Fire Ecology Research Needs, Identified by Research Scientists And Land Managers[1]

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INTRODUCTION

In 1970, within the International Biological Program (IBP), the National Science Foundation established the Coniferous Forest Biome research organization. The overall goal of the Biome program was the analysis of the structure and function of western coniferous forest ecosystems. As a part of this endeavor, the Fire Ecology Project was established in 1973.

The general objective of the Fire Ecology Project has been to conduct an analysis of problems on the natural role of fire in the functioning of western coniferous forest ecosystems. This paper presents a part of the problem analysis. Specific objectives were to survey

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the opinions of environmental scientists and land managers as to specific fire ecology problems, to evaluate the literature on ecologic effects of fire, and to use these two categories of information in the design and computer implementation of system models as an approach to problem solutions.

Such models are sets of quantitative statements representing dynamic processes in landscape ecosystems. These sets of statements can be programmed on an electronic computer and can be used to imitate various ecosystem responses to changes in such quantitative fire attributes as fire periodicity, fire intensity, amount of fuel reduction, burn-area size, shape, and location.

BACKGROUND

The National Science Board (1972) of the National Science Foundation recommended quantitative modeling of ecologic effects of fire as a high-priority research activity. Bunnell (1972), Goodall (1972), and Innis (1973), identified several specific functional benefits in using a systems modeling approach. Of these, we think that land managers could benefit from:

1. Prediction of system response to imposed changes in fire attributes or to changes in ecosystem structure (fuel loadings). Such predictions of fire effects can be used to determine fire prescriptions;

2. extension of the range of relevance of a particular field investigation to other sites and other seasons. This benefit can only be achieved by viewing one's concerns in a systems context;

3 provision of simulation games with which managers can get a feeling for the possible consequences of optional fire-land management strategies.

Those from which we think fire ecology scientists could benefit are:

1. Consideration of a wider set of variables affecting a particular ecological response to changes in fire attributes than any single investigator is able to observe in the landscape;

2. clarification of concepts and exposure of investigators' tacit assumptions;

3. clarification of relationships between system components;

4. collation of a number of different scientists' research data; and

5. comparison of similarly structured systems that have different rates of change.

Within the last few years, various aspects of natural resources management have begun to employ systems modeling approaches. Van Dyne's (1969) book describes several of these efforts. Other examples can be found in Walters and Gross (1972) for big game management; Watt (1964) for pest management; the Water Resources Research Institute at Clemson (1970) for watershed management; and Smith and Williams (1973) for range management. In discussing the integration of fire management with land management, we feel this approach should be encouraged and investigated.

Forrester (1961) stressed that validation of a given system model can only be done with respect to the purpose that initially motivated the modeling activity. The degree of specificity of purpose is a controversial issue, although, outside of systems ecology, Phenicie and Lyons (1973) present a good argument for developing a tactical step-down plan for identification of research purposes at various resolutions.

The importance of specifically identifying the important system problem before designing the model cannot be overemphasized. Moreover, this problem must be selected from among a variety of other possible problems before modeling activity is actually begun. It can be argued that the selection of priority problems is based upon expected behavior of the system before modeling, that is, selection is based upon intuition. It has been found that actual behavior of the system model might be counterintuitive (Kane et al., 1973), or show "unexpected consequences" (Holling and Chambers, 1973). This possibility might lead to the conclusion that the original problem is not important.

Acknowledging this, one still must identify the problem to be investigated at the outset. Experience in the Desert Biome modeling group has shown that problems are best identified as questions, and that the particular format used for formulating questions about systems is important. A format we think is effective is:

What is the effect of a change in ... as seen in ...?

Our stress on fire-ecosystem principles in identifying problem areas was preceded by the emphasis Wright and Heinselman (1973) placed on identifying fire ecology principles. Along with providing a practical focus for modeling activity, identification of problem areas can be useful for theoretical ecology investigations. Watt (1973) comments, "Important applied problems often constitute the best available examples of important theoretical principles."

The importance of identifying specific problems for modeling is also emphasized by May (1973):

> In ecology, I think it is true that tactical models ... applied to specific individual problems of resource and environmental management, have been more fruitful than has general theory, and they are likely to remain so in the near future.

A particular sequence of activities often characterizes the manner in which this approach is applied to problem solving. An orderly progression starts with problem identification, and leads to decisions on what is conceived as "flowing" through the system, such as, energy, moisture, minerals, population densities, area sizes, or some other quantity, and decisions on the most germane time and space resolution. Often an interaction diagram is constructed at this stage in order to identify the important interactions between system components.

A flow chart can then be constructed showing which are input variables, which are output variables, which are variables describing the internal state of the system, and which are the controlling processes affecting the rates of change of variables. Quantitative hypotheses are selected to describe relations between the system components in the form of a computer program. One then attempts to invalidate the set of hypotheses he has synthesized (a process often referred to as validation) by comparing the system model input and output behavior against that of the real-world system being modeled.

METHODS

Two different activities were conducted in the course of this problem analysis. One was the identification of fire-ecosystem problems and their relative priorities. The other was determining the feasibility of achieving first-approximation system model designs for high-priority problems by examining the hypotheses and data content of the research literature in fire ecology.

Questions Survey

The first step taken in identifying the problems was to contact 800 land managers and environmental scientists in the 13 Western States and two western Canadian Provinces. They were asked to describe what they thought were the most pressing problems with regard to understanding the biological and physical impact of fire in western coniferous forests. Social, economic, political, and esthetic problems were not solicited because of the nature of the program under which this activity was conducted. The geographic scale of contacts was determined by the biome-scale nature of the parent organization. We tried to select land managers at the middle rather than the upper end of the administrative structure. Details of this survey and a list of the question responses received may be found in Taylor et al. (1975).

From this questions survey, 910 sets of questions emerged. A subsequent task was evaluating the priorities for research. Obviously, the question sets had to be synthesized into a more manageable number of units. Each of the question sets was classified according to a predetermined set of keywords. Each set then was keypunched and loaded onto magnetic tape. We used the "FAMULUS" programs (Burton et al., 1969) to sort through the question sets. We then synthesized them into 24 system-type problem areas (appendix A).

In this activity, we paid considerable attention to fire-ecosystem level problem areas with respect to the characteristics of ecosystem functioning, as indicated across the top of Figure 1. Other levels of biological organization, such as organ and organism, were regarded as secondary, in keeping with the Analysis of Ecosystems emphasis in the US/IBP.

The view of fire ecology in a systems context requires that various attributes of fire events be identified and treated as quantitative variables. These fire input variables for various fire-ecosystem simulation models are listed as rows in Figure 1. The fire variables are specific and can be quantified as we have identified them. The ecosystem characteristics are a mixture of subsystems and some specific variables (Fig. 1). One should frame questions by looking at the rows

		Energy exchange processes	Moisture exchange processes	Nutrient exchange, decomposition	Primary productivity	Litter accumulation	Animal food chains	Species diversity	Ecologic succession	Stability — Resiliency
TEMPORAL	Reburn frequency									
	Burn date									
	Fire duration									
LASTING	Fuel reduction									
	Fuel disfiguration									
GEOMETRIC	Spread rate									
	Flame height, width									
	Burn area size, shape, location									
TRANSIENT	Heat intensity									
	Temperature gradient									
	Radiation spectral composition									
	Smoke concentration, composition									

Fig. 1. Interaction matrix for characteristics of fire and ecosystem function.

of Figure 1 and by asking how changes in these attributes of fire will affect specific variables involved in the ecosystem properties across the top of the matrix. All questions we received in the questions survey fit someplace into this interaction matrix.

Priority Evaluation

After determining a variety of fire-ecosystem problem areas, we were faced with evaluating priorities among them. Within the last 15 years, such "think tanks" as Rand Corp., Systems Development Corp., and TRW, have developed technological forecasting techniques in the operations research field. An instructive introduction to these techniques for analyzing possible future courses of events is given in Bright (1972). One technique, the Delphi Method, is usually used to predict future dates at which a given technical or social development will have occurred. It is characterized by three features:

1. Anonymity of participants with respect to each other;
2. statistical summarization of group response; and
3. controlled feedback of group judgments and other information to participants through a sequence of iterations or rounds.

At the beginning, the elements in need of evaluation are sent to the participants making up the Delphi Panel. The panelists make their individual evaluations and return their replies to the design team. This team (the authors, in this case) then tabulates a group response for the entire panel on each item and sends it back to each panelist with his own original evaluation.

The group response on each item is usually presented as the median rank because it is not affected by an extreme outlier value, as is the arithmetic mean. In addition, the interquartile range is used to present the 25th and 75th percentile responses for each item evaluated.

Panelists are asked in round number two to reconsider their original evaluations in view of the entire panel's group response and if their original judgments lie outside of the interquartile range, they are asked to reevaluate their position. If they choose to remain outside of the interval they are asked to justify their decision and thereby display their reasoning. Hopefully, information supplies or deficits, which they have, that the majority of the panel does not have will become apparent. These comments are included anonymously in the next round that is sent back out to the panelists.

Anonymity precludes the personality effects that inevitably prevail in conventional face-to-face committee meetings. The Delphi process assumes that the interpersonal differences in evaluation within a given professional set of people at any one time are at least as important as the differences in decisions displayed by any one individual over a span of time, where that span has seen feedback of new information to each individual during his sequence of decisions.

To date, the greatest use of the Delphi Method has been in government, industrial, and business planning. Bright (1972) indicates that by 1972, around 1,000 Delphi studies had been conducted around the world. Research, development, and application of the Delphi Method continue, with Linstone and Turoff (in press) soon publishing a book on the method.

Rather than using the Delphi process for prediction of future dates of technical developments, we used it to evaluate the relative need of land managers and scientists for solutions to our 24 fire-ecosystem problem areas. Our literature review of the Delphi Method uncovered only three published attempts by others to apply the method in natural resources research and management planning (Brown and La Chapelle, 1973; Dee et al., 1973; and Kane et al., 1973).

Since we assumed that the perceptions of land managers as a group and environmental scientists as a group differed from each other, we decided to run two independent, but simultaneous, three-round Delphi experiments on the 24 problem areas. Dalkey (1969) shows that there are diminishing returns in selecting Delphi panels larger than 10 to 15 people, if diminishing returns are viewed as the degree to which the Delphi panel response deviates from the real-world state of affairs. We selected 12 land managers for the one Delphi panel and 12 environmental scientists for the other. Neither of our two groups realized that the other was going through the Delphi process. In selecting the panelists, we went through the responses of all respondents to the questions survey to identify those whose questions best met certain criteria:

1. Demonstrated field experience in coniferous forests;
2. demonstrated field observations of forest fires;
3. demonstrated apparent interdisciplinary concerns;
4. were oriented toward principles of ecosystem functioning.

A concerted effort was made to avoid selecting any respondents who obviously were narrow subject area specialists as we felt they would be prone to evaluate the problem areas from a single vested interest. This selection procedure produced two sets of 35 people for the scientist and land manager groups. From a statistical view, these are defined as our populations, although this entire approach is dependent upon judgment sampling and cannot be treated with conventional statistical analysis. We wanted only 12 participants for each panel. These were selected randomly from the two groups. While not a part of our selection criteria, it appeared that neither of our two groups contained ultra-conservative or ultra-liberal individuals with respect to fire in the landscape. We sent each prospective Delphi panelist a letter of explanation asking his agreement to participate.

Anonymity of panelists is an established convention of the Delphi procedure. We can show, however, the generic professional affiliations of the land manager and scientist panels, which were as follows:

LAND MANAGERS	
Federal/National	9
State/Province	3
	12
SCIENTISTS	
Academic	7
Federal/National	4
State/Province	1
	12

Figure 2 is a map of their distributions.

The panelists were asked to imagine that they were responsible for setting research priorities and received proposals for the problem areas in appendix A. They were asked to rank each one, with 1 as highest through 11 as lowest priority, with the condition that they could use the same rank more than once. They were asked to consider all coniferous forests in western North America.

Both Delphi exercises were conducted in three rounds during May-July, 1974. Results of both panels' evaluations of the problem areas are presented in the next section.

Literature Search

The FAMULUS computer programs were used to store 3,200 citations of fire ecology publications and other literature useful in designing fire-ecosystem models for western coniferous forests. Special abstracts indicating data content and conditional logic were

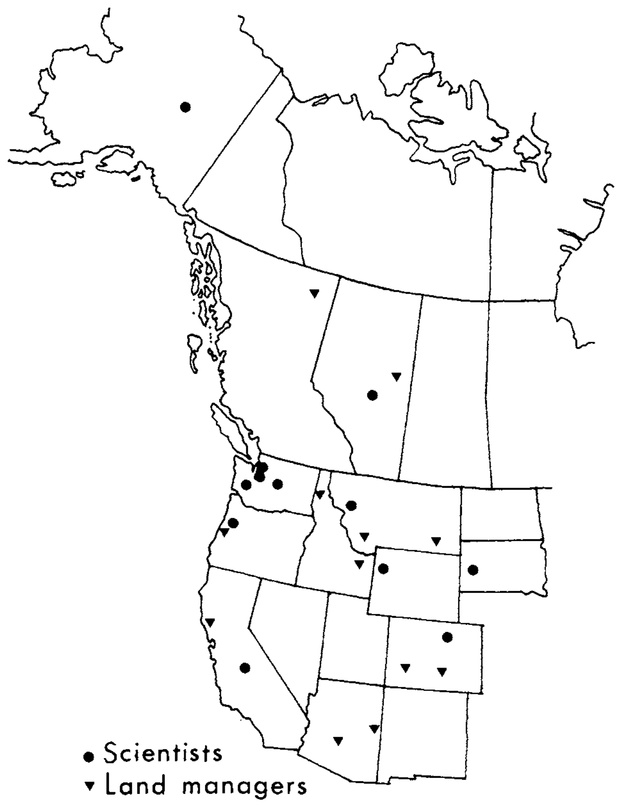

Fig. 2. Locations of 12 land manager Delphi panelists and 12 scientist Delphi panelists.

written for about 400 of the articles. Copies of the printout of this file have been sent to some 50 university libraries, research institutions, and individuals in the United States, Canada, and Australia.

RESULTS

Delphi

The results should not be interpreted as fire ecology research needs of all land managers or of all environmental scientists in western North America. They do indicate the desired priorities of samples from subsets of both groups. Each subset, by our evaluation, consists of some penetrating thinkers in respect to ecology. After round number 1, one individual in each panel dropped out for reasons unknown to us.

The results of the third round of ranking the 24 problem areas by the Delphi panel of land managers are shown in Figure 3A. The highest rank, 1, is to the left and the lowest rank, 11, to the right. A variation in the median ranks assigned by the land managers for the various problem areas is clearly evident as one looks from top to bottom. A variation between problem areas can also be seen for the magnitude and direction of the interquartile range. Variation can be interpreted as the relative degree of consensus for a given problem area resulting after the third round among the 11 land managers.

For example, problem area 5 (the way in which fires might cause soil water repellency, the subsequent processes that break down repellent layers, and the effect on tree regeneration) shows a high median rank with considerable consensus. In contrast, the problem dealing with fire effects on physical processes in streams and subsequent stream biological productivity (problem area 7) has an equally high median rank, but not as great a consensus on that rank among the 11 land managers. Interestingly, this group achieved a high degree of consensus that the problem of fire interactions with small mammal population dynamics, seed gathering, tree reproduction, and predator prey relations (problem area 17) should be ranked relatively low (rank=8). In contrast, they gave the same median rank (8) to the problem of fires producing various snag densities and the importance of such habitats for supporting bird food chains (problem area 16), but they could not agree with each other. Lack of consensus is indicated by the relatively large interquartile range. Figure 3B shows results of the scientist panel on the same 24 problem areas.

Comparisons of the evaluations of two problem areas by the scientist panel and the land manager panel can be seen in Figure 4. Land managers agreed upon the high rank for the fire-soil water repellency problem (problem area 5); scientists could not achieve

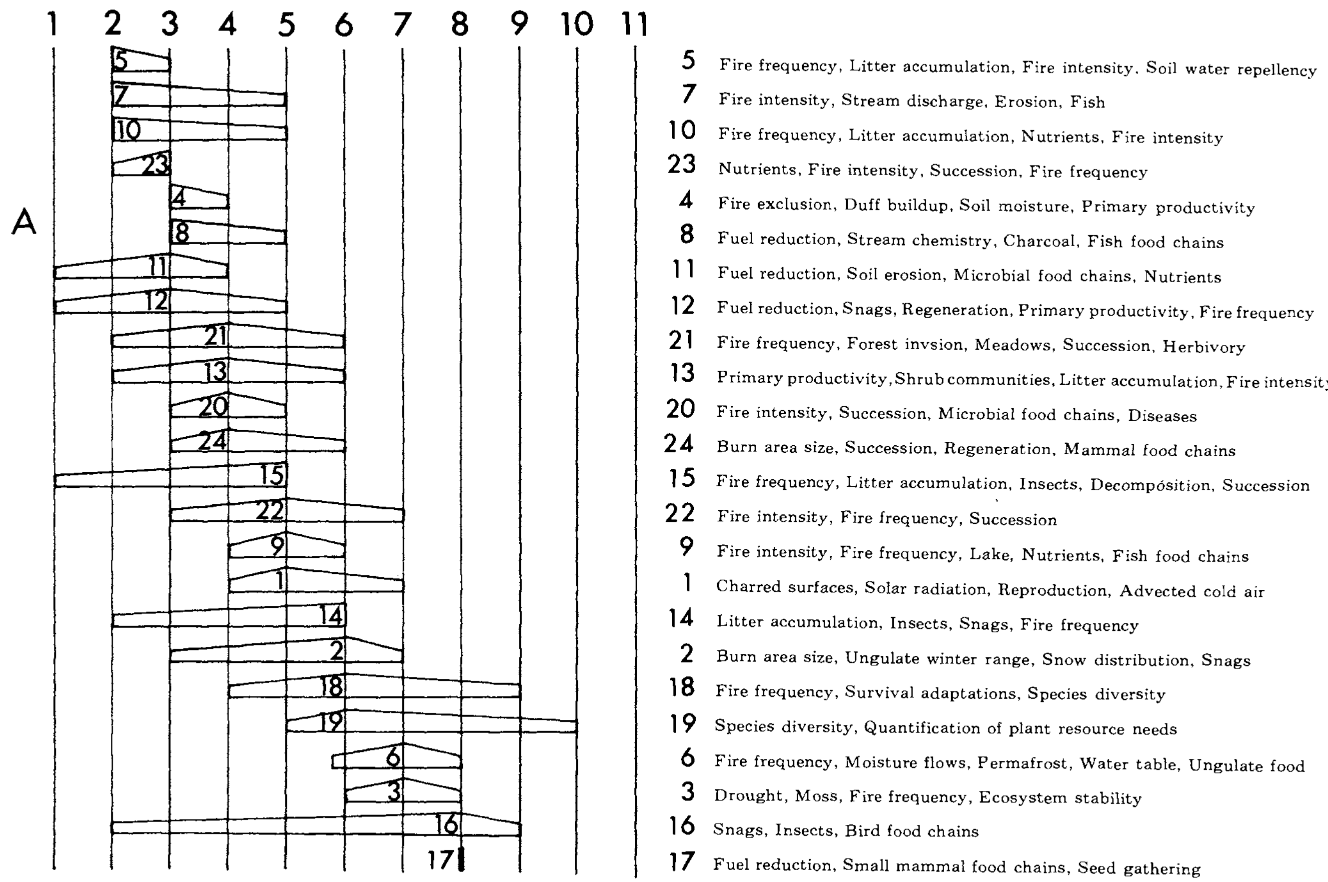

Fig. 3(A). Median rank and interquartile range for land manager Delphi panel on 24 problem areas. Examples of the interquartile range and median location are shown for problem area 16. Problem area 17 has an interquartile range of zero; at least half of the panel chose rank = 8.

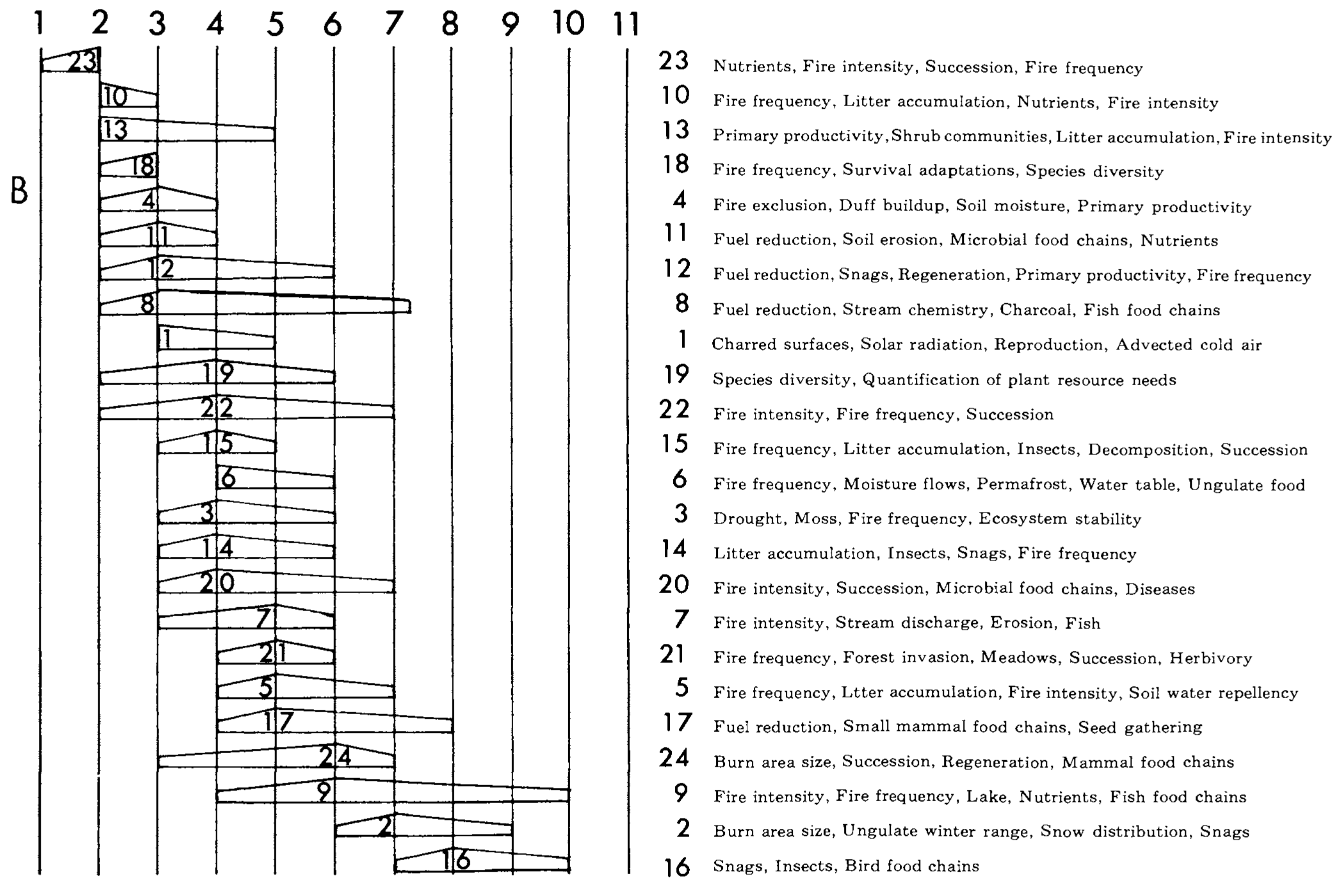

Fig. 3(B). Median rank and interquartile range for scientist Delphi panel on 24 problem areas.

as great a consensus, but did indicate that the problem was not as important to them. In contrast, for problem area 18, the scientists agreed that considerable importance should be attached to the problem of genetic response of plants to changes in natural fire frequency and the form taken by adaptations to fire to sustain species diversity and ecosystem stability. Figure 4 shows that the land manager panel did not rank this problem area highly, even though they could not achieve a strong consensus.

We think it is important to look at the combined responses for both the land manager panel and the scientist panel on any problem area. The land managers are likely to have more field experience under a variety of conditions. The scientists are likely to have a greater depth of understanding of environmental processes and complicated interactions. They are also likely to have better access to the most recent literature on a given problem area than the managers and perhaps are held more accountable for their understanding of it as they fulfill their role.

Figure 4 may not be the best format for jointly comparing the land managers' and the scientists' evaluation for various problem areas. We suggest that a more easily appreciated representation is to locate each of the problem areas on a grid, according to the medians from both Delphi panels. This could be done at the end of any of the rounds.

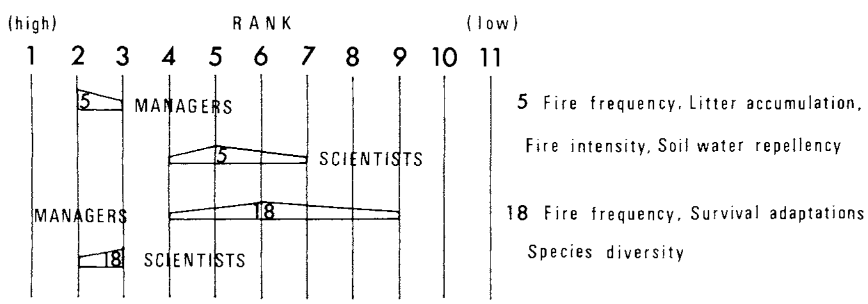

Fig. 4. Examples of third-round group median ranks and interquartile ranges for two different fire-ecosystem problem areas for land manager panel versus scientist panel.

If done at the end of round number one, and again at the end of the final round, we should be able to see how the Delphi process leads to a change in the evaluation of problem areas, by both land managers and scientists. This change is shown for each problem area in Figure 5. For any problem area, the tail of the arrow indicates the median ranks for both panels from round number 1. The heads of the arrows indicate the median ranks for both panels for round number three. Problem areas 20 and 23 did not change in median ranks from both panels throughout the three-round Delphi.

In Figure 5, we see that problem area 8 assumed a higher median rank from both panels through the three rounds and also assumed agreement in the median rank between the two panels, even though neither panel was aware of the other's existence. This problem area

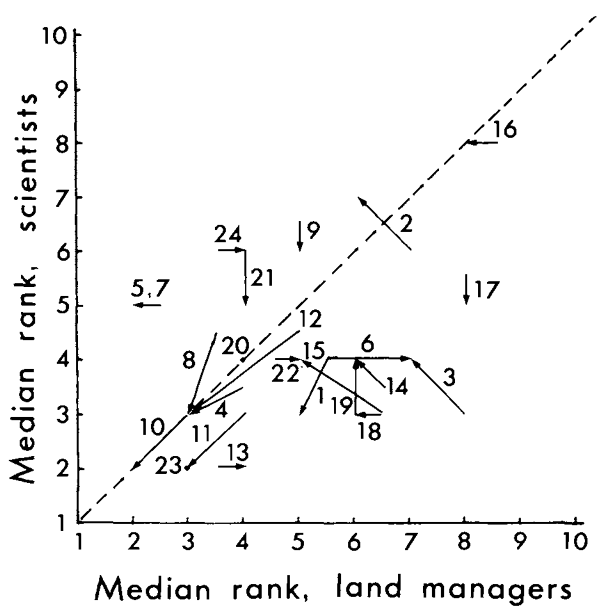

Fig. 5. Changes in median ranks for problem areas throughout the three-round Delphi. Tails of the arrows are located at first-round medians and tips of arrows are located at third-round medians after panelists' reconsiderations. Numbers on the grid identify problem areas found in appendix A.

deals with the possible effects of fires on stream water quality and subsequent biological productivity.

Problem area 6 in Figure 5 deals with changes in fire attributes as they might affect permafrost and vegetal patterns in the northern forests, in contrast to possible effects on the hydrologic system and large mammal habitat availability in temperate forests free of permafrost. As a result of the three-round Delphi, this problem area assumed a lower median rank among the land managers, but its evaluation did not change among the scientists.

In such comparisons, any problem area that becomes located toward the upper left of the grid (Fig. 5) is evidently more important to the land manager panel than to the scientist panel. Any problem area that becomes located in the lower right portion of the grid is evidently more important to the scientist panel than to the land manager panel. Any problem area that becomes located on the straight line of slope +1 demonstrates agreement in median ranks for both Delphi panels.

Each problem area can be primarily associated with one of the characteristics of ecosystem functioning. Figure 6 shows how these groups of fire-ecosystem problem areas cluster in median-rank space. It is evident that both groups ascribe a high importance to the fire-primary productivity problem areas (12 and 13 in A) and also to the fire-nutrient cycling problem areas (10 and 11 in B). The fire-species diversity problem areas (18 and 19 in C) appear to be of greater importance to the scientist panel than to the land manager panel. Similar evidence is shown for the fire-food chain problem areas (14, 15, 16, and 17 in B) and two of the three problem areas dealing with fire and effects on meteorological energy flows (1 and 3 in A). Apparently, there was some tendency for our land manager panel to favor problems of fire and aquatic response (7 and 9) to a greater extent than the evaluations of the scientist panel, although problem area 9 is only marginally favored.

Figure 6 is a representation of the central tendency, expressed by the median rank for both panels on all 24 problem areas. These figures do not show relative convergence or divergence in panel rankings of problem areas. If we use the same graphic procedure, but

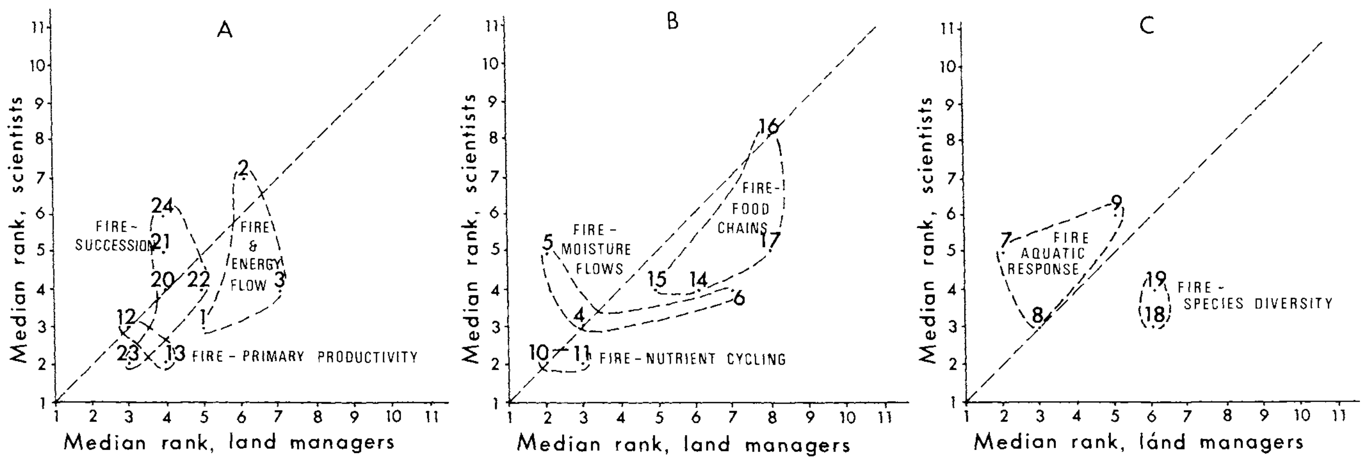

Fig. 6. Problem areas graphed by median rank from round number three for scientist versus land manager panel.

use magnitudes of third-round interquartile ranges for each problem area, we get a picture of this relative convergence (Fig. 7).

In this figure, the closer a problem area lies to the origin (0,0), the greater was the convergence of opinion of both Delphi panels on its rank. The closer a problem area is to, say, the point with coordinates (6, 6), the greater was the divergence of opinion on the ranks given the problem area. A problem area lying to the upper left in the grid indicates that our scientist panel couldn't agree on the deserved rank, but our land manager panel could. A problem area lying in the lower right indicates that our land manager panel could not agree on the deserved rank, but our scientist panel could.

In terms of consensus, the group of problem areas dealing with fire effects on nutrient cycling (10, 11, and 23), and especially that dealing with fire-nutrient cycling in terms of nutrient exchange processes in an ecological succession context (23), demonstrates the greatest agreement between both groups, as is shown in C.

To this point, we have examined the comparative results between scientists and land managers in terms of group median ranks, and alternatively, in terms of the relative agreement or disagreement for certain problem areas.

In approaching our conclusions on operational priorities for the various problem areas, we need to look at each problem area in the four dimensions of group median ranks, and interquartile ranges for both groups simultaneously. Figure 8 (A and B) provides this information for each panel separately. Problem areas located nearest the lower left corner are considered of high importance and those nearest the lower right corner are considered of low importance.

As an example, in A, the land managers display relative agreement that problem areas 4, 5, 7, 8, 10, 11, and 23 are of high importance and that problem areas 3, 6, 9, and 17 are of low importance. They could not agree that problem area 12 is highly important nor that problem areas 16, 18, and 19 are of relatively lower importance. One can derive similar information, but for different problem areas, for the scientist panel by examining the four corner areas of B.

In an attempt to combine results of both Delphi panels, C was produced by taking the arithmetic mean of the two panels' group median ranks (third round) on each problem area and also the arith-

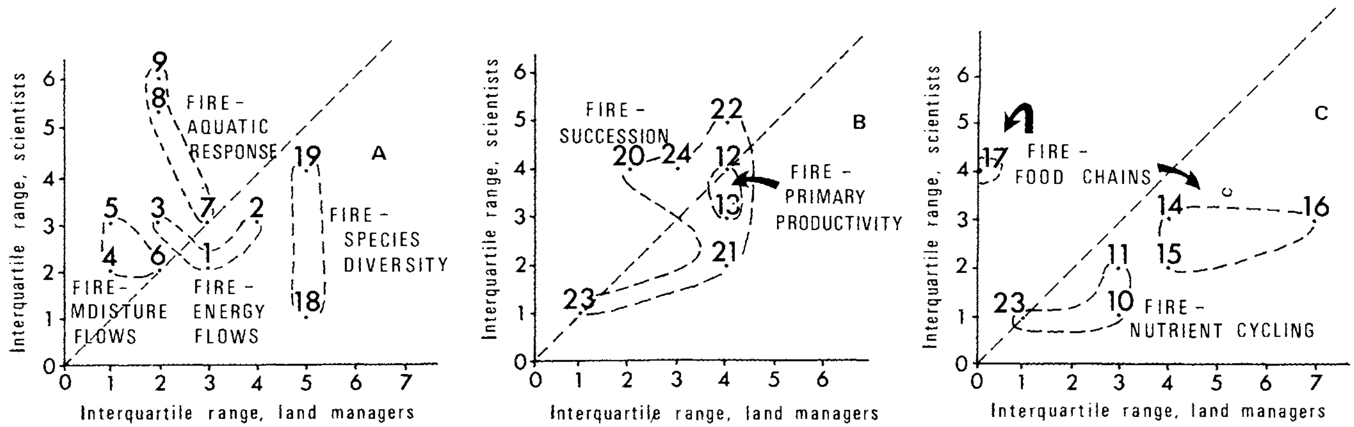

Fig. 7. Problem areas graphed by interquartile range from round number three for scientist versus land manager panel.

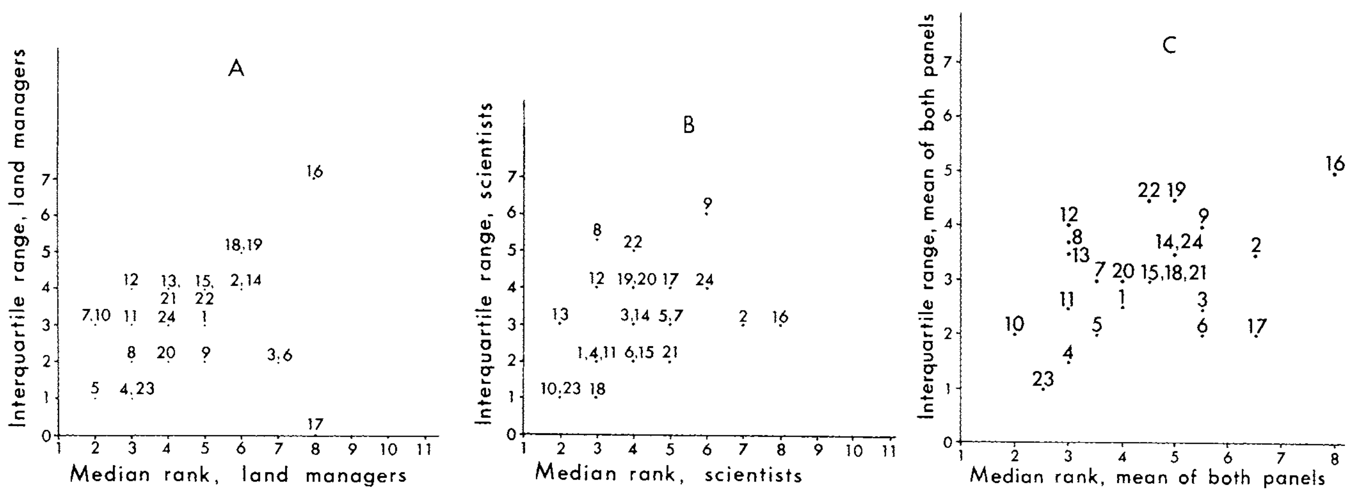

Fig. 8(A). Problem areas graphed by group interquartile range and group median rank for land manager panel. (B) Problem areas graphed by group interquartile range and group median rank for scientist panel. (C) Problem areas graphed by mean of both panels' interquartile range and mean of median rank.

metic mean of the two panels' interquartile range. The combined panel results indicate that our fire-nutrient cycling problem areas (10, 11, and 23) are ranked as most in need of research. Two of the fire-moisture flow system problem areas (4 and 5) also provoked this response. Of least relative need for research as expressed by combined panel results are three other problem areas dealing with fire-moisture flow response (2, 3, and 6), although panel members could not agree among themselves on this issue. The problem area (17) dealing with small mammal food chains was also indicated as having little interest to both panels when results are combined.

Literature Search

General results from our study of the fire ecology literature show that 1,000 new publications are due to appear during the present period, 1974-78 (Fig. 9). Space does not permit a review of the literature of various effects of fire on ecosystems. Pertinent, though, is the small extent to which this knowledge has been integrated into quantitative computer models that might be used for the problem areas interpreted as high priority in this study.

We could locate only two publications dealing with the design of dynamic system models of the effects of wildland fire on the environment (Agee, 1973; Woodmansee and Innis, 1973). The latter publication does not treat the fire process quantitatively. On the other hand, several authors have quantitatively modeled the effects of environmental structure and processes on fire attributes in ecosystems (Van Wagner, 1967; Kourtz and O'Regan,1971; Deeming et al., 1972; Rothermel, 1972; Rothermel and Philpot, 1973; Lindenmuth and Davis, 1973; Stevenson et al., 1975).

CONCLUSIONS

Possible Sources of Error

Some bias is probably inevitable because panelists did not equally match the four major criteria upon which they were selected. This inequality includes differences in environmental and ecological training, in part a consequence of the unavailability of certain spe-

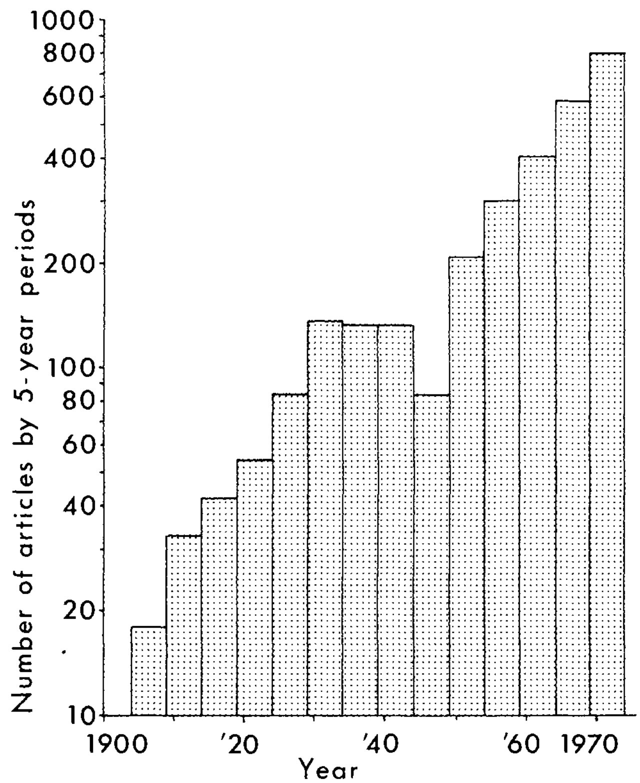

Fig. 9. Occurrence of articles in the literature file of the Fire Ecology Project by 5-year intervals.

cialties at university professional schools. We hope to have minimized this source of bias through our screening procedure.

Some panelists said they ranked some problems as having lower importance because the problems were too complex—"Too many variables." We argue that this is the reason for planning to use a systems modeling approach in the first place. Some panelist could not appreciate this, which is understandable; systems ecology is a relatively new area of the environmental sciences. The variability in understanding the capabilities of a modeling approach, as opposed to a conventional field observation research program, may well have affected various panelists' perception of the problem areas.

Aside from the degree of complexity, the degree of specificity or generality at which a problem area is defined might have affected the rank it received.

With respect to value system differences between the two panels, we think the following conditions could lead to different priorities for each panel: land managers focus on the availability of one or several resource products demanded by society from specific ecosystems; scientist focus on the search for principles that can be used in the management and stability of production.

The above distinctions highlight the possible underlying differences in world views when it comes to evaluating research priorities in environmental sciences.

Interpretations of Priorities

We make our interpretations of operational priorities for fire-ecosystem problem areas from Figure 8 for the land manager panel separately, the scientist panel separately, and for both panels together. In these figures, some problem areas have lower numerical group medians, some have higher. Some have smaller interquartile ranges, some have larger. On this basis, we interpret 25 percent of the problem areas that have the lower numerical group medians and smaller interquartile ranges as problem areas with "clientele-oriented" high priority.

Because of the limitations discussed above, we conceive of a separate group of problem areas which we call risk-oriented high-priority problem areas. These are 25 percent of the problem areas that have the highest numerical group medians (apparent low priority) and smaller interquartile ranges. While the panels agree that these should be of lower need for research, this very agreement might be a red flag indicating that important discoveries might be made through research on these problem areas. The absence of literature or other "publicity" on a set of relationships, might lead panels to respond with a lower rank for the problem areas.

Table 1 shows our interpretation of which problem areas fall into these priority classes. The problem areas that do not appear in one

Table 1. Problem area priorities in terms of 25 percent, most extreme group median ranks, and smallest interquartile ranges.

Panels	High Clientele-Priority	
Land managers	4	Fire exclusion, duff buildup, soil moisture, primary productivity
	5	Fire frequency, litter accumulation, fire intensity, soil water repellency
	23	Nutrients, fire intensity, succession, fire frequency
	7	Fire intensity, stream discharge, erosion, fish
	8	Fuel reduction, stream chemistry, charcoal, fish food chains
	10	Fire frequency, litter accumulation, nutrients, fire intensity, decomposition
Scientists	10	Fire frequency, litter accumulation, nutrients, fire intensity, decomposition
	18	Fire frequency, survival adaptations, species diversity
	23	Nutrients, fire intensity, succession, fire frequency.
	1	Charred surfaces, solar radiation, reproduction, advected cold air
	4	Fire exclusion, duff buildup, soil moisture, primary productivity
	11	Fuel reduction, soil erosion, microbial food chains, nutrients, fire intensity
Combined	4	Fire exclusion, duff buildup, soil moisture, primary productivity
	10	Fire frequency, litter accumulation, nutrients, fire intensity, decomposition
	23	Nutrients, fire intensity, succession, fire frequency
	5	Fire frequency, litter accumulation, fire intensity, soil water repellency
	11	Fuel reduction, soil erosion, microbial food chains, nutrients, fire intensity
	1	Charred surfaces, solar radiation, reproduction, advected cold air
Panels	**Low Clientele-Priority (High Risk-Priority)**	
Land managers	3	Drought, moss, fire frequency, ecosystem stability
	6	Fire frequency, moisture flows, permafrost, water table, stream flow, ungulate herbivory
	17	Fuel reduction, small mammal food chains, seed gathering
	1	Charred surfaces, solar radiation, reproduction, advected cold air
	9	Fire intensity, fire frequency, lakes, nutrients, fish food chains, succession
Scientists	2	Burn area size, ungulate winter range, snow distribution, snags
	16	Snags, insects, bird food chains
	24	Burn area size, succession, regeneration, mammal food chains

	5	Fire frequency, litter accumulation, fire intensity, soil water repellency
	7	Fire intensity, stream discharge, erosion, fish
	21	Fire frequency, forest invasion, meadows, succession, herbivory
Combined	3	Drought, moss, fire frequency, ecosystem stability
	6	Fire frequency, moisture flows, permafrost, water table, stream flow, ugulate herbivory
	17	Fuel reduction, small mammal food chains, seed gathering
	2	Burn area size, ungulate winter range, snow distribution, snags

of the priority classes can be considered as indeterminate, in view that the Delphi panels were not able to reach a consensus on what their ranks should be. We notice that the land manager panel's high-risk priorities prevail in the high-risk priorities for combined panels. This is because they could achieve greater consensus on what is of lesser need to them than the scientist panel could.

We make these conclusions from two panels of 11 land managers and 11 scientists. They were presumably considering the entire Coniferous Forest Biome on a regional scale. At a local scale for a particular management district, priorities could be entirely different from the indications we have for the regional scale. These priorities should not be interpreted necessarily as needs for collection of more field data. The first necessary activity is to synthesize what is already known by putting together system simulation models according to these priorities. That procedure will determine the kinds of additional field data needed. If we already had comprehensive ecosystem models on the computer, these are apparently the kinds of problems that our land manager panel and scientist panel would want to throw at it from the regional scale. With this knowledge, we can make sure that the ecosystem models we design for the computer can be addressed to these problems.

One of the next steps in applying a systems modeling approach is to postulate flow charts for the system variables involved in each of the high-priority problem areas. Because space precludes the presentation of detailed flow charts and since further pursuit of the details of this analysis might be of greater immediate interest to the fire ecology scientists than the fire-land managers, we shall present only gross interaction diagrams. These show the subsystems involved for one of the high-clientele priorities, Figure 10 for problem area 10, and one of the high-risk priorities, Figure 11 for problem area 17, for both panels combined.

What are the implications for land managers? They should be aware that there is a growing movement for scientists to heed and use their indications of problems that need to be attacked. It is partly the managers' responsibility to identify specific fire effects problems for which they need solutions.

What are the implications for scientists? In regard to the relative accessibility of recent research information, those researchers, who are responsive to land managers' needs, face a problem. The land managers' awareness of existing knowledge on a particular problem may lag several years behind the researchers' knowledge. This situation, which is by no means recent, raises the problem of how investigators can best be responsive when selecting their problems to investigate. A long-term solution undoubtedly involves setting up information exchange systems that will reduce the time lag between information discovery by researchers and information accessibility and diffusion in useable form. One example of an attempt at this is the "firebase" program described by A. R. Taylor and E. E. Matthews (USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah).

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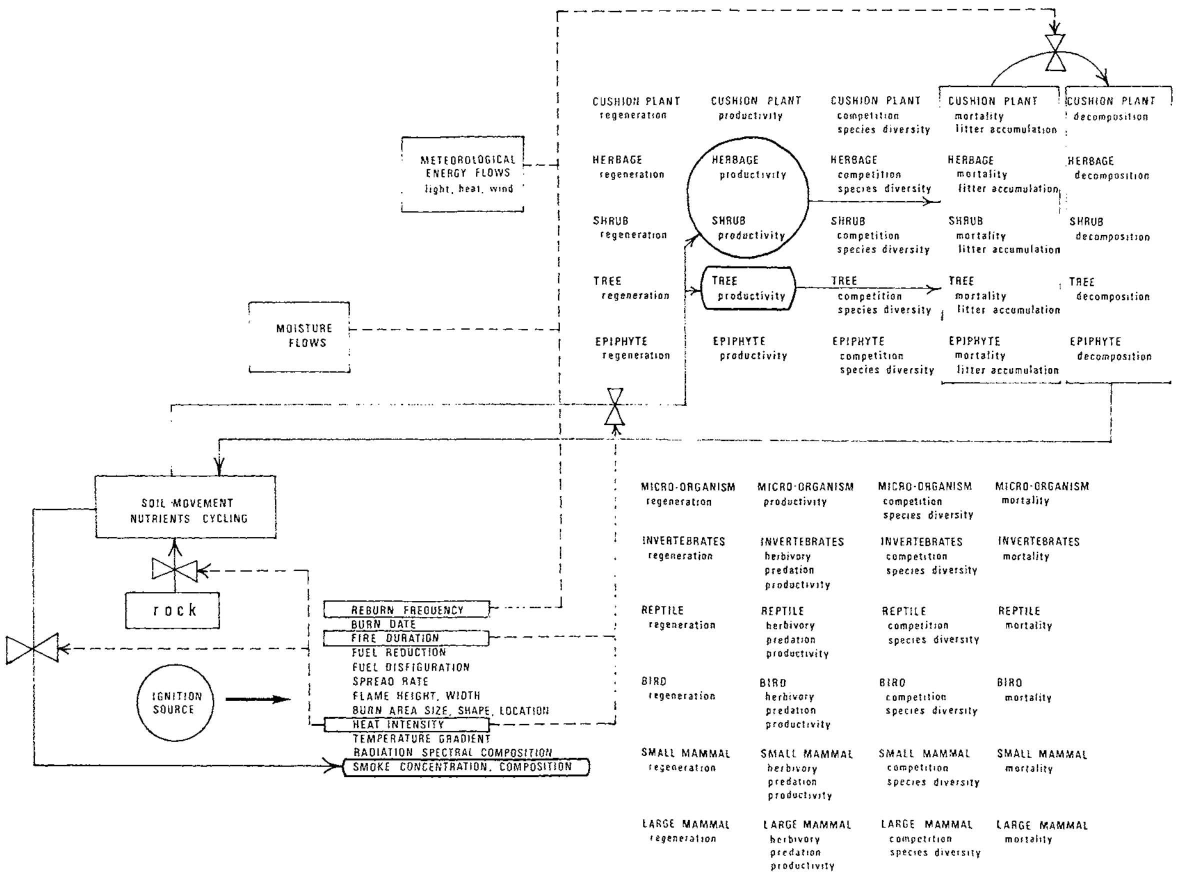

Fig. 10. Fire variables and subsystems involved in problem area 10, a high-clientele priority problem area, based upon combined results of land manager and scientist panels (see Table 1 and appendix A).

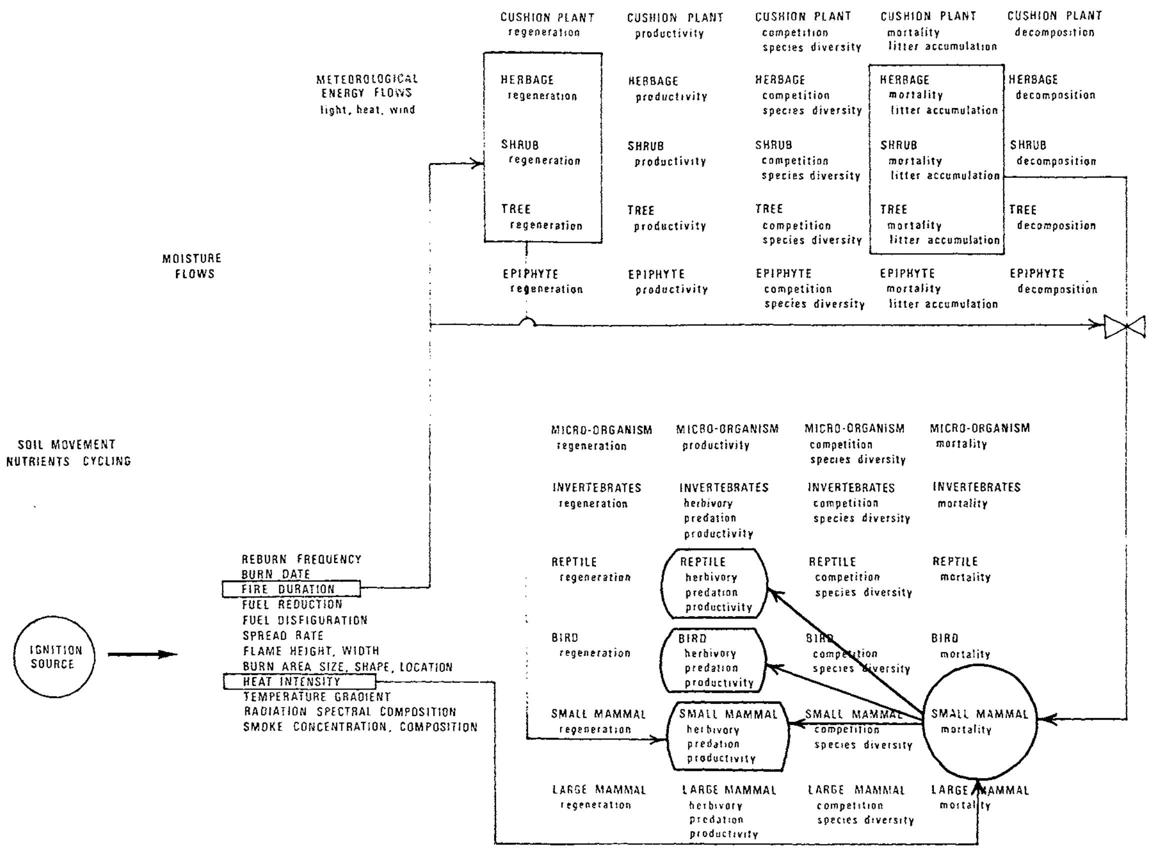

Fig. 11. Fire variables and subsystems involved in problem area 17, a high-risk priority problem area, based upon combined results of land manager and scientist panels (see Table 1 and appendix A).

A good part of this investigation could not have been attempted without the patient participation of 12 land managers and 12 scientists around the western United States and Canada. To them, we express our thanks. For helping with sticky nuts and bolts of computer program debugging, our appreciation is due Mr. Steve Henry and Ms. Marge Blazevich of the University of Montana Computer Center.

While acknowledging the help of all of these individuals, we take full responsibility for the conduct and interpretation of this research.

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APPENDIX A

Fire Ecology Survey

(1)

Blackened ground absorbs more solar radiation than naturally colored surfaces. The additional heat might cause earlier spring plant growth for some species. However, regional weather could still bring frost, snow, and cold spring winds. What is the effect of the latter on vegetal productivity from an earlier start on burned land, as compared to vegetation that greens up a month later on unburned soil? What is the effect of post-ground fire needle-cast under Douglas-fir, as seen in the litter microclimate on the forest floor? If this increases the proportion of reflected solar radiation, over what it would otherwise be, is this significant in controlling the pattern of regeneration of understory plant species following the fire?

(2)

What is the effect of crown-fire area size on the availability of ungulate winter range in subsequent winters? Is winter carrying capacity increased, or is new browse unavailable because of drifting snow, wind crust and ice layer formation? Does more winter range become available due to faster melting of the snowpack from standing charred snags? What is the effect of different snag densities on the melting rate of the snow pack in the first, fifth, and fiftieth spring after the fire?

(3)

With an increase in geographic latitude, one finds forest areas characterized by moss ground cover which experience a few short periods conducive to fire propagations. The rapid response of fire-related phenomena would seem to indicate that relatively few, very large fires are a necessary component of the northern boreal forest. Consider: (a) the rapid drying of cladonia moss, and the minimal upper portion that must be available to support combustion, (b) the continuous nature of this fuel type, combined with a fully integrated, extremely flammable (spruce-fir) aerial fuel component that provides rapid transition to the crowning stage in a fuel type (true fir) noted for fire brand initiation. The ease of cladonia moss ignition ensures a high ignition probability upon contact. (c) The coincidence of weather systems, that involve a combination of sustained high winds and severe drying, with a period when foliar flushing, and frozen soils may result in severe depression of leaf moisture content, the combination of weather, and the peculiarities of the fuel complex, indicate a natural system that ensures maximum burned area in the short time available.

What is the effect of fire exclusion on the stability of this ecosystem to persist in the future?

(4)

In many areas of ponderosa pine, we find "dog-hair" thickets which have grown up in the last 20-60 years, due to fire exclusion. Presently, they are biological deserts, and certainly, fires would have changed this situation, if allowed to burn in the past. Management activities can replace fire to some extent in the removal of trees. However, the ecosystem is still left with a build-up of duff. What is the effect of changes in duff thickness on the penetration of water into the soil, and on the establishment of other plants? Is it possible for the litter layer to short-circuit the flow of moisture to tree roots? How dry must the rooting zone remain before no net annual growth in the tree system occurs? Does tree tissue water stress influence flammability?

What is the effect of different degrees of duff reduction by fire, on the site moisture budget, available plant nutrients, and subsequent regeneration of various tree species?

(5)

What kinds of fires, in what kinds of ecosystems, produce water repellency in soils? How does temperature relate to the depth of hydrophobicity? How does heat affect soil structure? What is the effect of increasing the length of time between fires, and thereby the dead organic matter, as seen in the tendency toward water repellent layer formation? What are the processes that break down water repellency of soil layers? What is the effect of changes in available soil moisture on the survival percentage of various tree seedling species?

(6)

With increasing latitude northward, a large portion of the coniferous forest is black spruce growing on muskeg sites, often associated with permafrost. Much of the area has been repeatedly burned. Does frequent burning of this type of forest tend to prolong the wet state, because of the loss of the moisture-removing effects of transpiration? Would long-term total exclusion of fire tend to promote drying of the site through increased transpiration by the added forest cover, or would the rate of evaporation from the same site in a fire-denuded state, exceed moisture-loss by transpiration? What are the effects of differing intensities and frequencies of fire on the development, or subsidence, of permafrost in northern latitudes?

Southward from the permafrost zone, if fire were to reduce large forested areas, what could we expect from the increase in ground water (annual precipitation that otherwise would have been transpired by the trees, but would now percolate down)? Could saline seeps develop? Would flows increase at springs as the water table rises?

Beneath old growth stands continually protected from fire and logging, what effect is expected in stream flow as the stands become more and more decadent? Under this situation, watershed conditions are better in the upstream watershed, generally. Stabilization of the streambeds is resulting from the exclusion of fire. But, willow patches thrive on disturbed stream channels. Thus, wildland fire in the upland watersheds might have some value in maintaining food resources for large mammalian herbivores in the food chain. What is the effect of various kinds of fire events, versus natural stream channel disturbance, in maintaining these food resources? Are watershed drainage patterns influenced by fire frequency-plant dominance relations, or merely by soil moisture-rock composition relations?

(7)

What effects may be expected related to the discharge regime of streams from fires of various intensities located within their drainage basins? What is the effect of fire on snow accumulation, snowmelt, and timing and magnitude of peak runoff? Recognizing that sometimes fire results in soil loss and resultant degradation of stream channel quality, what time frame can be expected to naturally restore stream regimen to a level to support fisheries after the watershed has been stabilized? Can this be artificially regenerated through the introduction of fertilizers, microorganisms, and aquatic biota? How much, for how long, and by what processes do fires alter total water production, sedimentation, and erosion from forested watersheds?

Is it possible that, with natural fire frequencies, the fuel loads away from a stream were kept relatively low, such that intensities of fires were not usually great enough to ignite the stream bank vegetation?—But with fire exclusion, increased fuel loads lead to such fire intensities that streamside vegetation is removed? Would heat generated in a large forest fire be sufficient to directly kill aquatic invertebrates, fish, etc. in small mountain streams?

(8)

What effects do forest fires have on the chemical content of streams, both in the area of the fire and downstream? What changes in water quality (E. G. PH, dissolved oxygen, nitrate and phosphate content) would be associated with fires adjacent to streams? Does fire sterilize the soil, thus reducing the nutrients entering a stream and thus reducing the productivity of the stream? What chemical constituents can be expected in runoff from burned-over forest ecosystems? How much ash or carbon can a trout fishery withstand without substantial loss of fish? What effect does ash and charred material have on the oxygen level in a stream? How far downstream does carboniferous waste material travel? What effect does fire have on aquatic invertebrates so vital in the fish food web? Are some aquatic insects more resistant to habitat change caused by fire than others?

(9)

What are the long and short-term effects of forest fires of various intensities, sizes, and frequencies on the nutrient levels in mountain lakes? Is productivity affected significantly? What changes occur in the planktonic, fish, benthic, and shoreline communities? What changes occur in the input of terrestrial insects which would serve as imported fish food? What effect does fire and resultant change in detrital accumulation have on organic and inorganic substrate composition and mineralization in bottom sediments of lakes? Under what conditions could fire exclusion on forested slopes accelerate aquatic succession in adjacent lowland water bodies, and subsequently eliminate waterfowl habitats?

(10)

What is the effect of fire exclusion on the proportion of system nutrients (1) tied-up in dead litter and debris, (2) tree growth rates, and (3) protein content of herbage and shrubs?

What is the effect of various degrees of heat injury to leaf, stem and root biomass, as seen in levels of soil nutrients required to survive the injury? What is the rate of surface rock decomposition, and nutrients volatilized in the smoke column, from fires of various intensities? What percentage of total pre-fire nutrient reserves is available to plants after fires of various intensities and fuel loadings?

(11)

In forest ecosystems with contrasting rainfall patterns, what is the effect of various amounts of ground litter and duff consumption by fire, as seen in root mortality, variation of available plant nutrients with soil depth, and degree of soil stability? How are levels and types of soil microorganisms affected by fires? Does occasional low intensity burning increase soil microbial activity and allow for retention of nutrients in the ecosystem, or are the released nutrients lost to runoff and deep percolation? Are red soils following burning indicative of sterilization? What is the effect of various pre-fire biomass levels on the relative mortality of soil fauna and the amount of soil organic matter remaining after a fire?

(12)

What is the effect of different degrees of duff consumption by fire on subsequent regeneration success of conifers? What factors are important to lodgepole pine regeneration, and what, besides fire intensity, affects reproduction density following fire? How long is the regeneration period for interior Alaska black spruce stands following fire? Under what conditions will a south-facing slope present natural regeneration problems after crown-burn in ponderosa pine? Do scorched and burned trees left standing (as opposed to bare snags) affect the rate or success of regeneration? Is it wise to fall snags in old burns? Do they, once felled, provide needed shade for seedlings? What is the net effect of different intensities of fire on reforestation? Removal of certain amounts of fuel may be considered beneficial; beyond what point may that be considered a detriment? Is there a relationship between the amount and kind of revegetation and the time of year a fire occurs? If a fire occurs in July or August, what is the relationship to one that occurs in September or October?

What is the response of vegetation (changes in production rates by species) to burning at various fire intensities and at various times of the year? What effect do light ground fires, at 3 to 5 year intervals have on growth rates of even-aged ponderosa pine pole, and young saw timber stands when competing vegetation is not a factor? What volume of tree growth has been lost due to excessive competition from brush species as a result of fires in forests?

(13)

What is the effect of different densities of elk populations on reproduction of aspen, (1) with fire exclusion, and (2) with fires of various frequencies and intensities? What amount of ground cover is needed to create the type of fire needed to obtain an optimum deciduous shrub plant community for ungulates? Could a too-heavy fuel supply adversely affect the establishment of such a seral plant community? What ungulate browse species regenerate best after burning?

In the Pacific Northwest, which important wildlife forage species, if any, root sprout or crown sprout, after fires of searing intensities? Are any species encouraged by fire, other than through opening the forest canopy? What effect does fire intensity have on nutrient content of resprouting shrubs, and what is the change in production of shoots by length, number, or dry weight?

How is arboreal lichen productivity influenced by different kinds of fires?

Can grasses be maintained as an understory component in a ponderosa pine stand when fire is excluded? Under what conditions might the bases of snags act as refugia for the pioneer forbs, because of increased soil moisture from snag interception and stem flow after rain?

(14)

A number of destructive and beneficial insects spend a part of their life cycle, particularly the overwintering stages, in the duff. What is the effect of changes in litter accumulation on survival and distribution of insects that overwinter in the duff? Is fire periodicity in fact governed, to a large extent, by the occurrence and timing of insect attacks, disease outbreaks, windstorms and previous fires? What is the effect of changes in the fire frequency, and season of fire, as seen in the periodicity of insect epidemics, and leaf or root disease epidemics? How significant are various intensities of insect defoliation, or tree killing, in increasing fire intensity and rate of spread? Since insects can produce dead standing snags, what is the probability of lightning striking a dead standing tree and igniting it, as opposed to a live tree? Does a surface fire, of moderate intensity, increase the possibility of a residual stand being attacked by bark beetles? If so, how great is this increase?

What effect does wood smoke concentration have on the viability of airborne insect and spore populations? How much heat can a tree take before it becomes weakened to the point that bark beetles are attracted to it? What is the effect of varying intensities of ground fires on insects and other arthropods inhabiting the litter, duff, and soil in various forest ecosystems? What might be the effect of changes in the intensity of a fire, as observed in the density of viable seeds in the soil and the density of soil arthropods?

(15)

What is the nature and rate of organic matter accumulation and decomposition in different forest ecosystems? How do they change with stand age? How are they affected by periodic and endemic events, such as disease and/or insect epidemics, and windthrow? This should be considered for a variety of ecosystem types and include mean fire frequency. Has surface fire exclusion in coniferous forests resulted in an increase in populations of cone-feeding insects that spend a part of their life cycle in the litter? Has surface fire exclusion in coniferous forests reduced populations of insects that parasitize other insects, by altering the species composition of flowering and fruit bearing ground cover which is important as a food source for adult parasitoids, such as the Ichneumonids?

Has fire exclusion in some coniferous forests increased their susceptibility to bark beetles and Douglas-fir tussock moth by allowing an increase in the true fir understory components? Is fire exclusion likely to preserve insect-infested, or disease-infected, residual trees which will form a source of infestation/infection to the succeeding stand?

Is fire exclusion likely to enhance the accumulation of disease inoculum and insect populations? There is a need to understand interrelationships between forest fires and insects. For example, lodgepole pine stands are passed on to future successional stages by light/medium fires with the aid of the mountain pine beetle. What would happen if fire were excluded entirely? Possibly, stand dynamics would depend entirely on bark beetles, that is, there would be total stand destruction without the aid of fire to regenerate the stands. On the other hand, would fire exclusion in ponderosa pine stands yield denser stands, and more lost material for bark beetles? Is there the possibility that more stems per acre could be carried forth?

(16)

After fires, many tall snags and stubs may remain. Such snags might represent the most attractive sites for feeding and nesting of hole-nesting birds and mammals. Do such snags represent a significant fire hazard by attracting lightning, or is this only important along ridges and on hills? Do the snags represent significant habitats for insect pests? Are insect outbreaks, following fires, necessary to maintain bird populations?

(17)

What is the effect of different degrees of fuel consumption on density of viable tree seeds on and in the soil, in terms of seed-gathering rodent population densities? What is the extent of burrowing small mammal mortality in a fire with various degrees of fuel consumption of the duff horizon? What is the effect of varying amounts of fuel reduction on the susceptibility of small mammal herbivores to predation? Are light surface fires, in dense and even-aged conifer stands detrimental to the omnivorous marten and fisher populations?

(18)

The stability of ecosystems to persist in the presence of disturbance has often been related to the degree of species diversity in the ecosystem. Diversity in turn would seem to depend upon the stability of the individual species in the community. This species stability would seem to depend upon genetic diversity and the adaptations, as well as adaptability of the species to periodic disturbances such as fire events, flooding, avalanche, insect attacks.

From a plant ecology and forest succession standpoint, an important aspect of understanding the ecological effects of fire lies in the area of adaptations to survive fire. Knowledge of the mechanisms and/or strategem employed by at least the "ecologically important" species of post-fire forest communities would give an insight to their initiation and provide the key for predicting their composition. (1) What physical form (morphologic) does the fire survival adaptation take? (2) Where is the morphological feature located with respect to the ground and what is the effect of various fire intensities and frequencies? (3) For dispersal adaptations, what are the timing limitations?

Is the bark thickness greater in the progeny of trees that survived in periods when fire was frequent (for example, ponderosa pine trees now over 300 years old) than in progeny of trees now reproductively mature (50-60 years) that have not been subjected (I.E., selected) to periodic fires? Has there been a change in this morphologic feature in two generations?

(19)

In order to predict the results of competition between plant species, and the diversity of plant species (or community composition) following any given fire event, or following long-term fire exclusion, we need diagrammatic quantification of various individual plant species' germination, growth, regrowth (following tissue loss), and mortality responses to variations in light, heat, available moisture, available nutrients, exchangeable toxic compounds, and proportion of tissue lost. This information should be obtained for various phenologic stages during different seasons, for the plant species' life cycle. This information should be synthesized from the plant ecology, forestry, and physiology literature for commonly occurring forbs, grasses, shrubs in coniferous understory and seral habitat types, and epiphytes in the overstory, as well as for various conifer species.

For species diversity of wildlife in the food webs, we need to know dietary preferences (and seasonal changes) for insect, arthropod, reptile, bird, small mammal, and large mammal herbivores, occurring in and around western coniferous forests.

(20)

What effect does fire have on fungal and microbial succession and processes? In the aftermath of various fire intensities, what changes should be expected in nitrogen fixation, decomposition-decomposer succession, mycorrhiza formation and succession of mycorrhizal fungi, sulphur fixation, and root pathogens? What is the effect of varying fire frequency on geographic location of diseases and what are the effects of these diseases on subsequent site productivity and successional patterns? Does fire have any measurable effect on the levels of heart rot and/or butt rot found in successor stands?

(21)

Is forest invasion of mountain meadow grazing areas ever the result of fire exclusion? What are the long-term wildlife effects of small parks being allowed, through fire exclusion, to reseed with conifers? What is the effect of decreasing the fire frequency as seen in the rate of forest encroachment on range lands? To what extent does the exclusion of ground fire from subalpine meadows promote lodgepole pine and red alder encroachment on natural grass ecosystems? In montane Douglas-fir/lodgepole pine forest, what rate of tree invasion can be expected on grassland when fire is excluded and also what effects on water yield does this have.

(22)

What are the effects of fire on secondary succession? Is the frequency, timing, or intensity of the fire most important on, 1) the successional vector after the burn?, 2) the first cover type to establish on the burned area?, 3) the recovery time to original state?

What ranges of fire behavior are effective in changing successional stage in alpine transition zones? What cycle lengths are involved in subalpine successional stages, and what is normal fire periodicity in high elevation subalpine and alpine types in the mountain west?

What is the effect of changing the seasonal timing and reburn frequency on the dominant post-fire plant species in pinyon-juniper invaded sagebrush communities? Many open, overmature aspen stands fail to produce suckers. Can fire exclusion prevent aspen suckering in these old stands, and will these stands revert to grassland or shrubland, once the overstory is gone, rather than develop into coniferous forests?

What are the relative fuel flammabilities of coniferous species and how are these values related to their successional positions? What changes in species composition will take place in ground and shrub layers with different fire intensities? Can one predict post-fire succession, knowing original vegetation and characteristics of the fire? Are successional stages of longer duration following a reburn on an area burned one or two years ago?

(23)

How and to what degree are key nutrient cycling processes (chemical solution and fixation, biological mineralization and uptake, and transfer mechanisms of the major nutrients N,P,K,CA, within the soil) affected by forest fires of different kinds and intensities? How long do these effects last and what are the consequences for long-term successional processes? Is there a point where soil damage from fire precludes regeneration of some conifers, while others would successfully regenerate and also stabilize the soil? Consider each forest type: does the repeated burning of a preclimax forest system cause continued reduction of the nutrient bank? If yes, how much of a nutrient reduction? What fire frequency must occur to keep the system at each seral stage?

(24)

For a given ungulate population density, do small burns display retarded ecological succession by virtue of being over-browsed? What is the relation between burn size and shape, and population density which would cause various degrees of retardation? Considering pioneer plant species, whose seed dispersal range is limited by wind, can changes in the size of crown burns affect the rate of secondary succession throughout the burned area? What are the reasons that unburned islands are left when slope, winds, fuels, etc. all indicate that the whole slope should burn cleanly?