An Evaluation of Three Biome Programs

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United States involvement in the International Biological Program (IBP) was first considered by an ad hoc committee of the National Academy of Sciences in 1963. In that year, the executive council of the International Union of Biological Sciences and the 10th General Assembly of the International Council on Scientific Unions approved the concept and plan of the IBP. The first U.S. programs were established in 1967 (*1*). As early as 1970, U.S. participation was formally endorsed by Congress with a total commitment of more than $50 million. Most of the funds were administered by the National Science Foundation (NSF) under a special program that terminated on 30 June 1974. Approximately one-third of the U.S. money went into studies paralleling those already in operation under the IBP in other countries. The remaining two-thirds, between $30 million and $35 million, was committed to a unique American idea—the fusion of terrestrial and aquatic productivity programs into a set of five integrated research programs that dealt with the major ecological biogeographic zones (biomes) of North America (*1*).

Five biome studies were funded: Tundra, Coniferous Forest, Eastern Deciduous Forest, Grassland, and Desert. Each biome study was to develop a major field research program that would provide a broad base of detailed original data to be used for the development of ecosystem models. It was argued that an integrated research effort of such scope would benefit basic ecology by adding to our understanding of the structure and function of ecosystems and would provide a sound basis for resource management. The biome programs were unprecedented in scope. There was no way to judge the practicality of the implemented procedures, but the proposals to NSF claimed that the techniques of systems science and the science of modeling had advanced to the point that a massive integrated research program could move from the initiation of field studies to complete ecosystem analyses in 4 to 5 years (*2*).

At the end of the IBP authorization in June 1974, NSF asked Battelle's Columbus Laboratories to review and evaluate the status and accomplishments of three of the five biome programs—Eastern Deciduous Forest (EDFB), Grassland (GB), and Tundra (TB)—and compare them with another integrated program, Hubbard Brook, and with ongoing individually funded research. An account of that review (*3*) and its findings is given below.

Organization and Funding

Since they were first funded in 1968, the three biome programs have spent $22.4 million of NSF funds on integrated research in ecology. This just about doubled NSF support to ecology. NSF provided $18.8 million for individual grants in ecology during the same time period (Table 1). Close to 500 senior scientists, 127 master's-level students, and 102 Ph.D. candidates participated in the biome programs. From 1970 through June 1974, 60 percent of the three biome programs' budget ($12.7 million) was committed to field studies. The biomes awarded about 650 individual annual subprojects for field studies between 1969 and 1974. About $7.8 million of the $12.7 million was committed to researchers at 57 institutions other than those administering the three programs. Forty percent of the funding ($8.6 million) went into the modeling, synthesis, and management.

The mode of funding from NSF seems to have precluded effective planning. Each biome program received short-term funds that were enough for the establishment of an office, but there was not enough time to assemble a team to outline and develop a substantive plan for achieving the final goals. The central office had only a few months to prepare and submit a proposal that would justify a 4- to 5-year program with an annual budget of $1 million or $2 million. Full funding was released on acceptance of this proposal.

The average annual grants to the biome programs were $1.25 million for EDFB, $1.49 million for GB, and $0.90 million for TB. In the case of the EDFB and GB programs, the funds were released to the directors for administration by the biome offices. Review panels at NSF did influence the emphasis and direction of some aspects of the biome programs but, as a rule, the directors of the programs had nearly as much latitude in assigning funds as does the principal investigator of an individual grant. Funds for the TB were administered somewhat differently, in that NSF, in selected instances, chose to assign grants directly to cooperating institutions and thus apparently exercised more control over the division of funds to subprojects. In EDFB and GB, grants to other institutions were made as subcontracts from the biome program office. Each of the three biome programs had a central executive committee that advised the director.

Perhaps the most serious problem was the timing. Funds had to be committed to field studies long before a modeling team could be assembled and develop overall plans for an ecosystem model. There is no public record of how the biome program managers solicited and evaluated subprojects to be funded (*4*), nor did they record any detailed plan for fitting the projects together. Most of the substantive material in the proposals was concerned with broad overall goals and gave little attention to the specific organization of the research.

Areas of Study

The central theme of the biome programs was that great benefits would result from the analysis and synthesis of data produced by a broad, coordinated research program. Whether or not the biomes constituted a balanced research effort was determined by comparing the biome programs with the patterns of research resulting from nonbiome proposals and studies (*3*).

In general, ecological research falls conveniently into four compartments: the abiotic compartment and three biotic compartments—producers (green plants), consumers (animals), and decomposers

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(bacteria, fungi, and some animals). Two devices were used to estimate the research interest in each of these compartments. The first was a review of information published in technical journals. Since it was impossible to review all ecological publications, the journal *Ecology* was chosen as a basis for comparison. This journal has a broad base of editors with both botanical and zoological interests and is one of the more prestigious outlets for the publication of original ecological research. The second indicator was the allocation of grants for ecological research by the Ecology and Systematic Biology section of NSF (1969–1974). The awards by NSF presumably indicate what panels of distinguished ecologists consider to be exciting research. When the papers from *Ecology* and the nonbiome grants awarded by NSF were reviewed (Fig. 1), it was apparent that animal studies received far more attention than studies of any other component. The bias was greater in the case of NSF support. Nearly 60 percent of the ecology grants were for animal studies, while there was very little research on decomposers.

Neither NSF-sponsored, non-IBP research, nor the research described in *Ecology* has a balanced coverage of the biotic compartments of ecosystems. Relatively little of the research deals with decomposers and producers. It is apparent that one of the most important aspects of ecosystem functions, the belowground systems that involve root metabolism, decomposition, and nutrient cycling, was neglected. This is a serious void because all materials must pass through those systems each time they cycle. The crucial significance of such research was recognized only toward the end of the biome programs. It became apparent that if the biome programs were to develop a comprehensive data base for understanding ecosystems, they would need to fund subprojects with a very different balance of compartmental coverage than is found in *Ecology* or grants from NSF. This departure did indeed occur (Fig. 1). Thirty-seven percent of the subprojects supported by the three biome programs were committed to studies of producers and the remaining subprojects were evenly divided between consumer, decomposer, and abiotic studies.

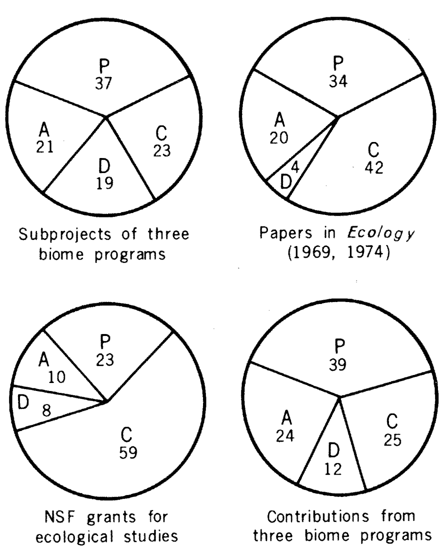

Fig. 1. The allocation of research effort in *Ecology* and NSF grants for ecology compared with the three biome programs. The portion (in percentages) given to producers (*P*), consumers (*C*), decomposers (*D*), and abiotic factors (*A*) is indicated. The data are based on 110 papers from *Ecology*, the 749 grants for ecological studies funded by NSF over the study period (Table 1), the 654 subprojects, and the contributions in the 481 open literature publications from the three biome programs.

As a block, the subprojects from the three biome programs gave a more uniform coverage of compartments than did papers reported in *Ecology* and grants funded by NSF. The research in the biome programs deviates from other ecological research in directions that are likely to produce a better factual basis from which an understanding of ecosystems can be developed. The three biome programs considered here supported 121 subprojects dealing with decomposition while NSF awarded only 60 grants for decomposer studies in the same time period. At the other extreme, NSF awarded 442 grants for studies of consumers while the biome programs supported only 148 consumer studies. These facts make it quite clear that the biome programs did materially alter the pattern of support for ecological studies and that the alteration was one that will provide better coverage of neglected components of ecosystems.

It is also notable that the expended funds paid off in terms of research. The coverage in the published literature closely follows the division of funds among subprojects (Fig. 1).

Open Literature Contributions

Open literature is defined as those publications that are readily available in journals or from publishers, the National Technical Information Service, and other sources with wide distribution. Currently, the open literature publications of the biome programs are the only significant contributions available for analysis. The sets of more than 140 papers from each biome program provided an unusual opportunity for developing ways of evaluating the output of three large scientific programs with similar overall objectives.

The contents of the nearly 500 papers published from the three biome programs were examined in order to determine the nature of the research reported from each program. An analysis of the contents of the papers was used to consider whether the published reports provided a basis for synthesis and modeling of an entire ecosystem. If the original goals were adhered to, the publications resulting from each biome program might be expected to (i) be a set of papers providing a balanced coverage of each compartment, (ii) reflect the integration and coordination of the programs by having a broader coverage than other ecological papers, and (iii) emphasize the dynamic relations within and between compartments more than do other ecological papers.

These three aspects were measured by scoring papers according to their contents. Publications from biome programs were assumed to be similar in quality to other published papers since all had passed the peer and editorial review re-

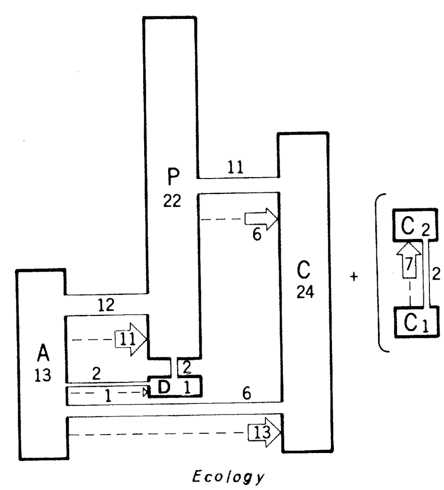

Fig. 2. Relations and balance of effort reported in *Ecology*. The number of within compartment studies that dealt with producers (*P*), consumers (*C*), decomposers (*D*), or abiotic (*A*) compartments are indicated by the numbers appearing in the appropriate box and by the size of the box. The number of inputs to a compartment are indicated by numbers appearing next to or inside the arrows connecting pairs of compartments or trophic levels (C_1 and C_2 are predator and prey studies) and by the size of the arrow. Transfers between compartments are diagrammed as corridors connecting the appropriate compartments. The width of the corridor is directly proportional to the number of contributions. The relative size and numbers indicate the number of contributions to compartments (numbers in the box), to input studies (arrows), and transfers (corridors connecting boxes).

quired for publication. More detailed quality judgments were not attempted because there is no objective way of determining whether the nearly 500 published papers from the biome programs were qualitatively better or worse than other papers in the field. Each paper was scored for the usual four ecosystem compartments it covered—producers, consumers, decomposers, and abiotic factors. When compared with *Ecology* (Table 2), no significant differences were found in publications from the GB. The other two biome programs, TB and EDFB, differed significantly from the *Ecology* sample but not from each other. These two programs dealt with natural ecosystems that were subject to perturbation. The heavy emphasis on producers and decomposers (54 percent of the subprojects in EDFB and 64 percent in TB) reflects their concern and nutrient cycling and energy flow in the systems. As might be expected because of the importance of grazing and grassland areas, the GB funded more subprojects involving herbivores than did EDFB and TB (*3*).

A new kind of analysis was needed to consider breadth of content and emphasis on interrelations of the four compartments. It was necessary to indicate the ways in which the data in a paper may contribute to an ecosystem model. This was done by scoring papers for the kinds of information they contained and entering the total number of contributions in a block diagram of ecosystem relations (Fig. 2). If a study dealt with specific organisms at one trophic level or simply described abiotic factors in ways that contributed little or nothing to an understanding of functions between compartments, it was classified as a "within compartment" study. Examples include studies dealing with abundances of earthworms, bison mating, ordination of plant communities, and the phenology of oaks. Many papers considered only the inputs to a recipient compartment. For example, phytotron experiments may characterize responses of plants to constant temperatures without reference to the natural abiotic regimen. Gut contents of birds, insects captured in spider webs, and ingestion by aphids are studies of inputs to consumers but such data sets tell nothing of the compartment from which the food was taken. Studies limited to what a compartment received were classified as "input" studies. When the relations of two compartments to each other are considered, they may contribute to understanding the functions coupling the compartments. In cases where the independent functions affecting each of two or more compartments and their coupling were characterized, the study was termed a "transfer."

Table 1. Annual NSF funding of the three biome programs and NSF support for ecological research.

Year of funding	Eastern Deciduous Forest Biome	Grassland Biome	Tundra Biome	NSF grants for ecology
1969	$ 200,663	$ 851,027*		$ 3,205,070
1970	229,338	1,800,002	$ 351,000	2,397,776
1971	1,200,000	1,874,482	1,003,700	2,640,640
1972	1,992,354	2,055,000	1,192,509	2,898,355
1973	2,100,000	1,996,579	998,000	4,460,716
1974	1,800,000	1,800,000	936,900	3,182,841
Total	7,522,355	10,377,090	4,492,700	18,785,398

*Combined funding for 1968 and 1969.

Breadth of coverage was a characteristic in which the biome programs differed greatly. Figure 3 shows the sums of all the topics that the biome program papers addressed. If a paper considered only one compartment or input, the number of contributions equaled the number of papers read. If more than one compartment or transfers or both were considered, then the number of contributions exceeded the number of papers. For example, there were 299 contributions to compartments in the 161 papers reviewed from the EDFB (a transfer was scored as a contribution to two or more compartments). This represented an average of 2.43 different contributions in each paper (Table 2), which was far more than for any other program considered by us. Transfer studies involving the abiotic compartment were responsible for this breadth of coverage (Fig. 3). Such studies were apparently a direct outgrowth of the extensive radionuclide transfer studies that were pioneered at the Oak Ridge site and of the established interest in modeling at the University of Wisconsin.

The reviewed GB papers (176) were a bit broader in scope than those in *Ecology*, while the TB publications (144) were about the same. The pooled data might obscure trends in a biome research program that would portend changes in the future. However, when the papers published in 1974 and those still in press at the time of the review were compared with the earlier papers of a biome program, there were only slight trends toward greater breadth of coverage. Differences in the breadth of coverage of the publications of each biome program were clear right from the start, thereby suggesting that the breadth of research undertaken by a biome program was a function of the people drawn into the program rather than a consequence of management broadening the approach of subproject leaders.

The question of whether papers deal with dynamic aspects of compartments is important because models of ecosystem structure and function depend on an accurate knowledge of the interactions within communities. Studies classified as inputs and transfers (Fig. 3) deal with dynamics, while studies within compartments are at best descriptions of static conditions. About 54 percent of the contributions from the GB and the *Ecology* sample, 45 percent of the TB contributions, and more than 60 percent of the work from the EDFB dealt with the dy-

Table 2. Contributions (in percent) of papers to various compartments.

Compartment	Eastern Deciduous Forest Biome	Grassland Biome	Tundra Biome	*Ecology*	Hubbard Brook
Producers	41	34	41	34	27
Consumers	15	37	24	42	17
Decomposers	16	11	11	4	8
Abiotic	28	18	24	20	48
Number of contributions	299	257	189	168	145
Contributions per paper*	2.43	1.98	1.61	1.66	1.61
Number of papers reviewed	161	176	144	110	107

*Each paper is scored for the number of compartments covered and the number of ways in which the data were used.

namic ecosystem relations (Table 3). Not only did the EDFB papers deal with dynamics more often than any of the other literature samples, but they also changed through time. There was a significant decline in the frequency of studies within compartments and an increase in the transfer studies from the EDFB. This was the only statistically significant temporal change seen in the entire analysis of published reports.

The analysis of published work was necessarily limited because there is still much information and data yet to appear. Biome directors argue that the best is yet to come. However, the patterns of publication over the last 4 or 5 years are the only tangible indications an unbiased judge can use to make predictions. With the sole exception of the coverage of dynamics by EDFB papers, publications have followed a fixed pattern. If there is to be a change in the scope of published reports, it will be an abrupt shift in the kind of paper published and will be a phenomenon occurring after the end of the IBP.

The papers from the EDFB appear to offer the best resource for studying the structure and function of ecosystems because of the balance of compartments covered, the greater breadth of content per paper, and the attention to the dynamic relations. The GB publications do not differ from the papers in *Ecology* in these aspects, while the papers from the TB fall short of the papers in *Ecology* in the measures mentioned above. These are only averages. The major influence of any research program is likely to lie in a few exceptional papers. Still, it is reasonable to expect the biome programs to generate a different kind of research because all associated researchers had more opportunities for discussion and exchange of data and, presumably, organized the programs to fit together and address broader goals than is possible in the research reported in *Ecology*. Thus, it is legitimate to ask if the investment in planning and integration affected the performance of the average biome scientist so as to produce research different from that of individual researchers publishing in *Ecology*. The answer to that question is no.

Table 3. Static and dynamic coverage (in percent) of the three biome programs, *Ecology*, and Hubbard Brook program.

Program	Within	Input	Transfer
EDFB	40	11	49
GB	46	29	25
TB	55	27	18
Ecology	45	29	26
Hubbard Brook	26	54	20

Modeling

Ecosystem models were one of the central goals for each of the biome programs. Originally, the models were intended to be general enough to deal with large regions, precise enough to allow for meaningful applications in management decisions, and realistic enough to add new insights to theoretical ecology. These overly ambitious goals were not achieved. Time has shown the wisdom of Levins' (*5*) postulate that there has to be a trade-off between generality, precision, and reality. An increase in one aspect of a model comes at the cost of the others. The second fact which came to light is that modeling is still an art. The techniques of programming, the choice of mathematical equations—stochastic, deterministic, differential, difference—and selection of software, and the methods for condensation, building in modularity, or developing a hierarchical structure are still being explored and debated (*6*). Perhaps in the future a technology will emerge from these explorations that will be efficient at dealing with the complexities of studying an entire ecosystem, but currently these technical difficulties seem to have been the greatest factor in the biomes' failure to achieve their goals in modeling.

Two ecosystem models, the Terrestrial Ecosystem Energy Model and the Comprehensive Lake Ecosystem Analyzer, were published (*7*) by the EDFB. The GB model ELM is still in manuscript (*8*) and the TB shifted its emphasis to models of processes or compartments (*9*).

If the open literature is a good measure of the resources available to modelers, then an analysis of modeling would be expected to coincide with conclusions obtained in the publications review above. This was the case. The EDFB program that published the largest portion of broad-based papers dealing with the dynamic aspects of ecological compartments was the only one to approach the original goal within the time period of IBP.

Currently, the models of ecosystems

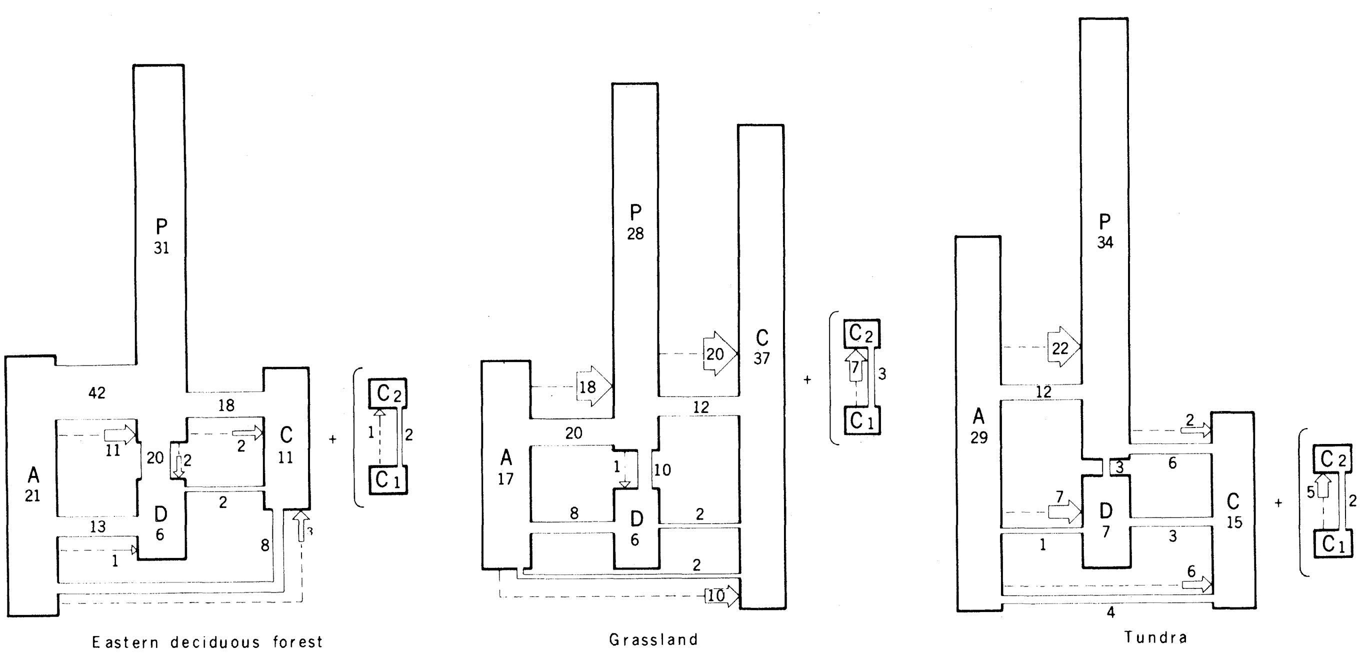

Fig. 3. Relations and balance of effort in the three biome programs. Abbreviations and conventions are the same as for Fig. 2.

have serious limitations and seem to have been forced out in spite of technical difficulties. They have not met the original goals as far as accuracy and application in ecological theory and management is concerned. It has been argued that the original goals were unrealistic and a shift of emphasis was desirable. The TB did just that. A preliminary ecosystem model was developed and very likely could have been refined into a working model with limited precision. Evidently the basic limits to the model were recognized and the decision to concentrate on component models was made. As a result, the TB modelers published a variety of smaller-scale component models.

All the biome programs produced some process or compartment models. Approximately 100 of these have been identified and more than 25 are fully documented. The shift of emphasis to such models was greatest in the EDFB and TB. These models usually explore a variety of modeling techniques and appear more likely to enjoy application in either basic research or applied problems.

The biome programs came at a time when ecologists were just beginning to do large-scale modeling (*6*), thus the expenditure of more than $3 million in modeling efforts ($0.6 million for EDFB and about $2.5 million for GB; expenditures for TB modeling were not available for our study) (*10*) provided an immense impetus to the field. It will be years before there is enough perspective to judge what part the biome program models will play in the development of modeling in ecology. Despite the disappointment in large-scale models, the researchers from the biome programs are firmly convinced of the value of modeling. Vigorous research at the process and compartment levels has emerged from the biome programs, and many of these use a smaller-scale team approach.

While the specific modeling goals were not achieved, alternative approaches to modeling were taken. If a significant fraction of the 700 scientists and students associated with the biome programs are able to follow their expressed interests in modeling, it will have a very great impact on the science of ecology in the future.

Impact on Scientists

The biome programs are being phased out by NSF. Any continuation of studies developed within the biome programs is back in the hands of participating scientists, who must compete for funds within the traditional NSF system. More than 70 percent of the scientists, both field researchers and modelers, who had long-term (3 years or more) association with the biome programs were interviewed by telephone in the Battelle study (*3*). The interviews consisted of questions that could be answered by means of simple yes or no responses to determine what effect participation in integrated research programs had on the research and development of participants and whether their attitudes were changed in ways that might affect the kind of research they would pursue in the future.

The conclusions reached in the review of published reports and modeling were verified by these interviews. About half of the field scientists submitted projects and carried out their research with little attention given to the detailed needs of the overall program. Generally, attempts to make the project fit the needs of modelers were made later in the course of the project. Very few of the field scientists felt the requests put to them by management were difficult to meet or interfered with their own basic research plan. Data from nearly all the field projects were given to the modelers directly, rather than through the formal procedures for data exchange.

The modeling difficulties were honestly admitted. Despite the fact that most of those interviewed have serious reservations about the value of the current models, they expressed no feeling of discouragement. In fact, there was considerable enthusiasm for the kind of team research that would lead to better models. This was most strongly expressed by workers in the EDFB and TB (*10*). There was less enthusiasm for modeling and team research among the GB personnel. Thus, the scientists most likely to pursue integrated research in the future come from the programs with the lowest administrative cost and a policy of decentralizing work so that fieldwork, synthesis, and modeling involved direct personal contact.

Role of Management

The concept of central control was put forth in proposals and from 15 to 25 percent of the budget [about $3.4 million for EDFB and GB (*10*)] was spent on the integration and coordination of research. In addition to the preparation of proposals and the administration of budgets, the central management arranged for and covered the cost of special services, including data banks, publications, data processing, and travel. There is no evidence that management did much more toward integration than select a set of projects that seemed appropriate to the general problems described in the proposals. In the case of the GB and TB, the directors served multiple roles in management, field research, and modeling.

Each of the three biome programs investigated in our study was unique in its beginning, thus each of the three central management groups was faced with a unique set of problems. In the case of the GB, the program was developed independently at Colorado State University at Fort Collins. The total program, including the construction of the headquarters building, had to be organized and implemented, together with the selection and establishment of research sites and the assembling of a team of qualified researchers and modelers from other institutions. The EDFB at Oak Ridge, Tennessee, was a consolidation of five ongoing research programs: Oak Ridge in Tennessee, Lake Wingra in Wisconsin, Lake George in New York, Triangle in North Carolina, and Coweeta in Georgia with a research site in North Carolina. Each site was independently managed. The TB, administered by the University of Alaska and the Cold Regions Research and Engineering Laboratory, was able to capitalize on a long history of research at Point Barrow as well as the research being done in connection with oil and gas exploration on the north slope of Alaska. Scientists were drawn from groups already committed to working in the tundra. In many instances, the biome program funding for EDFB and TB permitted the assembled workers in these two programs to continue their ongoing research.

According to responses to the telephone interviews, the most valuable contributions of the central management to integration were the internal reports that were mandatory in the case of the GB, and strongly encouraged but not required in the EDFB and TB. These reports, together with the workshops, symposia, conferences, and seminars that were arranged by management at a cost of more than $1 million in travel money, made significant contributions to the exchange of ideas and data. Thus, central management was most effective in providing opportunities for integration. The success in integration depended on the initiative of the researcher. Neither the management nor the modeling teams assumed a direct role in defining specific objectives and directing research. More than 95 percent of the researchers contacted had contributed data to the modeling efforts of the biome programs. Half of these reported that the data were originally collected with no knowledge of the appropriate sampling procedures and data format.

There was considerable discussion of the type of structure needed to assemble the data required for modeling and synthesis. Once assembled, the data were to be put into a central data bank. Currently, none of the three biome programs has a functional data bank capable of supplying comprehensive data sets on request. The TB data bank was abandoned early in the program and the money was put into research. The lack of a data bank had no apparent effect on exchange of data between workers assigned to the TB. The other two programs were plagued with the problems of acquiring, organizing, editing, and verifying information in data sets so that data could be entered into the data banks. These problems were never solved. Two factors may have contributed to the failure of data banks. (i) The fieldworkers and modelers were quite content with exchanging data through personal contact as demonstrated in the TB. (ii) A protocol and format for data collection was either lacking or was not followed.

A detailed examination of the data sets in the data banks or waiting to be processed (*11*) shows that very little field data were forwarded to the central offices. There is no clear effort being made to assemble the data collected under the biome program. This reflects either a failure of integrated research to produce coordinated data sets or a reluctance on the part of the researchers to release data to the data banks and to the public. There are plans for establishing one central repository for all biome program data sets (*12*), but this was proposed without much attention to the fundamental reasons for the failure of the data banks.

Another unresolved matter is that of synthesis volumes. The original goals and objectives of the U.S. section of the IBP stated that all data and information acquired during the U.S. program would be compiled and published in synthesis volumes at the end of the IBP. The titles and editors of these were to be determined by the U.S. executive committee for the IBP. There are still no firm plans for the synthesis volumes. A list of projected titles was issued in July 1973. However, the list has been substantially changed several times and the status of the volumes from the U.S. biome programs was still uncertain in July 1975. There is no easy way to trace the source of the difficulties in this effort, but it would seem to reflect a lack of central

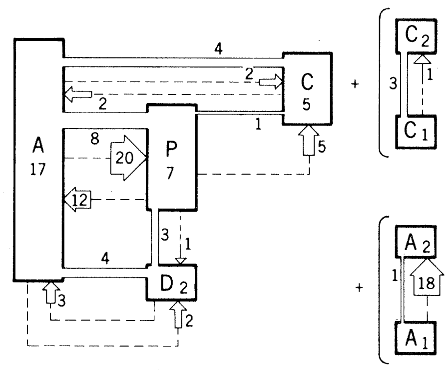

Fig. 4. Relations and balance of effort in the Hubbard Brook program. Abbreviations and conventions are the samé as for Fig. 2.

control. The biome programs are closing down with indefinite plans for the assembly and publication of large-scale interpretive volumes. In lieu of this, each of the three biome programs investigated is reported to be actively preparing summaries of its own work which may be published independently at some future time.

Fieldworkers had the usual complaints about management doing little more than generating annoyances and red tape. Yet the majority found their work with biome programs to be an important departure from earlier patterns and indicated a desire to work on integrative programs in the future. This feeling of having participated in something worthwhile could not have been achieved without some managerial direction.

Success in the biome programs seemed to occur when management kept close contact with fieldworkers and facilitated the informal exchange of data and ideas between field researchers and modelers. When management operated in an ad hoc fashion (TB) or involved independent sites (EDFB), there was a responsiveness to the research opportunities that was not anticipated in proposals. Goals were shifted as they must be in any basic research project.

Small units with funds of less than $0.5 million, such as the EDFB sites and the independent grants under TB, seemed most effective. Many of these units have plans for continuing research within the competitive granting structure of NSF.

The Hubbard Brook Program

Because of the effectiveness of smaller units and the trend toward decentralization within the IBP biome programs, it was of special interest to study a smaller-scale integrated research program. As it evolved, the Hubbard Brook program gradually developed into an integrated research program. The program was established in 1962 with the goal of investigating mineral cycling in a closed watershed. Its cumulative budget, administered by two principal investigators, was $1.4 million through 1974. Annual allocations from the beginning through 1968 averaged $130,000; from 1969 to the present, $190,000. In contrast, the annual budgets of the five EDFB sites ranged from $100,000 to $400,000.

A total of 107 publications and prepublications were reviewed in connection with this program. Significant differences were found in these publications (Fig. 4) as compared with those of the biome programs. Forty-eight percent were concerned with abiotic factors; 75 percent dealt with abiotic and producer relations (Table 2). This is in keeping with the objective of studying nutrient flow and productivity. Thus, Hubbard Brook papers dealt with ecosystem functions more frequently than did those of either the three biome programs or *Ecology*. Most of the work (54 percent) dealt with energy inputs.

The exchange depicted in the Hubbard Brook studies reflects an adherence to the original plan for studies of nutrient and hydrologic interactions. Such studies provide a central core of facts from which studies of ecosystem functions could be developed. Other ecosystem studies were developed from the basic information collected early in the study.

Modeling was not a specific objective of the Hubbard Brook program, but word models were a natural means of defining the components of the nutrient cycling of the system. These word models have been expanded into both descriptive models based on correlations and deterministic mathematical models. Such models are effective for determining the completeness and validity of the data. They can be used to estimate trends that are general properties of other ecosystems. In addition, they appear to be reasonably detailed and refer to a single site rather than a total ecosystem. Forest Service and meteorological data were put together in a general model, JABOWA (*13*), for describing timber production for the region. Field scientists in the Hubbard Brook program turned to modeling as the data required it. The modest modeling effort seems to have produced models flexible enough to be altered for application to other systems.

Because of its lower rate of funding, the Hubbard Brook program did not involve as many scientists as the biome programs. There were 41 scientists and

22 students representing eight institutions and organizations over a 13-year period. Management problems were dealt with informally and did not require any significant portion of the grant funds. The Hubbard Brook program has been more productive in terms of quantity and has produced papers with qualities judged to differ significantly from other published reports. These deviations correspond with the goals of the study. Hubbard Brook is well above the biome programs in terms of meeting its objectives. However, in terms of educating or directly influencing scientists in the conduct of integrated research, it has not been as broadly effective as comparable biome programs.

Summary and Conclusions

United States participation in the IBP began in 1969 and ceased in 1974. During that time, three of the U.S. biome programs, TB, GB, and EDFB, spent more than $22 million on research concerned with the structure and function of ecosystems. The infusion of funds into these programs had a variety of results.

1) It produced an emphasis in terms of subprojects funded on nutrient cycling and decomposition in ecosystems that was greater than from nonbiome research in general.

2) It afforded support for more than 700 scientists and graduate students at 60 institutions across the United States.

3) It established an awareness of the advantages of team research and modeling in solving large and complex problems related to resource management.

4) It produced nearly 500 (as of 1974) publications that differ from nonbiome publications in the kinds of things covered.

5) It demonstrated that the effort put into integration so far has produced papers with only slight differences with respect to breadth of coverage and attention to dynamic relations than the average paper published in *Ecology*.

6) It taught a painful and expensive lesson concerning the ability of systems analysis and modeling to contribute to a research program when that program's original goals and research plans are revised and developed during the course of the program.

7) It left undecided the fate of synthesis volumes that were to summarize the major findings of the U.S. contribution to the IBP.

8) It produced two data banks that did not serve as a means of data exchange for biome program research and cannot respond to "any significant number of outside requests for data" (*12*).

9) It produced three large models of ecosystems that show the difficulties of handling detailed ecosystem functions at the present state of the art of describing nature.

10) It diverted much of the modeling effort into more than 25 process and compartment models that used a variety of approaches to deal with practical and theoretical biological problems and identified significant gaps or misunderstandings of ecosystem functions.

11) It showed that decentralization did not inhibit the exchange of information between scientists but rather encouraged scientists to be more responsive in identifying and pursuing alternative goals.

During the time from 1969 to 1974, NSF was involved in funding three kinds of ecological problems—large integrated studies (biome programs), smaller-scale integrated studies directed toward the solution of problems associated with segments of an ecosystem (Hubbard Brook), and grants to individual investigators. Results of the Battelle study indicate that long-term, small-scale projects resembling the Hubbard Brook study were less complex, less costly, and tended to be relatively more productive.

References and Notes

1. E. B. Worthington, Ed., *The Evolution of the IBP* (Cambridge Univ. Press, London, 1975) gives the history of the IBP. For a brief history of the United States and IBP, see *Report No. 6, U.S. National Committee for IBP* (National Academy of Sciences, Washington, D.C., 1975).
2. R. L. Burgess and S. I. Auerback, *Eastern Deciduous Forest Biome Memo Report 71–21* (1971); G. Van Dyne, in *Mathematical Models in Ecology*, J. N. R. Jeffers, Ed. (Blackwell, Oxford, 1972). These papers deal with plans. One article was written after gaining experience in running a biome; R. V. O'Neill, in *Aquatic Ecosystem Modeling* (Resources for the Future, Washington, D.C., in press).
3. The Battelle report to NSF on "Evaluation of three of the biome studies programs funded under the foundation's International Biological Program (IBP)" is available from the National Technical Information Service, Springfield, Va., and consists of two sections, a summary and overview and a detailed 278-page documentation section which includes a summary of subprojects, a complete list of publications, lists all data sets from GB and EDFB, lists all theses, gives a detailed budget breakdown, and records the results of telephone surveys. Conclusions and statements of fact are based on the data in the documentation.
4. The proposals of EDFB and TB gave progress reports from the previous year's subprojects without indicating which subprojects would be continued. Requested funds were usually close to the annual award except for GB. Funds requested in GB proposals were close to 40 percent greater than the awards and 2.7 more projects were proposed in the grant than were funded. The GB proposals are of no value in indicating what did happen in the program.
5. R. Levins, *Am. Sci.* **54**, 421 (1966).
6. R. G. Wiegert, *Annu. Rev. Ecol. Syst.*, in press.
7. R. Park *et al.*, *Simulation* **23**, 33 (1974); H. H. Shugart, R. A. Goldstein, R. V. O'Neill, J. B. Mankin, *Oecol. Plant.* **9**, 231 (1974).
8. An 11-part monograph on ELM was available in manuscript from G. Van Dyne.
9. M. E. Timin, B. D. Collier, J. Zich, D. Walters, *U.S. Tundra Biome Report 73-1* (1973).
10. Detailed budget breakdowns for TB were not available for analysis either from NSF or from the TB central office.
11. Of the 160 annual data sets filed for EDFB, there are only eight sequences of data for more than 1 year. There were 104 sequences in the 573 GB data sets, but still no evidence of systematic efforts to file data sets that complement each other. These data sets are listed in (*3*).
12. O. L. Loucks and N. McElreath, *TIE Committee on Ecosystem Studies* (Institute of Ecology, Madison, Wis., 1975).
13. A summary of Hubbard Brook, prepared for an NSF site visit in 1973, relates the history of the program. This is unpublished.

14. Supported by a contract from NSF to Battelle, Columbus Laboratories. All correspondence or requests for reprints should be addressed to R. A. M. at Battelle.