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A Woodland Research Strategy based on Mathematics and Computers

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1. Introduction

Traditionally, in Britain, scientific research is conducted by allowing the individual scientist to select his own topics for research from within a broad field of interest, and to develop his own methods of investigation. Great emphasis is usually given by scientists to the need for freedom to follow their ideas, wherever these ideas may lead, and to use whatever methods that may seem appropriate at the time. While no-one would quarrel with this general thesis as a philosophy, the cost of scientific research has increased very greatly over the last few decades, not only because of the increasing numbers of scientists and supporting staff employed, but also because of the increasing complexity of the research itself, and the costs of the equipment and materials involved. The tax-payer is, therefore, faced with an ever-increasing bill for scientific research, and, quite rightly, is demanding an increasing voice in the appropriation and allocation of money for this purpose. The situation has been aggravated by a number of expensive and well-publicised failures in technological and scientific development, and scientists can no longer regard themselves as beyond the need to be accountable to the tax-payer and to the share-holder.

Many scientists now belong to research organisations and have to justify their research proposals to research directors. In the universities, scientists have to justify their requests for research grants to committees who examine very carefully the cases made for the use of people and expensive equipment for research purposes. The direction of research requires the clear definition of objectives, and an understanding of the criteria by which the success or failure of the effort provided can be judged. Attempts are sometimes made to classify research as pure, basic, basic objective, applied, mission-orientated, etc., but the allocation of the research to such categories makes little difference to the need for clearer thinking about the strategies and tactics to be employed in the planning of research.

2. Research Strategies and Tactics

The use of the overtly military terms "strategy" and "tactics" may seem strange within the context of scientific research, but the terms have the same connotations within the two areas, and are helpful in distinguishing between the levels of planning and organisation that are necessary. In defining a research strategy, it is necessary to define the objectives to be achieved, the timing of the various stages, and the forces to be employed, i.e. the research methods, disciplines, and equipment. At the tactical level, the section leader, or the individual research worker, has to decide on the day-to-day deployment of the resources allocated to him, so as to achieve the objectives that he has been set, or that he has set for himself. In this paper, I shall mainly be concerned with strategies, partly because I feel that almost all of the attention to the working methods of scientists has so far been given to tactical considerations.

In the choice of a research strategy, particular consideration has to be given to the technological environment in which the research objectives will be achieved. Except for very short-term research, such a choice necessarily involves a forecast of the technical, social, economic changes that are likely to take place. Research directors and advisory committees are presumably expected to be able to make such forecasts better than younger scientists because of their wider experience, although there are obvious disadvantages in extrapolating from past experience.

In the past, forcasting of changes affecting research policies has depended almost entirely on subjective judgements, but it seems likely that the more objective techniques of technological forecasting will be used, and some interesting examples of technological forecasting in fields of primary national importance are given by Bright, 1968.

The importance of competition in the selection of research strategies has perhaps been underestimated. The dramatic examples of the race to the moon, and of the development of supersonic aircraft, as well as in many industrial processes show quite clearly the effects of such competition as a spur to greater scientific productivity, and not all of this greater activity can be attributed to money alone. We may be naive in eliminating overlap between the programmes of our national research organisations, and greater creativity might result from deliberate competition between organisations for prestige and for resources. The individual scientist would then need to decide between a relatively safe, but modest, advance, and an improbable, but dramatic, breakthrough, and be accountable for the choice.

For the research director, the selection between proposed research strategies is perhaps the most difficult of tasks. Factors such as technical feasibility and the relevance of the strategy to the urgent needs of the organisation are usually regarded as important, but what values, apart from purely subjective ones, can be given to these factors? Economists urge the use of cost-benefit analysis and other techniques, and there are fields of activity in which it is possible to assess the benefits of the research, and to balance the probability of the research succeeding against these benefits. In many fields, however, the benefits from given strategies are more speculative. One possible approach is through the use of game theory, and Williams, 1966, gives some entertaining examples of the choice of strategies in situations of uncertainty.

In research, as in military combat, an important factor in the choice of strategies is the correct assessment of the forces that are available, but, in research, these forces include not only the resources of men, money and materials, but also the reserve of new techniques and methods. The application of a technique or a theory developed in one particular field of activity to some quite different field may provide the essential key to a successful strategy. The value of new methods is frequently recognised at the tactical level - the danger lies in the failure to recognise the importance of new methods at the strategic level.

The most important developments for research scientists, and the least exploited, at present lie in the field of computation and mathematics. In part, the developments spring from the wider use of electronic computers, which have made possible completely new techniques of computation and new concepts in the capture, storage, and use of data. It is not merely that computations can now be carried through in brief fractions of the times formerly required, although the gain in speed and accuracy is phenomenal. The ability to store data so that they are immediately accessible and can be used in greater quantities places into the hands of the research scientist ways of exploiting information that have never previously been available. Furthermore, the computer programs by which the computers are operated provide unambiguous records of the methods that were used, in contrast to the days in which the scientist's working methods were usually lost, even to himself, within a very short time.

Associated with the use of electronic computers are the new mathematical techniques which have been developed to exploit the increased power of computation. As yet, these techniques have been used only sporadically and in limited fields of application. Most of the application has been at the tactical level of scientific research, and this is not surprising in that the techniques do not usually lie within the experience of research directors and the senior scientists who are responsible for research strategies. Some of these techniques, and their implications for research strategies, are outlined briefly below.

3. Mathematical and Computing Techniques

(a) Analogue and Digital Computers

The development of electronic computers has already been referred to, and most research organisations are now well aware of the need for more sophisticated computational facilities. However, in Britain, the provision of electronic computers has not kept pace with the need for computing facilities in the universities, and many research organisations outside the universities are in an even worse position. The latest report of the University Computer Board makes it quite clear that the struggle to maintain even the present level of availability is being lost by administrative delays, and by the failure of those who control research budgets to realise the need for and the urgency of greater investment in computers if our research strategies are to be effective.

Such computing facilities as we have are usually oversubscribed, with the result that the conditions and administrative procedures for their use inhibit the ordinary bench scientist from any close contact with the computer, and may discourage him so effectively that he is reluctant to employ mathematical techniques in his research strategies. The wider availability of remote terminals to large computer installations may remove some of these discouragements, as will the more extensive installation of "small" computer systems, which are in fact many times bigger and more powerful than any machines available a few years ago, in individual research laboratories. The need is for the bench scientist himself to achieve a satisfactory interface with computer systems, and to gain familiarity with the concepts and procedures which he can build into his research strategies.

The development of the digital computer has usually been stressed in the arguments for the need for better computing facilities in scientific research. The analogue computer, in which numbers are manipulated as physical quantities rather than as digital representations, has been less popular, but, in recent years, the interest in analogue machines has revived. Many computers operate effectively as "hybrids" between analogue and digital techniques, and an interest in the wider application of analogue techniques has been stimulated by mathematical simulations of real situations. For the scientist who is prepared to invest some effort in obtaining the necessary mathematical background, the use of analogue or digital techniques to simulate the biological, chemical, or physical processes with which he is concerned may be extremely rewarding, and Gore, 1969, gives some examples of this approach.

(b) Analytical Techniques

R. A. Fisher and F. Yates effectively began the development of modern ideas of statistical analysis, by which the interacting effects of many factors could be determined in carefully planned experiments and by detailed analysis of the results of such experiments. Unhappily, there are many fields of scientific research in which the basic ideas of the design and analysis of experiments have never been effectively used. There are still some scientists who regard "simplicity" of experimental design as a virtue, where "simplicity" is a substitute for investigating the interaction of experimental treatments and for ignoring the underlying variability of their experimental material.

The development of the digital computer has extended the power and effectiveness of the available analytical techniques so greatly that Yates, 1966, has written of this development as "the second revolution in statistics". As a result, it is now possible to investigate the effects of many interacting treatments on limited and variable experimental material. Without computers, experiment and survey designs have to possess a certain degree of balance if their results are to be readily interpreted; the availability of computers has increased the range of experimental possibilities in situations of real complexity. In biological research, in particular, the importance of the resulting gain in research efficiency is vital, and affects profoundly the choice of research strategies. The combination of variable experimental material, sometimes extremely limited in amount, exposed to a variable environment, and experimental treatments with complex interactions, has, in the past, forced many branches of biological research into a narrow range of strategies. The way is now open for the wider exploitation of the analytical techniques which have been developed in the last ten years.

(c) Multivariate Analysis

Among the analytical techniques which have become important for research scientists are those which lie within the broad framework of multivariate analysis. These include the techniques which have been developed in recent years for the investigation of large numbers of variables simultaneously. It is not always realised just how much of what we regard as modern science has been dependent upon investigation of one variable at a time, or the relationship of one variable with a small number of other variables which have been varied within a determined framework. The availability of analytical techniques for many variables simultaneously varying, made possible by the use of electronic digital computers, enables the essential dimensionality of research problems to be investigated and the choice of the critical variables for further research to be made. Other multivariate techniques enable research scientists to investigate the discrimination between a priori groups of individuals, or to investigate the essential relationships between groups of variables. Multivariate analysis has not yet been sufficiently widely applied for us to know what can be achieved by their deliberate exploitation as research strategies, but the possibilities are exciting and the economy of research effort foreshadowed by some preliminary investigations suggests a likely increase of research effectiveness by several orders of magnitude.

(d) Systems Analysis and Simulation

In addition to strictly analytical techniques, there are many relatively new ways by which mathematical ideas can be used to achieve a synthesis of real-life situations. Such simulations may be deterministic, so as to exploit analogue and digital computing techniques associated with differential equations, or they may be probabilistic, so as to exploit computing techniques associated with sampling from statistical distributions and stochastic processes. There are many examples of the application of such methods to individual problems, but few examples of the deliberate choice of research strategies with these methods at their heart.

One of the main advantages of the definition of a research strategy in terms of simulation and mathematical synthesis is that the results of the research are expressed as a mathematical model which can be used directly by managers and others to predict the consequences of their actions and to make decisions about the practical management of particular situations. The lag between research and the practical application of research results is frequently an important factor in many sectors of our economic life, and the expression of the research results as a working model helps to reduce the time-lag to a minimum. A second important advantage is that the synthesis quickly reveals the areas of research where more information is required, and helps research administrators to allocate resources more effectively.

(e) Trend-Surface Plotting

In addition to the analysis and synthesis of experimental situations, there are exciting new possibilities in the visual display of information. The automatic production of maps, diagrams, and even cine-films from data by computers fitted with graph-plotters or cathode-ray tubes enables the bench scientist to be in more intimate contact with his data than ever before, and using sight, perhaps the most effective of all our senses for monitoring incoming information. One of the most interesting interactions of visual and analytical techniques in recent years has been in the development of trend-surface plotting in stratigraphic research (Harbaugh and Merriam, 1968) in which observations of a variable at random points in two- or three-dimensional space are analysed to find the simplest convenient representation of the variation in space, and the results plotted graphically. The technique has not yet been widely exploited outside the field of geology, but offers considerable promise in many research areas where subjective interpretation of observations has previously been the only method available.

(f) Numerical Taxonomy and Information Analysis

New techniques important for research strategies are not confined to situations where data are recorded as counts or continuous variables. A wide interest in the classification of objects of all kinds has been stimulated by the development of numerical taxonomy, in which subjective methods of classification are replaced by objective mathematical methods capable of handling diverse categories of observations. The recently published proceedings of a symposium on numerical taxonomy (Cole, 1969) demonstrates the range of methods and applications that have already been found.

It should perhaps be stressed here that new techniques do not provide a substitute for the human intellect, or for the well-established human qualities necessary for the conduct of scientific research. New techniques do, however, greatly extend the range of possible achievement, and it is important to see that our research strategies pay sufficient attention to them. Techniques should never be overvalued; they are frequently underestimated.

4. Woodland Research in the Nature Conservancy

The woodland research policy of the Nature Conservancy has been described by Jeffers, 1968. Broadly, the Nature Conservancy undertakes research into problems of woodland ecology for the following purposes:-

(a) to provide the necessary advice to the Regional Officers of the Nature Conservancy on the acquisition and management of woodland reserves and on conservation and wildlife protection within such reserves;

(b) to provide advice to other organisations and private land owners on the management of woodlands for purposes other than commercial forestry, i.e. conservation, amenity, recreation, wildlife protection, or the combination of these other purposes with commercial forestry;

(c) to monitor the changes taking place in British woodlands as a result of commercial forestry, agricultural practices, recreational pressures, etc., so as to predict, and possibly modify, changes likely to be damaging to the conservation of British woodlands.

The funds available for woodland research in the Nature Conservancy are at present about £100,000 per year, and are planned to increase to about £200,000 per year during the next five years. There is, however, no intention to make research into woodland ecology an open-ended investment, and it is necessary to choose research strategies which make the most effective use of the available resources. The current research strategies have been selected to minimise the requirements for additional staff, and place most emphasis on the purchase of the necessary capital equipment to make the existing staff, and the small proposed increases in staff, more effective by increasing their productivity. The strategies chosen result in staff complements which are unusual for research organisations in that they minimise the need for technical and laboratory assistants. As much of the laboratory and field work as possible is automated, and all data handling and processing is done by electronic computer so as to reduce to a minimum the staff of the research sections.

The current research strategies aim at the problems that are expected to be encountered during the next ten years, and the rather unconventional view has been adopted that it is too late to undertake detailed research into today's problems. The problems of the present day must be solved by the best information that is currently available - it is no help to the woodland manager to tell him to come back in five years' time when we have done some research on his problem. As experience is gained, and the problems change, it will be necessary to change the strategies, and technological forecasting along the lines suggested by Bright, 1968, is currently being undertaken to predict the environment within which the woodland manager will have to work in the next ten to twenty years.

The overall research strategy is based on the recognition that the essential feature of woodland ecology is variability, and that further progress in ecological research can only be made by studying the extent and nature of variability in ecosystems and by exploiting rather than minimising its effects. The individual strategies are defined by the level of the variability within the ecosystem, and the strategies designed to provide an unbiased estimate of the extent of the variability and to explore the nature of the variation.

Three levels of variability are at present recognised. The first is the variability between individual woodland sites separated in space and time, where the attention is concentrated on differences between sites expressed in terms of their climate, physiography, soil physics, soil chemistry, and soil biology, and the presence and growth of the plants and animals found on the site. The research strategy at this level exploits the techniques of multivariate statistical analysis and numerical taxonomy in the search for complex relationships between large numbers of variables, and the classification of sites by the smallest possible number of characteristic variables. The practical expression of the research strategy is the classification of woodland and potential woodland sites, which has been attempted for many years by ecologists and foresters but never satisfactorily achieved because of past difficulties of handling large numbers of variables and their inter-relationships. Because of the urgency for practical and objective methods of site classification in the choice of areas for conservation and research, about half of the resources for woodland research in the Nature Conservancy will be devoted to this strategy during the next five years.

The second research strategy is concerned with the variability within a given geographically located site, and concentrates on the changes in micro-climate, physiography, soil physics, soil chemistry, soil biology, and the responses of woodland plants and animals to these variables within defined sites. There are two sub-strategies within this level of variability, and the first of these is concerned with spatial variation of many variables at given points in time. The sub-strategy is designed to exploit techniques of multivariate statistical analysis, trend-surface plotting, and computer mapping. The practical aims of the research are to devise a method of monitoring changes in woodland sites which requires collection of samples and field sampling which can be undertaken by relatively unskilled staff, with all subsequent determinations and data handling automated so as to reduce costs, and to provide completely objective descriptions of the state of an ecosystem at the time of sampling. By choosing appropriate methods of sampling, changes taking place in the ecosystem within five or ten years can be accurately defined, and the low input of resources per site ensures that monitoring can be carried out over a wide range of sites with a limited staff of specialist ecologists.

The second sub-strategy of the within site variability is concerned with dynamic variation from year to year, from season to season, or even from week to week. The sub-strategy exploits the techniques of deterministic and probabilistic simulation, with the practical aim of building mathematical models capable of solving problems of woodland management. These problems currently include the regeneration of natural woodlands, the manipulation of nutrient and decomposer cycles in woodland and potential woodland sites, and the management of stand structures in natural woodlands and in woodlands in which wholly artificial conditions have been introduced by coppicing, etc.

The research results are expressed as working models on which, with the aid of a computer, woodland managers can gain experience of the management of their woodlands and of the results of their decisions in much the same way that a pilot can learn to fly a particular type of aircraft on a simulator without hazarding a real aircraft and its crew and passengers. It is estimated that about eighty per cent of the resources for woodland research will be devoted to these two within-site sub-strategies in five years' time.

The third level of variability is concerned with the variation between individual plants and animals, i.e. on sub-specific variation. It is astonishing how little is known about taxonomic variation of British woodland plants and animals even at the species level, and knowledge of the plasticity of woodland species is almost completely lacking. The distinction between genetic and phenotypic variation of tree species is essential if correct decisions are to be made about the conservation of particular pools of genes within woodland ecosystems, and if the effects of the widespread introduction of foreign provenances are to be correctly assessed. The research strategy at this level of variability is designed to provide this information. The strategy again exploits the techniques of multivariate statistical analysis and numerical taxonomy, at the level of the individual plant and animal.

All of the research strategies are dependent upon modern statistical analysis in which the convenient orthogonality of designed experiments will usually be lacking, because of the nature of the field observations. The analytical techniques are themselves completely dependent upon the use of analogue and digital computers, not merely as convenient tools for ecological research, but as an integral part of the whole process of data collection, data processing, and the presentation of the results. It is scarcely necessary to emphasise that the research programme demands the employment of ecologists who are themselves more thoroughly numerate than has been implicit in the ways that ecologists traditionally are trained, and the first stages of the research programme have, therefore, been a large-scale retraining and re-equipment of the research ecologists of woodland sections of the Nature Conservancy.

5. Project Planning

Research strategies which require a substantial input of capital equipment require careful planning, if the necessary equipment is to be available when it is needed, particularly where annual budgeting and five-year forecasts of expenditure, traditional in the administration of British research, are the basis of financial control. This is not to say that careful planning is not essential in research strategies which are based on people rather than equipment, but there may be sufficient room for manoeuvre in these strategies to minimise some of the worse consequences of research planning. Because of the need for accurate estimates of the use of resources, the woodland research sections of the Nature Conservancy have adopted a systematic method of project planning. Within each research strategy, there are a small number of research projects, and, for each of these, a project plan defining the scientific background, the objectives, and the criteria for judging the success of the project has been written. The basis of the project plan is a critical path network, in which the logical structure of all the activities that can be foreseen is expressed diagramatically, and to which is attached estimates of the times for the completion of the activities and of the resources required for these activities.

A separate control document is also prepared for each project recording the assessed priority of the project, its technical feasibility, the required date for the completion of the project, and any intermediate reports produced. The next useful date for the review of a project is determined from the critical path network, and is also entered on the control document. When this date arrives, the control document is placed on the desk of the research director, who then reviews, together with the project leader, the progress of the project. Any necessary changes in the priority, technical feasibility, date for completion, or in the network of activities and required resources are also made before the next date for review is fixed. In this way, the review of research projects is carried out with a minimum of direct supervision and interference by the research director. Perhaps even more important, projects for which either the priority or the technical feasibility become so low that the project is of little value to the organisation can be eliminated from the research programme - something which is very difficult to do by other methods of controlling research.

Scientists are notoriously opposed to any form of administrative control. Where only their own time and reputation are at stake, it may be sufficient to let them control themselves. Modern research strategies, requiring the integration of interdisciplinary teams of scientists, and the use of expensive equipment, need more effective methods of research administration if the resources of men, money, and materials, which are ultimately derived from the taxpayer are not to be wasted. Some opposition to the methods of project planning which have been introduced in the woodland research sections was expected, but the scientists concerned were quick to see the advantages of project planning, and have themselves made valuable contributions to the methods. The result is a far cry from the usual type of research programme, and the research strategies which are made possible by project planning and the development in mathematical and computational methods offer exciting possibilities for the future of woodland research.

6. Summary

Modern statistical and mathematical techniques, and the electronic computers on which these techniques depend, have introduced new concepts into the basic strategies available to woodland research. This paper describes the strategies which have been adopted by the Woodland Habitat Team of the Nature Conservancy, and the underlying techniques which are being employed. The practical objectives include the classification of woodland sites, the monitoring of changes taking place in woodlands and on woodland sites, an investigation of the dynamics of woodland ecosystems, and the exploration of sub-specific taxonomy and biological variation.

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