The efficiency of these latter processes is markedly enhanced by the *a priori* development of a clearly stated and focussed research hypothesis, combined with recognition of the logical assumptions and methodological constraints that should be inherent within it. Furthermore, often during the data interpretation or write-up stage, additional reflection and evaluation of the data may indicate to the scientist (or to a manuscript reviewer) that the test did not reflect the hypothesis as well as it might have. In such cases, further refinement or editing of the hypothesis statement should be made so that the final research output – the peer-reviewed publication – is as accurate and accessible to others as possible.

In essence, I assert that in addition to Darwin's assignation that pre-formulated hypotheses should drive data collection, hypotheses should also drive the knowledge dissemination and peer evaluation processes. In order for understanding and communication of newly generated knowledge arising from research to be of greatest benefit, the end goal of the research process should be an output (peer-reviewed publication or thesis chapter) that reports: (i) a hypothesis that was fully tested by the described experiment, model or survey; (ii) an interpretation of that test that relates directly to the hypothesis; and (iii) a conclusion that places the hypothesis test results in the context of current theory and knowledge.

Viewed in this way, there are several important cyclical elements within the research process leading to new scientific knowledge. The phases of hypothesis generation, literature review, and methodological considerations (circular arrow 'a' in Fig. 1) usually involve iterative cycles. This process leading up to the development of a workable research hypothesis is analogous to travelling up a spiral staircase in a multi-storey building where as one ascends, one repeatedly passes through a series of areal sectors between floor levels (e.g. North, West, South and East), before stepping off at the destination level. Critical evaluation of the data in relation to the initial research hypothesis may often lead to revision of the latter so that it more accurately reflects what was actually tested in the experiment or survey (circular arrow 'b' in Fig. 1). Ultimately, new knowledge is developed through iterative cycles of hypothesis-driven results that inspire further research ideas or questions (circular arrow 'c' in Fig. 1).

Multiple and null hypotheses

Multiple and Null hypotheses are related, but have different functions in scientific research. In speculating on an answer to an initial research question, multiple explanations (research hypotheses) can often be generated. This is a very useful 'brain-storming' process that can help identify and explore a range of possible explanations or answers for the phenomenon of interest. The practice of developing and testing multiple working hypotheses has long been recognised as promoting effectiveness and objectivity in science (Chamberlin, 1890). These multiple research hypotheses give rise to multiple separate experiments. New knowledge and understanding may be generated by testing the validity of each research hypothesis in turn, and eliminating those that are rejected (Popper, 1959). This falsification process is analogous to pruning back unwanted branches within a tree, whereby the investigator 'trims away' the false hypotheses to get closer to the most likely explanation for the phenomenon under observation. The logic of falsification is that new knowledge arises by eliminating false hypotheses, rather than proving the 'true' one. Thus, science progresses, and gets closer to final answers, by eliminating possible alternative explanations. The falsification approach is essential because it is not possible to prove something absolutely, beyond all doubt (Popper, 1959). For example, researchers cannot preclude the possibility that exceptions to their results may come to light in the future, or that new paradigms may replace the whole framework of knowledge on which the original hypotheses

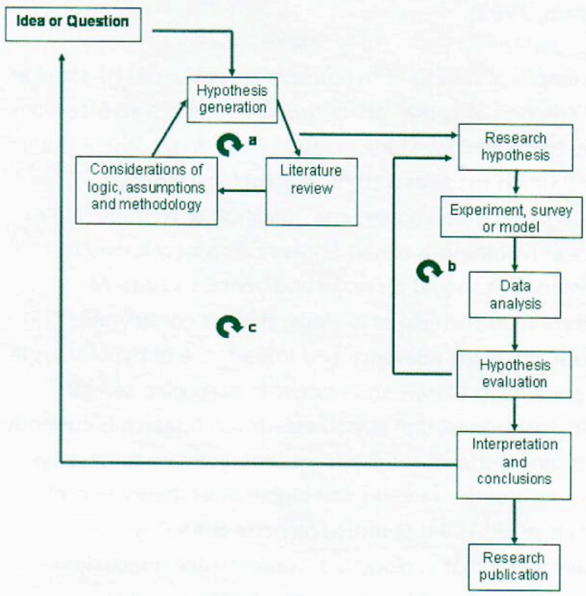

Fig. 1. The scientific research process, and the various cyclical elements within it.

were formed. Successive cycles of new hypothesis generation and falsification in knowledge generation are analogous to trimming a tree whilst climbing it – a 'logical tree' that retains only the essential 'truths' which explain some pattern in nature (Platt, 1964).

A similar logic is used in the individual experimental or validation tests of each research hypothesis. Hypothesis testing often involves collection of quantitative data, and the use of statistics. In this case, the hypothesis that is tested is not the research hypothesis, but rather its logical opposite – the Null hypothesis. The aim of the statistical test is to reject the Null hypothesis, meaning that its logical opposite – the research hypothesis – is likely true. Note that, in statistical testing of hypotheses, only two alternatives are possible and hence the research hypothesis must be framed so that it has a clear logical opposite that can be tested experimentally or by some other means. The binary nature of the Null hypothesis approach can present substantial limitations in ecological research and result in the testing of 'straw men' (Anderson *et al.*, 2000). In response, an application of likelihood theory has been developed that allows for statistical evaluation of a set of alternative research hypotheses (Anderson *et al.*, 2000). In any statistical test, a research hypothesis must be expressed at a high level of precision and detail. Research thinking and practice at this level are required fundamentally, but ecologists and other scientists need to exercise considerable balance and perspective in *reporting* their hypotheses. Otherwise, they run the risk of losing their audience in dull, circumstantial and lengthy text (Lawton, 1994). Therefore, the reported hypotheses in research publication outputs (and research development documents such as grant proposals) must strike a difficult balance between specific detail in relation to a particular experiment and general context in relation to the major unsolved problems of their science.

The appropriateness of hypothesis-driven research to different scientific disciplines

In many senses, the logical and analytical development and articulation of a precise statement encapsulating one's research focus is the very essence of the research process. This should be true for any branch of science. Furthermore, the precise articulation of the research focus is essential to communicating effectively that science to others (either for peer-review evaluation, or for dissemination). Certain branches of science (e.g., molecular biology and high energy physics) have apparently made much more rapid progress than others because of the systematic and rigorous application of repeated cycles of hypothesis generation and testing – 'Strong Inference' (Platt, 1964). I suggest that in comparing different scientific disciplines, what is at issue is how far up the 'precision hierarchy' one can reasonably go in the use of hypotheses for investigation. All research investigations should start with a general question, objective or hypothesis. The essential issue is the extent to which these can then be dissected into progressively smaller and more specific sub-questions, sub-objectives or sub-hypotheses.

In some branches of ecology, such as those that incorporate social and economic influences or that are concerned with the development of unifying theory, the rigorous push towards the level of precision required to develop research hypotheses may be inappropriate (Pickett *et al.*, 1994; Shrader-Frechette & McCoy, 1993). Furthermore, testing of some hypotheses may be impossible because of cultural, ethical or economic constraints. For other sciences, there may be logical as well as spatial or temporal constraints on evaluating large-scale integrating hypotheses (e.g., the Gaia hypothesis (Lovelock, 1987) in Earth Systems Science). Systems modellers (and experimenters) are often constrained in hypothesis generation by a lack of sufficient knowledge on the interactions between processes contained within their models. Nevertheless, hypotheses on the model outputs can be generated and tested through validation using recorded data or experimental manipulations, albeit often with spatial and temporal constraints. In some of the very new and highly integrative branches of ecology such as the 'adaptive cycles' and 'complex adaptive systems' approaches in ecosystem ecology, it may be most effective to relax the testability criterion at this time. Emphasis is placed on the *generation* of plausible multiple hypotheses (Holling & Allen, 2002), which themselves become the research 'output' that can be evaluated by others.

All scientific research should share a common drive to reach the highest attainable levels of accuracy in articulating explicitly the research focus *and* the research results. Whether the final form is a hypothesis, a specific research question or an objective will depend on the nature of the discipline. Where less detailed levels of precision have been adopted, it seems important that the researcher has at least fully contemplated the rationale for, and implications of, this choice.

Current patterns in use of explicit hypotheses in ecological research

Some of the leading national science funding agencies (e.g., National Science Foundation in the U.S., Natural Environment Research Council in the U.K.) specify in their guidelines to proposers that they expect to find explicit hypotheses in submitted research proposals, and rate proposals in part according to the quality of those hypotheses. For these agencies - which together support a wide range of ecological and environmental science research - the use of explicit hypotheses *is* a means of optimising the effectiveness of that research. Nevertheless, despite the apparent benefits of investing thought and effort in developing and articulating precise hypotheses in the scientific research process, many authors do not explicitly state hypotheses in their research outputs – their publications (Fig. 2). A preliminary survey of the Introduction sections of primary research papers in ecological journals suggests that slightly less than half contain explicitly stated hypotheses or predictions (Fig. 2). Almost 15% of papers examined contained nothing more than a single statement indicating the broad aim of the study. In this age of rapidly increasing volumes of published scientific information, such studies do not serve the deluged reader well.

Why do so many ecologists not explicitly state their hypotheses in their publications? Perhaps most researchers do go through the hypothesis-driven research process as described above, but then choose to report their results in a more general way that may appeal more to journal editors and a broad range of readers. A brief survey of the 'Instructions to Authors' for the leading ecological journals reporting primary research data indicates that only very few (< 5 %) even contain the words 'hypothesis' or 'specific objective', suggesting that many editors do not require or even encourage the use of explicit hypotheses. Those journals that are more precise on this issue tend to be the more prestigious in terms of Institute of Scientific Information 'impact factors'. The relatively new journal *Ecology Letters* had the highest percent increase in total citations in the field of ecology/environment for 2002-2003 (http://www.in-cites.com/journals/EcologyLetters.html), and is the only ecological journal I found that had a clear and definitive statement in its 'Instructions to Authors' to the effect: "...priority will be given to those papers exploring or testing clearly stated hypotheses". This same journal was the only one in my survey (Fig. 2) in which every paper contained a clear set of hypotheses or predictions, whilst the other journals had 50 % or fewer in this category.

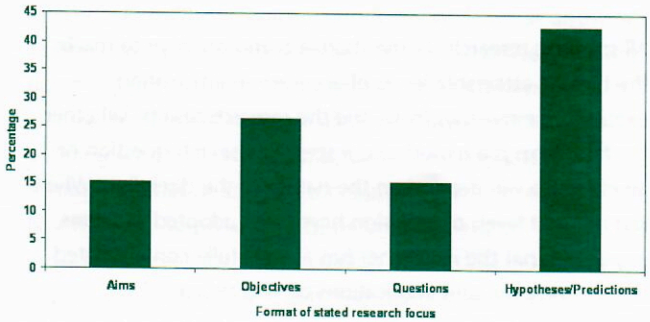

Fig. 2. Relative frequencies of different formats used to state the research focus of studies reported in a selection of recent ecological science journals. The formats are differentiated into categories of increasing specificity and detail from left to right. These percentage data are based on a survey of all primary research papers (n=98) in the 2004 first issues of the following journals: Ecology; Ecology Letters; Ecosystems; Microbial Ecology; Oikos; Journal of Ecology; Ecoscience.

Several other possibilities may explain why most scientific research publications in ecology do not contain explicitly stated hypotheses. The potential benefits of hypothesis-driven research described above may be more apparent than real for many researchers. Such scientists may deliberately choose to avoid the rigours imposed by the precision that is inherent in hypotheses, and opt instead for a less constricting approach centred on research questions or research objectives. Others may have found alternative methods that better suit them, or that are more effective for their particular branch of ecology. Whatever the reason, it is striking that whilst so many ecologists are familiar with the process of hypothesis-driven research (Fig. 1), and presumably instil it as fundamental core training for graduate and undergraduate students, less than half use it explicitly in publishing their research results.

Conclusions

All scientific researchers presumably strive for the highest attainable levels of precision in articulating explicitly their research goals *and* their research results. The use of hypotheses compels a scientist to articulate clearly and precisely the focus of his/her research. The hypothesis generation and testing framework (Fig. 1) provides a very effective means of conducting, evaluating and communicating research. This framework is strongly favoured by some of the world's leading science funding agencies, and seems to have been the method of many of the world's greatest scientists, past and present (Ayala, 1994). Although some ecologists may dissent when it comes to the utilisation of explicit hypotheses in the development of their research and many do not report hypotheses in their publications, it seems that we have yet to identify an alternative approach that would provide an even more effective method for most kinds of ecological research. Therefore, I conclude that the hypothesis-driven research process outlined here is as close as we've got to a common conceptual framework underlying the sciences. If so, it seems that graduate and undergraduate students of all scientific disciplines should receive basic training in it, and that ecologists in particular need to strive harder to adopt the hypothesis framework for the development and articulation of their research ideas, as well as the formulation of their ensuing publications.

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