Wildland Inventories and Fire Modeling by Gradient Analysis in Glacier National Park

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INTRODUCTION

THE rapidly increasing interest in wildfire modeling and enlightened fire management programs appears due to both: (1) the realization that traditional fire suppression programs are having serious deleterious ecological consequences; and (2) the recent advances in fire spread and intensity (combustion physics) models and quantitative inventory systems. This has resulted in fire management (let-burn) areas within some national parks and national forests, and intensive research towards real-time fire models (Stevenson, Schermerhorn and Miller, 1973; Kessell, 1973, 1975, in 1976b). In designing such real-time models, we wish to describe and predict both the behavior of a fire while combustion is occurring, and the short- and long-term impacts of the burn on the ecosystem

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(including the succession of plant and animal communities along a time continuum extending from time of burn to either maturity or another perturbation).

Traditionally, resource managers and many ecologists have viewed natural communities in terms of categories or classification units; each unit of the landscape is assigned membership within a class, and is then viewed as possessing the attributes of that class. The definition and description of each class will depend on the interests and prejudices of the classifier, and his anticipated use of the system.

> If he is most interested in vegetation structure, he may state a definition of a formation: Forests dominated by needle-leaved trees in subarctic and subalpine climates are members of community-type (formation) A. If his interests center on floristic composition, he may define an association: Plant communities in which several of the following character-species . . . occur together belong to community-type (association) *B*. If he is concerned mainly with dominant species, he may define a dominance-type Grasslands in which the two species *a* and *b* are more important than any others represent community-type (dominance-type) *C*. Such statements of class-concepts are also intensional definitions of community-types. The particular communities in the field for which a defining statement becomes true, which therefore conform to the class-concepts, constitute its extentional definitions. (Whittaker, 1973c).

Obviously, the utility of such a system depends both on the resolution of the classification method (number and refinement of classes recognized), and the correspondence between the real landscape and the intensional definition of the classes into which landscape units are assigned.

Despite the American preoccupation with canopy dominance and "habitat-types" (a "sociation" of both a canopy and understory species) (Cowles, 1899, 1901; Clements, 1905, 1916, 1936; Clements and Shelford, 1939; Daubenmire, 1952, 1954, 1966, 1968; Pfister, Arno, Presby and Kovalchik, 1972; reviewed in Whittaker, 1962, 1973c, 1973d), five major historical traditions have led to the development of 12 major approaches or schools of vegetation classification (Whittaker, 1962, 1973c). These include: (1) the physiognomic, structural or formation-type approach (reviewed by Beard, 1973); (2) the environmental or biotope-type approach (including Merriam, 1894; Emberger, 1936, 1942; Holdridge, 1947, 1967; Elton and Miller, 1954; Dansereau, 1957); (3) the landscape-type or biogeocoenose-type approach (including both landscape and microlandscape levels, as reviewed by Whittaker, 1973c); (4) the biotic area or province approach (Whittaker, 1973c); (5) the life-zone and segments of community gradients approach (Merriam, 1890, 1898, 1899; Kendeigh, 1954; Beard, 1955; *cf.* Whittaker 1973c, Beard, 1973; Aleksandrova, 1973); (6) the dominance-type approach (reviewed by Whittaker, 1962, 1973c, 1973d); (7) the vegetation dynamics approach (Tansley, 1911, 1920, 1939; Clements, 1916, 1928, 1936; Weaver and Clements, 1929; *cf.* Whittaker, 1953, 1974); (8) the stratal or lifeform approach (Gams, 1918, 1927; Lippmaa, 1933, 1935, 1939; Barkman, 1958; reviewed in Barkman, 1973); (9) the stratal combination, sociation, or in America, the "habitat-type" approach (Fries, 1913; Du Rietz, 1921, 1932, 1936; Daubermire, 1952, 1966; *cf.* Aleksandrova, 1973; Trass and Malmer, 1973); (10) the northern European site-type (understory) approach (Cajander, 1909, 1949; Cajander and Ilvessalo, 1921; reviewed by Frey, 1973); (11) the numerical classification approach (reviewed by Goodall, 1973); and (12) the floristic units approach best represented by the school of Braun-Blanquet (1913, 1921, 1932, 1951, 1964; English language review by Westhoff and Maarel, 1973).

Obviously, there is no single natural or "correct" method of classifying vegetation. The various methods of defining community-types imply different classifications of the same vegetation (*cf.* Whittaker, 1962, 1972, 1973c: Ellenberg, 1967). Whatever the method a manager chooses as the basis for an inventory system, the intent is to use a classification unit to describe a piece of the landscape; his method should be evaluated in terms of how well it preserves the information he desires for a particular application. From a multi-purpose management perspective, we may evaluate such systems by how well they: (1) retain the information necessary for a particular application; (2) maximize information return for a given cost; and (3) permit sufficient flexibility for other management applications. Specifically, for the design of an inventory method to be used as the basis for a real-time fire management model, we require: (1) sufficient refinement of vegetational, fuel, and site information to provide inputs to combustion models, and dynamic descriptions of the changes following combustion; (2) maximum information return for the lowest possible cost; (3) flexibility to use the model for management applications other than fire.

It is unfortunate for various classification schemes, including the currently popular "habitat-type" method, but non-the-less true, that (despite some exceptions) most natural communities do not fall into natural or distinct categories, but rather exhibit compositional characteristics which vary continuously in space and time in response to both spatial and temporal environmental gradients (Ramensky, 1926, 1930; Gleason, 1926, 1939; Whittaker, 1956, 1960, 1967, 1970a, 1970b, 1972, 1973a, 1973b, 1973c; Whittaker and Niering, 1964, 1965; Bray, 1956; Bray and Curtis, 1957; Kessell, 1976a; *cf.* Kessell, 1975). When class types or categories are imposed on these communities, there results an inherent loss of information due to natural and directed variation within each class; this natural variance is lost (or ignored) as one assumes that every community or stand assigned to a class exhibits the characteristics stated in the intensional definition of the class. This loss of information is directly proportional to the complexity of the landscape, and inversely proportional to the number of classes recognized. One can thus refine the system and decrease the information loss somewhat by increasing the number of (and thus refining the) classes recognized but only by incurring other, often even more detrimental, problems, including: (1) increased cost and complexity; (2) incurring an overwhelming number of classes to be recognized, defined, and described; and (3) realizing a less than satisfactory understanding of the dynamic relationships among the classes. When (as is frequently the case) the inventory system consists of a series of overlay maps or other graphic records, this refined and expanded class system either requires a very large-scale and expensive map system, or else results in such a large number of map types and symbols that the resulting visual complexity becomes overwhelming (Ellenberg, 1967; Colony, 1974). In addition, this refined, expanded, complex, and expensive class system designed for a given management purpose (such as fire) may be less than adequate for other management problems (such as trail construction, regulating backcountry use, minimizing people-bear interactions, or understanding elk-habitat relationships). Unfortunately, most current class-type, graphic-oriented information systems suffer a combination of the above flaws; when attempting to expand and refine class-oriented systems, it appears that one is damned if one does, and damned if one doesn't.

An alternative approach is to view and describe natural communities in terms of the spatial and temporal environmental gradients which affect their composition and structure—to use the methods of direct gradient analysis and indirect gradient analysis, or ordination, to quantify these natural relationships (Whittaker, 1967, 1973a, 1973b; Bray and Curtis, 1957; Bray, 1960, 1961; McIntosh, 1973; Orloci, 1973; Cottam, Goff and Whittaker, 1973; Gauch and Whittaker, 1972; Gauch, 1973; Whittaker and Gauch, 1973; Kessell and Whittaker, 1976). Thus an inventory—information retrieval system designed to describe each stand's location on each gradient which affects the biota allows retrieval of this information (Kessell, 1973, 1975).

For example, assume we are dealing with a mountain range where three gradients-elevation, topographic-moisture (topography and aspect), and time since the last burn—significantly affect the vegetation. The plant communities (and perhaps also the fuel and animals) are quantified in terms of the three gradients by making each gradient an axis in an abstract three-dimensional habitat-space model. Thus by describing (with an inventory system) each stand's location on each gradient (i. e. its elevation, topography and aspect, and time since burn), we may use the gradient model to retrieve the composition and structural characteristics of each stand. If a fourth gradient (such as soil development following primary succession) is also found to be important, we would add a fourth axis to the model and describe each stand's location on this fourth gradient as well. If we now wish to use the inventory to quantify fuel or animal distributions, we develop similar gradient models for the fuels and animals, and retrieve the information using the same stand inventory we first used for the vegetation. Such a model provides (1) a description of the communities (more refined than that provided by current class-types); (2) an understanding of their distributions and interrelationships along complex environmental gradients (not available from class-type methods); and (3) the basis for an information-retrieval system which is both straightforward and much more refined and precise than any class-type system currently in use. In addition, the gradient model approach lends itself to modern automatic data processing methods, while graphically oriented, class-type systems usually do not.

The remainder of the paper describes: (1) a simple step-by-step example of the development and use of such a gradient model for a hypothetical forest ecosystem; and (2) a documented description of the Glacier National Park model as it relates to fire management, including description of fuel loadings and spatial distributions, and the effects of the latter on stochastic elements of fire spread modeling.

A SIMPLIFIED EXAMPLE

Consider the need for an information retrieval system with one hectare resolution for a terrestrial system. A 25 hectare area of this hypothetical ecosystem is shown in Figure 1.

The 25 individual hectares are referenced by the Universal Transverse Mercator (UTM) coordinates at the southwest corner of each square. The land is forested, and the canopy is composed of three tree species (Alpha, Bravo and Charlie). The numbers in each hectare indicate the estimated number of individuals of each species within each hectare. The problem is to design an inventory system which offers both one hectare resolution comparable to field sampling error (not over 10%), and application to such diverse management problems as fire control, wildlife distributions, and backcountry trail design.

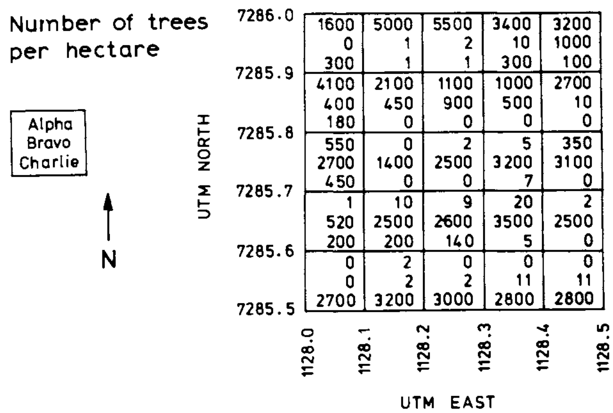

Fig. 1. A 25 hectare area of a hypothetical forest ecosystem containing three overstory species (Alpha, Bravo and Charlie). Coordinates are Universal Transverse Mercator (UTM) in Kilometers; each square is one hectare (100 m x 100 m). Plotted numbers are absolute densities of each species in each hectare.

A traditional class-type approach would classify each hectare by some standard method, and then design a mosaic map showing these various types. If each hectare is classified by the predominant tree species, then we have ten hectares dominated by Alpha (now recognized as "Type Alpha"), ten hectares dominated by Bravo ("Type Bravo"), and five hectares recognized as "Type Charlie", as shown in Figure 2. (Note that we have lost both the quantitative and qualitative information on the subordinate species). If we now plot these three types on a standard 7½ minute USGS topographic map (scale of 1:24,000), we obtain the resolution shown in Figure 3a; if we plot these types on a 1:125,000 scale map (the exact scale of the current Glacier National Park vegetation map) we obtain the resolution shown in Figure 3b.

Clearly, we have sacrificed considerable information by use of the type-mapping approach. Furthermore, if we now wish to describe the landscape based on understory shrubs which are important wildlife food sources, or based on the distribution of flammable fuels, or animal species, we must begin again, reclassify each hectare by the

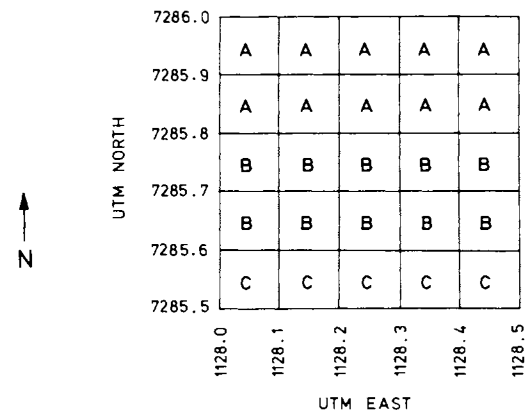

Fig. 2. A classification scheme based on overstory dominance for the hypothetical ecosystem.

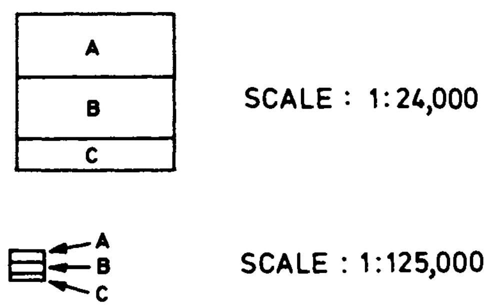

Fig. 3. Resolution of the classification scheme shown in Figure 2 for scales of (a, top) 1:24,000 and (b, bottom) 1:125,000.

new criteria, and construct new maps for each new management purpose.

In the actual practice, the manager must deal with much more complex vegetation patterns distributed over much larger areas. Loss of detail and information is compounded by attempts to maintain a legible and usable graphic format. But if we attempt to increase resolution by identifying and classifying various unions or associations of canopy and understory species, we can obtain the greater resolution only at the expense of increased graphic complexity.

For example, according to Glacier's Fire Control Officer, the current Glacier vegetation map (scale of 1:125,000) "has been simplified to the extreme (but) the map is virtually unusable to the manager. A melange of 21 colors and 114 symbols are crowded onto this chart in an attempt to maintain at least a pretense of accuracy. As a result the map gives the overall impression of a plate of chop suey. There is a certain amount of basic information displayed if the user is willing to learn the symbol table and study the map long enough to discern the distribution patterns. In the same manner the patron of a Chinese restaurant can pick out the bean sprouts and mushroom pieces if he has a pair of tweezers, enough time, and sufficient motivation. Complex as the Glacier map is, it does not have good enough detail to be used for precise decision making. Questions of wildlife habitats and range are difficult to answer, and fire management problems cannot be related to this map with an acceptable margin of safety." (Colony 1974).

Instead of imposing some type system upon the ecosystem, we

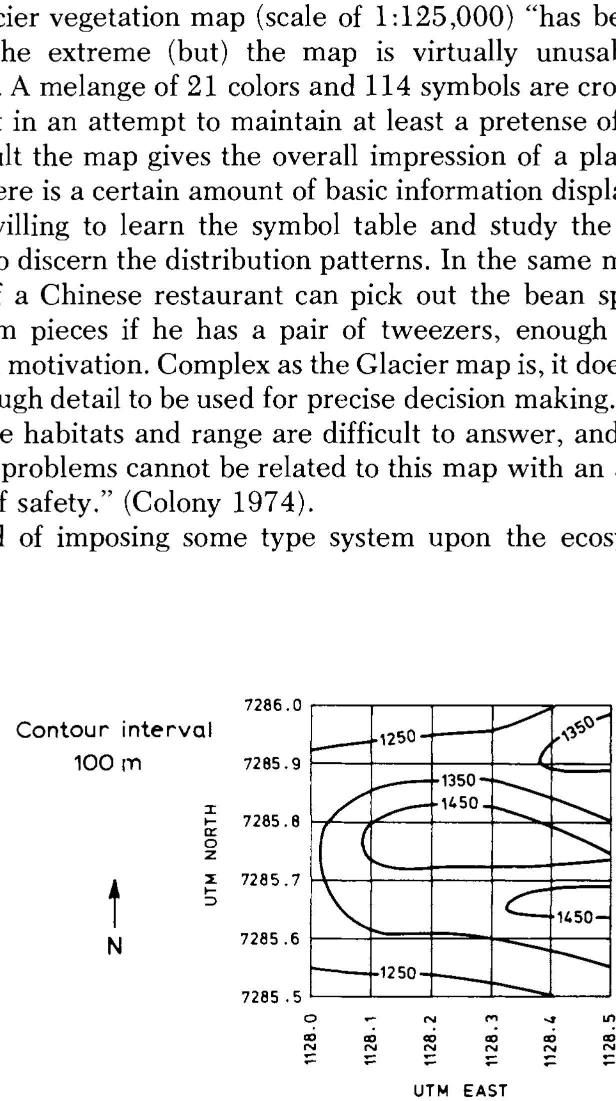

Fig. 4. Topographic map for the hypothetical ecosystem.

may alternatively view the underlying environmental causes of the distribution of various biota. A logical starting point might be a topographic map and/or aerial photo of our 25 hectare example. Such a topographic map is shown in Figure 4. Two environmental variables which influence biotic communities may be determined from this simplified map—each hectare's elevation and aspect (direction of exposure). We may use these two environmental variables as the basis of a hectare inventory system, and record each hectare's elevation and aspect, as shown in Table 1. We will assume that, for this simplified scheme, these two continuous environmental variables determine the biotic composition of the stands.

We now perform a "gradient analysis" on the area by sampling

Table 1. Hectare inventory for the hypothetical forest ecosystem.

UTM North	UTM East	Mean elevation (m)	Aspect
7285.5	1128.0	1250	S
7285.5	1128.1	1275	S
7285.5	1128.2	1290	SW
7285.5	1128.3	1310	SW
7285.5	1128.4	1340	SW
7285.6	1128.0	1370	SW
7285.6	1128.1	1400	S
7285.6	1128.2	1410	S
7285.6	1128.3	1470	W
7285.6	1128.4	1500	S
7285.7	1128.0	1410	W
7285.7	1128.1	1480	SW
7285.7	1128.2	1500	S
7285.7	1128.3	1470	S
7285.7	1128.4	1460	E
7285.8	1128.0	1330	NW
7285.8	1128.1	1360	N
7285.8	1128.2	1400	N
7285.8	1128.3	1390	NE
7285.8	1128.4	1320	NE
7285.9	1128.0	1240	NW
7285.9	1128.1	1250	N
7285.9	1128.2	1260	N
7285.9	1128.3	1290	NW
7285.9	1128.4	1370	NW

.05 hectare plots within the 25 hectare study area (and similar adjacent sites), and recording the density of each species Alpha, Bravo and Charlie as functions of these two environmental gradients. We obtain the "population diagram" shown in Figure 5. This diagram shows us that species Alpha is most common on north and east aspects between 1250 and 1300 meters elevation, while Bravo is centered on northwest, southeast and west exposures at about 1450 meters, and Charlie is most common on west and south slopes at 1250 to 1300 meters. (Note that the exposures are arranged from the wettest northeast slopes to the driest southwest slopes.) The contour lines connect areas of equal species density (trees per hectare; an alternative would be to plot relative, rather than absolute, densities). To retrieve the stand by stand composition for each hectare, we simply find the intersection (in Fig. 5) of the hectare's elevation and aspect, and then read off the density of each species. (In real life, the contour lines are represented by either a series of orthogonal polynomials or in matrix format stored on computer disk, while the inventory is stored on another disk file.) Thus indexing a stand by

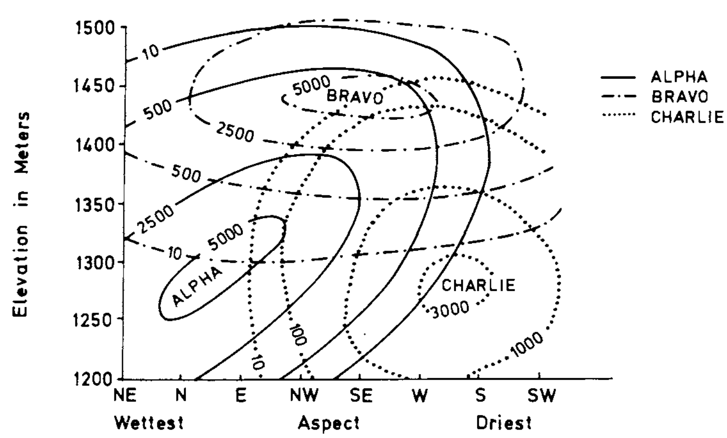

Fig. 5. Gradient population diagram for species Alpha, Bravo and Charlie which expresses absolute densities as functions of two environmental gradients (elevation and aspect). The contour lines (isodens) connect areas of equal density, while the plotted numbers are absolute densities (trees per hectare).

only its UTM coordinates allows the retrieval of all the original information shown in Figure 1 with a mean error of less than 5 percent. To apply such a system to a natural area, one needs two sets of information: (1) the "hectare inventory" (Table 1); and (2) the "gradient model" of the resources under consideration (in this case, the three species shown in Fig. 5). When these are stored on an ADP system, all information shown in Figure 1 can be retrieved by entering the stand's UTM coordinates alone.

Suppose that in addition to desiring quantitative information about tree species Alpha, Bravo and Charlie, we also desire quantitative information on shrub species Delta, Echo and Foxtrot (perhaps because we suspect they are important animal food sources). We simply construct a gradient model for these three new species, as shown in Figure 6a. We can now use the same hectare inventory (Table 1) to retrieve quantitative information on these three shrub species. Thus by knowing that the lower left hectare in Figure 1 (UTM of 7285.5 North, 1128.0 East) has an elevation of 1250 meters and south aspect (read off the inventory of Table 1), we retrieve the data that it also contains approximately 150 shrubs per hectare of species Foxtrot, 1500 shrubs per hectare of species Echo, and no species Delta. Note that the class type-mapping method, in addition to its loss of quantitative descriptions of each hectare, would require a new map describing the three new species; it is virtually impossible to group all six species into a single-characteristics type scheme, without a terrible loss of information, due to the poor correlation between tree distributions and shrub distributions. We could, of course, recognize habitat-types based on overstory-understory sociations (and thus recognize an Alpha-Delta habitat-type, an Alpha-Echo habitat-type, a Bravo-Delta habitat-type, a Bravo-Echo habitat type, a Charlie-Echo habitat-type, and a Charlie-Foxtrot habitat-type). However, we have still lost all of the quantitative and much of the qualitative information preserved by the gradient method. And if we plot these habitat-types on a 1:24,000 scale, 7½ minute USGS map, we obtain the mosaic shown in Figure 7; already we are approaching the chop suey stage, and in a system contain only three tree species and three shrub species. The reader is invited to imagine a similar mapping scheme for a mature deciduous cove forest in the

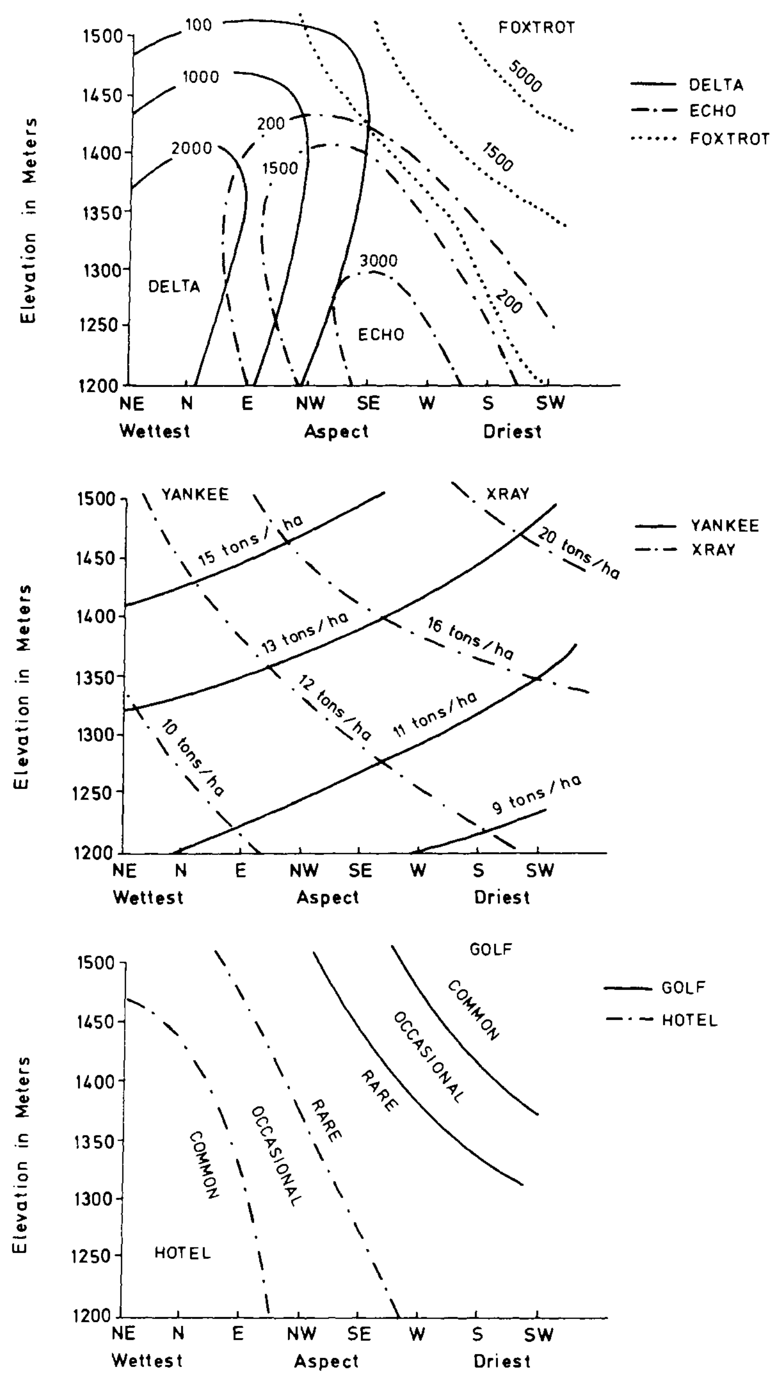

Fig. 6. (a, top) Gradient population diagram for shrub species Delta, Echo and Foxtrot (absolute density - shrubs per hectare). (b, center) Gradient loading diagram for fuels Xray and Yankee (loadings in metric tons per hectare). (c, bottom) Gradient habitat utilization diagram for animal species Golf and Hotel.

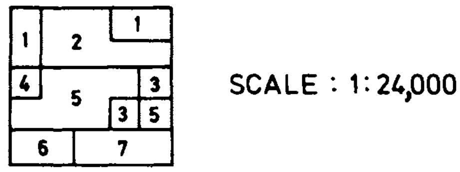

Fig. 7. A habitat-type classification scheme for the hypothetical ecosystem which recognizes tree-shrub sociations is plotted on a scale of 1:24,000. Type key: 1=Alpha-Delta; 2=Alpha-Echo; 3=Bravo-Delta; 4=Bravo-Echo; 5=Bravo-Foxtrot; 6=Charlie-Echo; 7=Charlie-Foxtrot.

southern Appalachains containing several dozen tree and shrub species.

If we now wish to use such a model for predicting fire spread rates under various weather conditions for this 25 hectare area, we can compute a similar gradient model for fuel loadings (in tons per hectare). For example, two fuel types Xray and Yankee (which perhaps correspond to large dead-down branchwood and litter, respectively) are shown in Figure 6b; they are quantifiable functions of the same two environmental gradients. Now the inventory (Table 1) for the hectare 7285.5 North, 1128.0 East informs us that the fuel loadings are approximately 14 tons per hectare and 10 tons per hectare, respectively, for fuels Xray and Yankee. These data, plus those for other fuel types not shown in this simplified scheme, may be entered into standard fire spread equations to estimate fire behavior on a hectare by hectare basis, simply by entering the UTM coordinates of a fire's location and current weather/fuel moisture. (Note that the elevation information in the inventory can be used to provide both slope estimates and altitudial-aspect corrections to dry bulb/wet bulb readings from weather stations at a different elevation.)

A similar gradient model can be constructed for the relative abundance of animal species, even if absolute population figures are unavailable, as shown for animal species Golf and Hotel in Figure 6c. Thus the hectare inventory for stand 7285.5 North, 1128.0 East (1250 meters and south aspect) tells us that both species are rare within this area, but that in stand 7285.6 North, 1128.4 East (with 1500 meters elevation and south aspect), we expect peak density of species Golf.

Note that the expansion of the system to handle shrubs, fuel data, and animals required no revision of the hectare inventory. New species and criteria may be added segmentally as each new gradient model is developed. A yet-to-be-completed study of bird species Sierra, Tango, Uniform, Victor and Whiskey can be later incorporated into the system. In this way, each new study builds upon previous research, and continuously increases the scope and utility of the system.

Also note that the traditional class-type mapping approach would require a new map for each new species or characteristic considered (imagine a version of Figure 7 which included all possible unions of dominant tree, shrubs, herbs, fuel loadings, animals, birds, etc.). Thus for an area such as Glacier National Park which contains over 1,000 species of vascular plants (Kessell, 1974), 1000 type maps would be required to produce only a portion of the resolution obtained from the full gradient analysis of the vegetation. (Of course, the gradient model also allows predictions of the biota of areas never sampled due to its use of biota—environment correlations). The more accurate and refined gradient model requires only one inventory (one record per hectare), and one polynomial equation (or matrix) per species, all stored on a digital computer.

The gradient model also shows inter-relationships among biotic components of the system, and between the biota and abiotic environment, wherever they exist, such as the correlation between the distribution of shrub Delta (Fig. 6a) and animal Hotel (Fig. 6c), and between shrub Foxtrot and animal Golf (Fig. 6a and 6c, respectively). If, in a real-life situation, Golf is grizzly bears and Foxtrot is huckleberries, a manager not only sees the correlation between the two, but can use the easily observed Foxtrot to indicate the likely presence of the more elusive Golf; he can thus avoid prime Foxtrot-Golf areas when designing backcountry trails (since he knows the combination of elevations and aspects to be avoided).

THE GLACIER NATIONAL PARK MODEL

Our study area (the West Lakes district of Glacier National Park) includes that portion of the park west of the Continental Divide which extends from the Canadian border south to the Lincoln drainage, and encompasses an area of about 160,000 hectares (640 square miles). Although the within-habitat, or Alpha, species diversity is fairly low (compared to an eastern deciduous forest, for example), the between-habitat, or Beta, diversity is staggering; communities range from xeric prairie remnants and ponderosa pine savanna to solid rock and glaciers, and from mesophytic cedar-hemlock forests to alpine tundra. This diverse habitat mosaic is further complicated by many natural disturbances, including glacial primary successions, slides and fellfields, hydric successions, and wildfire (Habeck, 1970a; Kessell, 1973, 1975, 1976b). Despite some general descriptive studies and more intensive research on certain communities and species (Standley, 1921; Lynch, 1955; Habeck, 1968, 1969, 1970a, 1970b; Habeck and Choate, 1963, 1967; Habeck and Weaver, 1969; Koterba and Habeck, 1971; Habeck and Arno, 1972; Lunan, 1972), no previous quantitative system- or modeling-oriented studies have been carried out in this area (Kessell, 1975).

GRADIENT MODEL OF THE VEGETATION

After summarizing the somewhat meager quantitative data available on Glacier's plant communities, we carried out detailed field work over the past 3 years, sampling over 700 .05 to 0.1 hectare stands. Within each stand, trees were recorded by species and di-

(a)

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PLOT 557   MCDONALD          WATERSHED

USGS 7.5 MIN. TOPO. MAP -  LAKE MCDONALD EAST

TYPE OF SAMPLE -  8 H                    DATE SAMPLED -  082373

LOCATION -  TRAIL LAKE MCDONALD - SPERRY CHALET

   UTM -    5388000 NORTH     0289250 EAST

COVER TYPE -  FOREST

ELEVATION -   1159. M   ( 3800. FEET)

TOPO. TYPES -  OPEN SLOPE          -  SHELTERED SLOPE
EXPOSURE  SOUTHWEST

PRIMARY SUCCESSION GRADIENT -  N/A

ALPINE (WIND-SNOW) GRADIENT -  N/A

DISTURBANCE -  BURN
     TYPE OF BURN -  UNDERSTORY
     APPROX. YEARS SINCE BURN    70
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TREE DATA -

SPECIES	NUMBER OF STEMS	REL. NUMBER OF STEMS (O/O)	BASAL AREA (SQ. M)	REL. BASAL AREA (O/O)
PICEA	7	5.9	0.22000	12.1
THUJA PLICATA	4	3.4	0.03500	1.9
PINUS MONTICOLA	14	11.9	0.26100	14.4
PINUS CONTORTA	35	29.7	0.25300	13.9
PINUS PONDEROSA	1	0.8	0.38500	21.2
LARIX OCCIDENTALIS	1	0.8	0.00200	0.1
PSEUDOTSUGA MENZIESII	56	47.5	0.66200	36.4
TOTAL	118	100.0	1.81800	100.0

7 SPECIES PRESENT

DIVERSITY MEASURES (RELATIVE DENSITY) -
HPRIME= 1.330 E TO THE HPRIME= 3.782 C=0.332
1/C = 3.011 EC = 4.004

DIVERSITY MEASURES (RELATIVE BASAL AREA) -
HPRIME= 1.589 E TO THE HPRIME= 4.898 C=0.232
1/C = 4.302 EC = 2.778

HERB AND SHRUB DATA -

QUADRATS USED -
3 1X1 M

	SPECIES	MEAN COVER	FREQUENCY
10102	LYCOPODIUM ANNOTINUM	0	0.33
61201	PTERIDIUM AQUILINUM	1	0.33
170000	GRAMINEAE	0	0.33
172800	POA SPECIES	1	0.67
221401	XEROPHYLLUM TENAX	2	1.00
471001	ROSA ACICULARIS	1	0.67
471400	SPIRAEA SPECIES	2	1.00
680101	ARCTOSTAPHYLOS UVA-URSI	2	1.00
690301	CHIMAPHILA UMBELLATA	1	0.67
850101	LINNAEA BOREALIS	2	1.00
681301	VACCINIUM CAESPITOSUM	2	0.67
882602	HIERACIUM ALBIFLORUM	1	1.00
990000	MOSS	2	1.00

TOTAL COVER = 5 13 SPECIES PRESENT

DIVERSITY MEASURES (COVER) -
HPRIME= 2.215 E TO THE HPRIME= 9.163 C=0.124
1/C = 8.052 EC = 8.801

FIELD NOTES -

PARTIAL CANOPY BURN OF MUCH OLDER BURN. P. PONDEROSA + LARIX SURVIVING BOTH BURNS. P. CONTORTA RESULTING FROM LAST BURN. CANOPY COVER 3 - 4. SEEDLING - SHRUB COVER 3 - 4.

Fig. 8. Typical stand summary printouts for (a) a forested slope near Lake McDonald, and (b, next page) an alpine meadow—Krummholz forest at Boulder Pass.

Heading data includes the information necessary to locate each stand along the environmental gradients. Trees are recorded by both density and basal area. Herbs and shrubs are recorded by absolute coverage on a seven-point scale, where: 0=Trace (less than 1%); 1=1-5%; 2=5-25%; 3=25-50%; 4=50-75%; 5=75-95%; and 6=over 95%. Five standard diversity measures (in addition to total number of species) are calculated for each stratum, and abridged field notes are included.

(b)

PLOT 523 KINTLA WATERSHED

USGS 7.5 MIN. TOPO. MAP - MOUNT CARTER

TYPE OF SAMPLE - 8 H WITH CORES DATE SAMPLED - 080673

LOCATION - BOULDER PASS

UTM - 5426900 NORTH 0712200 EAST

COVER TYPES - MEADOW - FOREST

ELEVATION - 2287. M (7500. FEET)

TOPO. TYPE - OPEN SLOPE
EXPOSURE NORTH

PRIMARY SUCCESSION GRADIENT - 50

ALPINE (WIND-SNOW) GRADIENT - PASS

DISTURBANCES - NONE

TREE DATA -

SPECIES	NUMBER OF STEMS	REL. NUMBER OF STEMS (0/0)	BASAL AREA (SQ. M)	REL. BASAL AREA (0/0)
ABIES LASIOCARPA	5	11.4	0.01900	7.6
PICEA	3	6.8	0.01500	6.0
LARIX LYALLII	36	81.8	0.21600	86.4
TOTAL	44	100.0	0.25000	100.0

3 SPECIES PRESENT

DIVERSITY MEASURES (RELATIVE DENSITY) -
HPRIME= 0.594 E TO THE HPRIME= 1.812 C=0.687
1/C = 1.456 EC = 2.780

DIVERSITY MEASURES (RELATIVE BASAL AREA) -
HPRIME= 0.491 E TO THE HPRIME= 1.634 C=0.756
1/C = 1.323 EC = 2.590

HERB AND SHRUB DATA -

QUADRATS USED -
3 5X5 M DIFFERENT MOISTURE CONDITIONS

SPECIES		MEAN COVER	FREQUENCY
150108	JUNCUS DRUMMONDII	1	1.00
150200	LLZULA SPECIES	2	1.00
160100	CAREX SPECIES	0	0.33
160100	CAREX SPECIES	2	1.00
160100	CAREX SPECIES	2	1.00
160115	CAREX DIOICA	2	1.00
160137	CAREX NIGRICANS	2	1.00
160158	CAREX SPECTABILIS	1	0.33
172800	PCA SPECIES	0	0.33
172804	PCA CUSICKII	1	0.67
221301	VERATRUM VIPIDE	0	0.33
250202	SALIX ARCTICA	0	0.33
250217	SALIX NIVALIS	3	0.67
300201	OXYPIA DIGYNA	2	1.00
300312	POLYGONUM VIVIPARUM	0	0.33
360204	ANEMONE OCCIDENTALIS	1	0.67
360708	RANUNCULUS INAMOENUS	1	1.00
360709	RANUNCULUS MACOUNII	0	0.33
400207	ARABIS LYALLII	0	0.33
440501	PARNASSIA FIMBRIATA	1	0.33
440608	SAXIFRAGA LYALLII	2	1.00

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470804  PCTENTILLA DIVERSIFOLIA         1        1.00
620401  EPILOBIUM ALPINUM               1        1.00
681003  PHYLLODOCE INTERMEDIA           1        0.33
760304  PHACELIA SERICEA                1        0.67
800205  CASTILLEJA OCCIDENTALIS         1        0.67
800206  CASTILLEJA RHEXIFOLIA           0        0.33
800904  MIMULUS LEWISII                 0        0.33
801505  VERONICA WORMSKJOLDII           0        0.67
860104  VALERIANA STICHENSIS            1        0.67
880101  ACHILLEA MILLEFOLIUM            1        0.67
880501  ANAPHALIS MARGARITACEA          1        1.00
880709  ARNICA MOLLIS                   2        1.00
881909  ERIGERON PEREGRINUM             2        1.00
882604  HIERACIUM GRACILE               0        0.67
883709  SENECIO RESEDIFOLIUS            1        1.00
883711  SENECIO TRIANGULARIS            2        1.00
990000  MOSS                            2        1.00

 TOTAL COVER = 6      38 SPECIFS PRESENT

DIVERSITY MEASURES (COVER) -
  HPRIME=  3.050   E TO THE HPRIME=        21.109   C=0.063
  1/C = 15.926   EC =  20.266


FIELD NOTES -

BOULDER PASS TRANSECT -
DETAILS ON ORIGINAL FIELD SHEETS.
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ameter (40,000 total), permitting the calculation of relative densities and basal areas by species; detailed site information, disturbance history, and location (UTM) were also recorded. In a third of these stands, herb and shrub covers by species were recorded. Typical printout summaries (done on a stand by stand basis) are shown in Figure 8. Analyses of these data, combined with subsequent aerial infrared photo interpretation, have identified ten major environmental influences on these communities, including:

(1) elevation
(2) topographic-moisture and aspect
(3) primary succession (soil development following glacial retreat and rock weathering)
(4) watershed location
(5) alpine wind-snow exposure
(6) secondary fire succession (time since the last burn)
(7) intensity of the last burn
(8) slide—fellfield disturbances
(9) hydric successions
(10) ungulate grazing

Extensive statistical analyses of these influences have revealed that the first six are best treated as continuous, or nearly continuous, environmental gradients, while the last four may be handled as categories (or types) imposed on the gradient scheme (Kessell, 1975a, 1976b). We thus use this six-dimensional habitat hyperspace model (with four additional categories) as the basis for a quantitative description of the communities, and as the basis of an information retrieval system aimed at real-time fire modeling.

Due to the inherent difficulty of visualizing a six-dimensional model, let us view the effects of one to three gradients at a time. Space does not permit the discussion of how the gradients were determined, the statistical interplay of direct gradient analysis and indirect ordination (Whittaker, 1967, 1973a, 1967b; Kessell, 1976a), their environmental interpretations, or their implications on population dynamics interpretations of the component species; that work is forthcoming (Kessell, 1976b). I shall simply present the results, and emphasize their applications to fire modeling.

Figure 9 shows the responses of four species (or species-complexes) to two environmental gradients—elevation and topographic-moisture (plus aspect). The abcissa is arranged from the wettest bottomlands to the driest peaks, ridges and flats, while the ordinate shows increasing elevation. The plotted numbers show relative density for each species at each elevation—topography combination; the contour lines (isodens) connect areas of equal relative density. All stands are mature, forested, and located in the McDonald drainage. We see that the species show continuous responses to both gradients. *Pseudotsuga menziesii* (Douglas-fir) exhibits a center of distribution on open slopes at 1500 m elevation. *Thuja plicata* (red-cedar) exhibits two optima, both low elevation bottomlands and draws (it is partially excluded from the ravines by *Tsuga heterophylla* as shown in Figure 13d). The *Pinus monticola x albicaulis* (western white—whitebark pine) complex shows three modes in unburned forests. The first is at low elevations (*P. monticola*). A higher mode (*P. albicaulis*) occurs on the driest slopes and ridges at about 2300 m elevation, as it tolerates drier conditions than its chief competitor, *Abies lasiocarpa* (Fig. 12d). The third mode occurs in the high-elevation ravines and draws (most of these are slide—fellfield areas), where its flexible stems

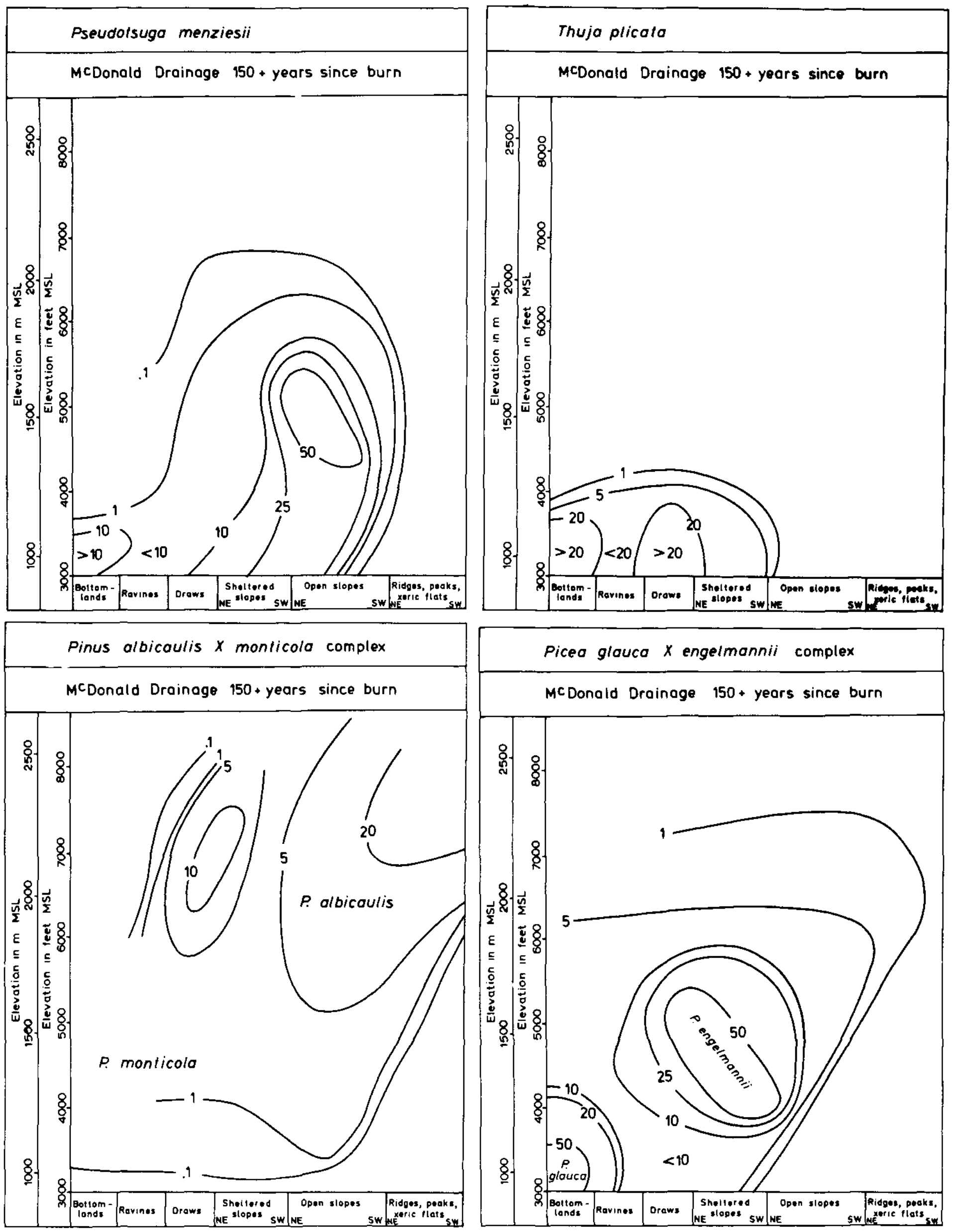


Fig. 9. Gradient population diagrams for (a, top left) *Pseudotsuga menziesii,* (b, top right) *Thuja plicata,* (c, bottom left) the *Pinus monticola* x *albicaulis* complex, and (d, bottom right) the *Picea glauca* x *engelmannii* complex, show the species' responses to elevation and topographic-moisture. The contour lines connect areas of equal relative density. All forests are mature and located in the McDonald drainage.

apparently better withstand the continual bombardment than does *A. lasiocarpa*. Figure 9d shows the *Picea glauca x engelmannii* complex (white—Engelmann spruce) described by Habeck and Weaver (1969); the predominantly *P. glauca* individuals exhibit a mode in the low elevation bottomlands, while the predominantly *P. engelmannii* populations prefer the sheltered slopes around 1500 m.

Other tree species, as well as shrub and herb species, may be described in terms of these gradients. Of course, micro-environmental and micro-topographic influences significantly affect these latter strata more than they affect the overstory, but overall distributions may still be described in the gradient framework, as shown in Figure 10 for *Acer glabrum* (mountain maple). (Also, we may use the gradient framework as the basis for a forest overstory classification system, as shown in Figure 11; but the loss of quantitative

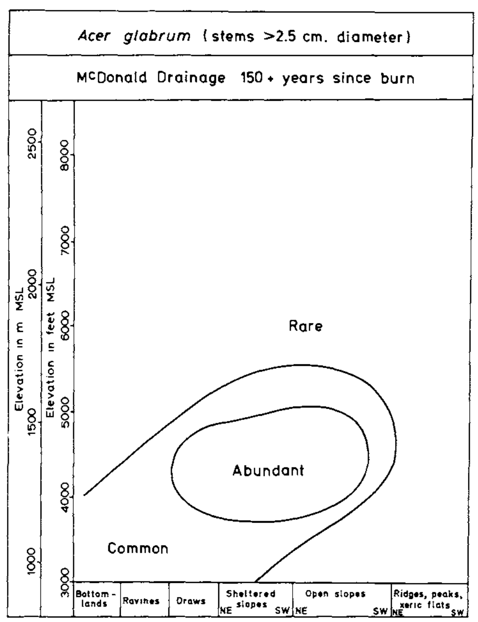


Fig. 10. Population diagram showing relative abundance of *Acer glabrum* as a function of the elevation and topographic-moisture gradients.

information makes this approach much less desirable than the gradient isoden method.)

In the above diagrams, we have viewed only mature communities, and described species distributions in terms of elevation and topographic-moisture. We may do the same for successional communities. Figure 12 shows the response of *Abies lasiocarpa* (subalpine fir) to these two gradients for four stand age groups (20—50 years, 50—90 years, 90—150 years, and greater than 150 years after burns which destroyed at least half of the canopy). Figure 13 shows the same scheme for *Tsuga heterophylla*, western hemlock. (Note that for the latter, increasing stand age brings higher relative densities but a smaller habitat range.) Alternatively, we might hold elevation constant and view a species' response to topographic-moisture and time since burn, as shown in Figures 14a and 14b, for *Tsuga hetero-*

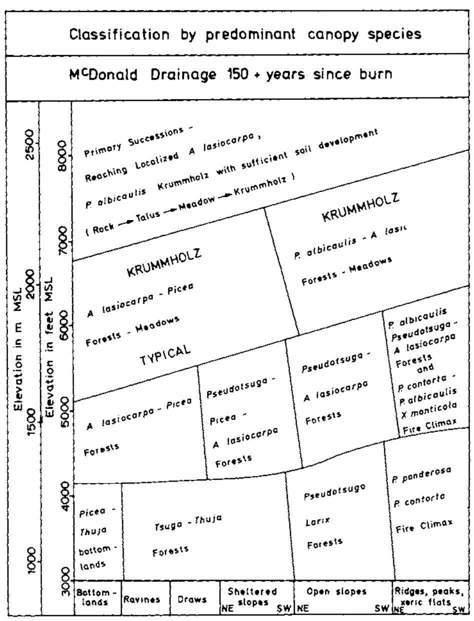


Fig. 11. An overstorv classification system for mature stands in the McDonald drainage expressed in terms of the elevation and topographic-moisture gradients.

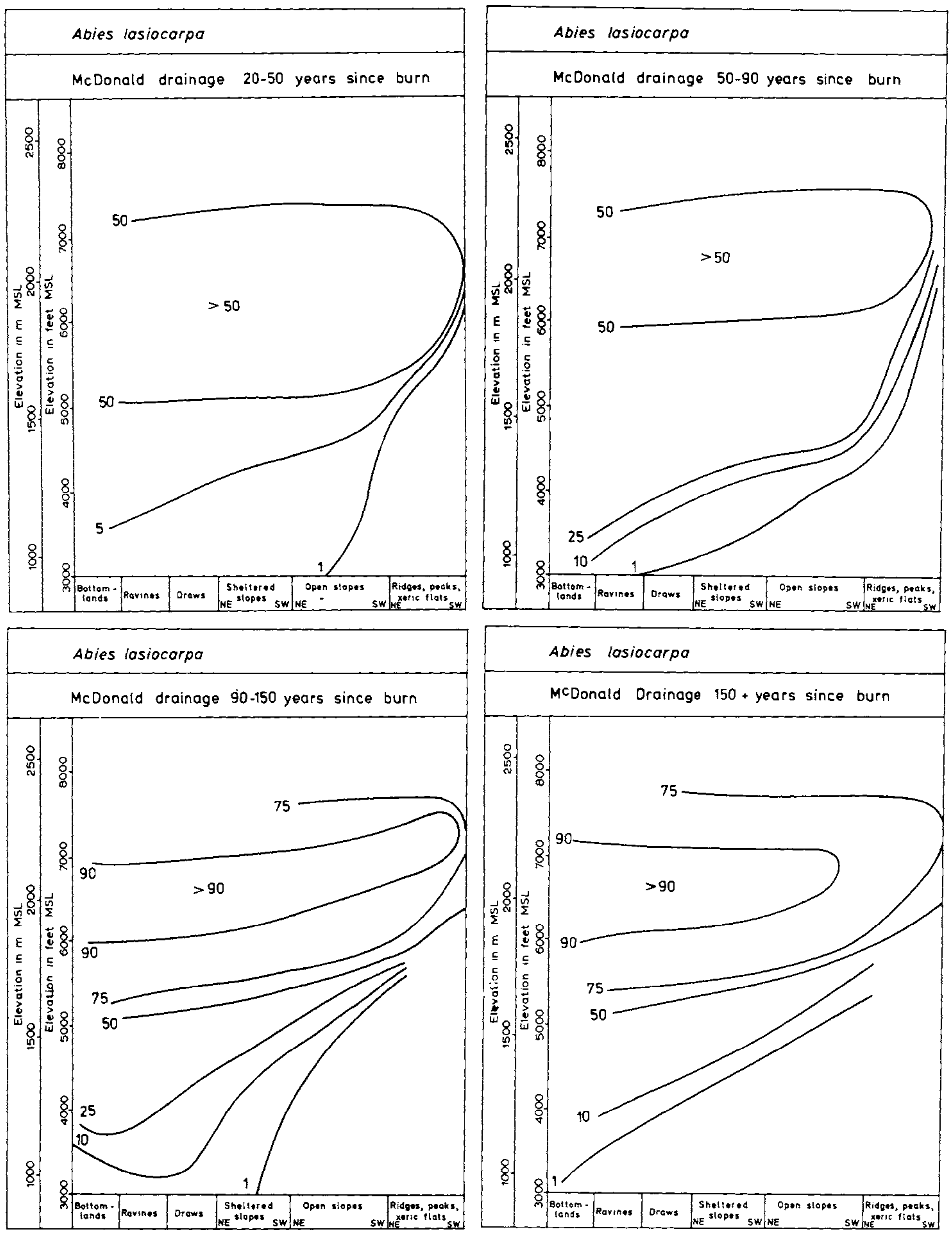


Fig. 12. Population diagram for *Abies lasiocarpa* shows the species' response to the elevation and topographic-moisture gradients for four stand age classes: (a, top left) 20 to 50 years after burning; (b, top right) 50 to 90 years after burning; (c, bottom left) 90 to 150 years after burning; and (d, bottom right) more than 150 years after burning. All burns destroyed more than 50 % of the canopy, and all stands are located in the McDonald drainage.

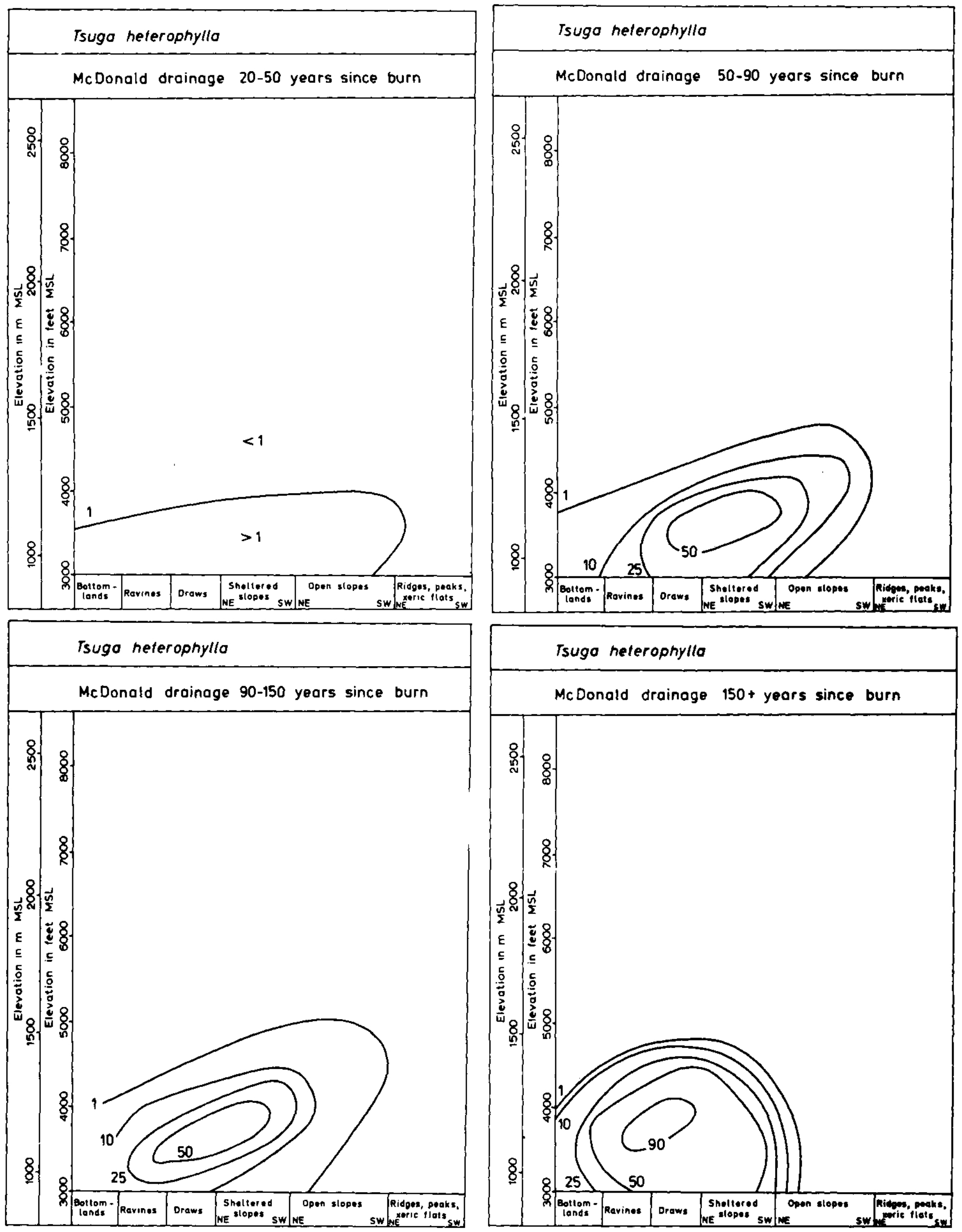


Fig. 13. Population diagram for *Tsuga heterophylla* using the same scheme shown in Figure 12.

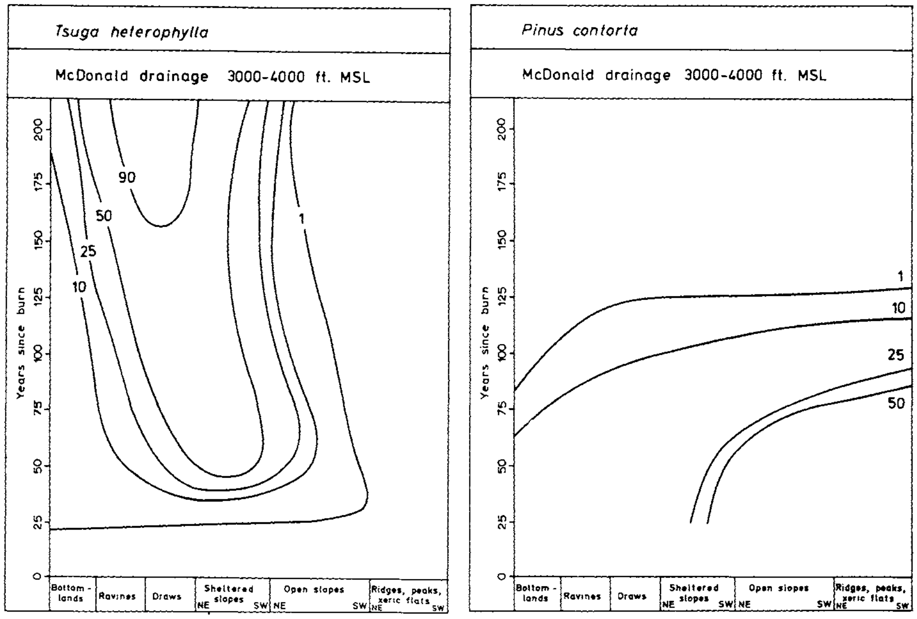


Fig. 14. Population diagrams show the response of (a, left) *Tsuga heterophylla* and (b, right) *Pinus contorta* to the topographic-moisture and time since burn gradients. All burns destroyed more than 50% of the canopy; all stands are located in the McDonald drainage between 900 and 1200 m (3000 and 4000 feet) MSL.

phylla and *Pinus contorta*, respectively. We thus clearly see the climax nature of the former, and the seral adaptation of the latter. We may now visualize the combination of all three gradients into a single three-dimensional model, as shown in Figure 15; response *a* indicates the 50 percent relative density isoden for a species such as *T. heterophylla*, while *b* shows the 50 percent isoden for a species like *P. contorta.*

Unfortunately, it is difficult to illustrate graphically more than three gradients at a time, although we have not yet discussed the other three gradients which affect Glacier's communities.

There exists a geographical moisture gradient along Glacier's west slope, due to both differences in precipitation and topographic sheltering, and perhaps the presence of Lake McDonald as well (Habeck, 1970a; Kessell, 1976b). The mesophytic McDonald drain-

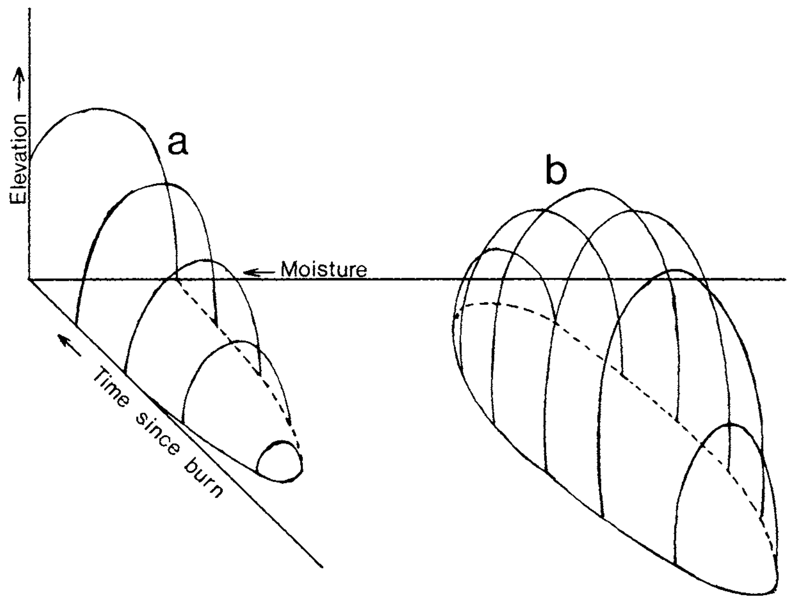


Fig. 15. Three-dimensional sketch shows the combined effect of the elevation, topographic-moisture and time since burn gradients on the 50% relative density isodens of (a) *Tsuga heterophylla* and (b) *Pinus contorta.*

age forests represent one extreme, while the Polebridge area's prairie margins—ponderosa pine savannas—lodgepole fire climax represent the other. The Bowman—Kintla Lakes drainages northeast of Polebridge are near the midpoint of this gradient, while the Camas drainage (just north of Lake McDonald) is intermediate to the McDonald drainage and the Bowman—Kintla drainages. Thus, as one moves north from Lake McDonald towards Polebridge, low elevation mesophytic cedar-hemlock communities give way to spruce forests, Douglas fir communities replace some spruce and subalpine fir forests, and the lodgepole fire-climax becomes more widespread. We may thus treat this as an additional gradient, or else recognize four watershed units within the West Lakes district, and complete the three-dimensional forest model shown above for each.

A fifth, extremely important, gradient influence on the higher elevation communities (above about 1500 m) is the continuum of primary succession corresponding to soil development following glacial retreat and rock weathering. It is best recognized by the major formation (cover) types which correspond to its development, as shown in Figure 16. (Note that this gradient does not directly affect the four-dimensional forest model described above, as forests are but a special case—the frequent end result—of primary succession, and represent but one extreme of this gradient). Primary succession development is the single most important influence on Glacier's alpine communities.

The sixth gradient describes the topographic sheltering of high-elevation communities, and their exposure to (or sheltering from) high winds. It is most important along passes and other high wind areas, where the effect is to cause increasingly xerophytic conditions and the equivalent of earlier (more primitive) primary succession

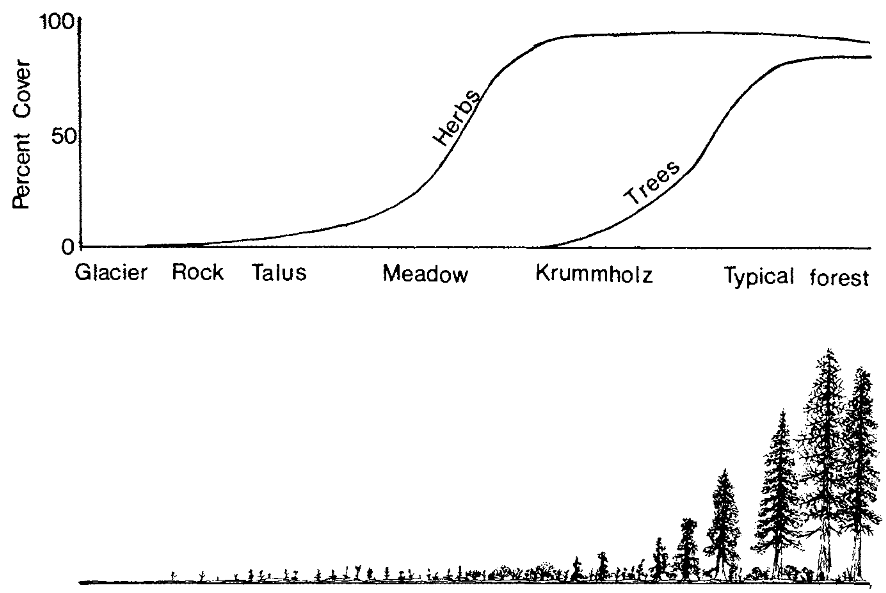


Fig. 16. Cover by herbs and trees, and typical formations, as expressed as functions of the primary succession gradient.

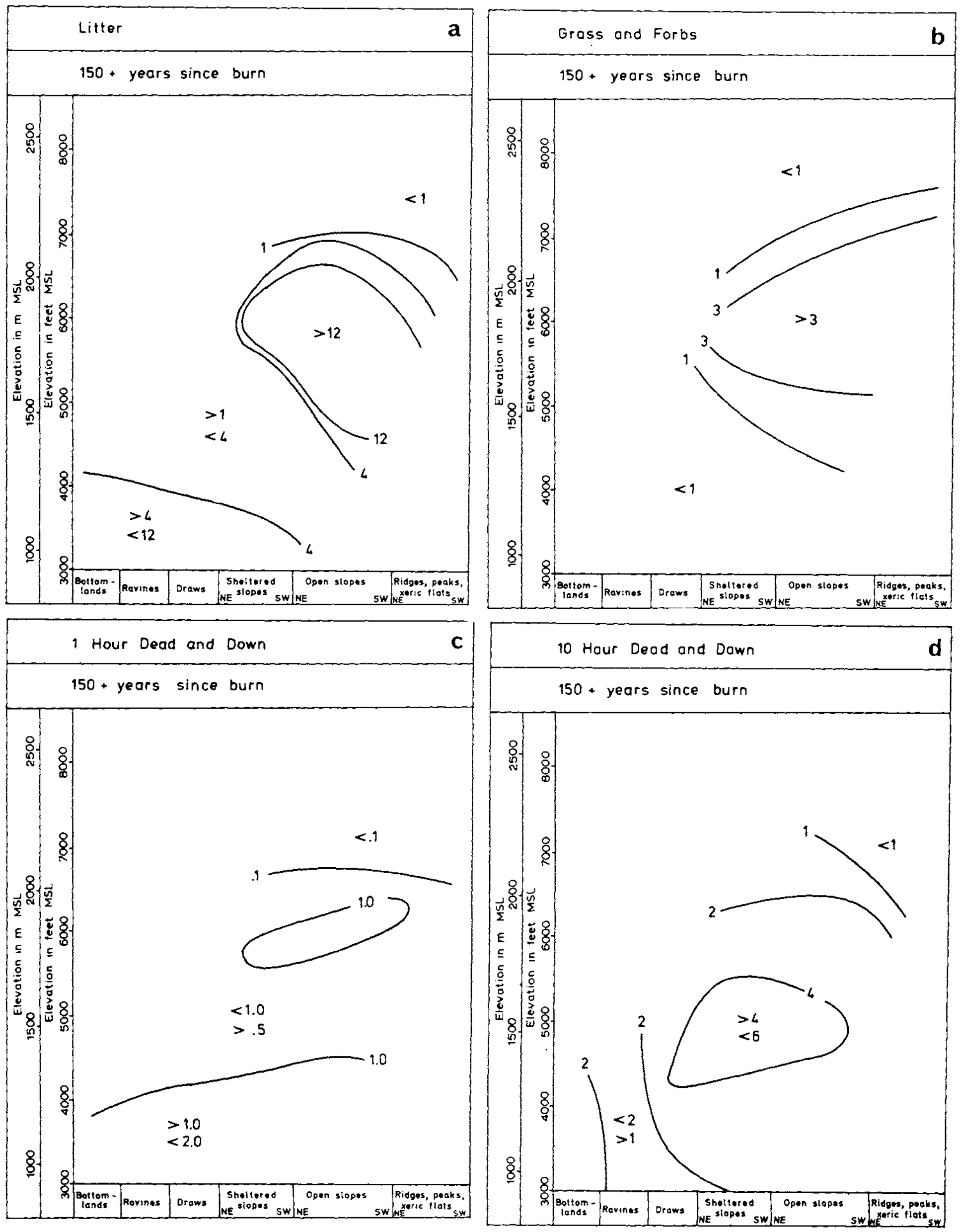
communities. Its application to the model is still being modified—it appears possible to include its effects by modifying a stand's location on both the primary succession and topographic-moisture gradients. Yet for now, it is being retained as a separate environmental gradient.

The four additional influences are treated as categories of variations, and include: (1) intensity of the last burn (full canopy, mosaic canopy, partial canopy, understory, or available fuel—these may be grouped into two classes depending on whether a burn destroys more or less than 50 percent of the canopy); (2) fellfields and slides; (3) hydric successions (both river floodplains and lake bottomlands); and (4) disturbances due to grazing in certain heavily-used ungulate winter ranges. Although plant distributions and community characteristics have been quantified in terms of the last two gradients and four disturbance categories (Kessell, 1976b), space limitations prohibit their presentation here.

Gradient Model of the Fuel

In addition to describing the distribution of plant communities along complex environmental gradients, one may use the same modeling framework to quantify the distribution of flammable fuels. We use a modification and expansion of Brown's methods (1971a, 1971b, and personal communication) which include measurements of the spatial distribution and contagion of fuels as well as fuel loadings. These parameters were quantified for over 200 stands during the past summer.

Figures 17 a-f show the loadings of six fuel types in response to the elevation and topographic-moisture gradients; the plotted numbers are loadings in metric tons per hectare, while the contour lines ("isoloads", if you will) connect areas of equal loadings. All of these communities are forested (canopy cover greater than 50 percent), and all are mature (unburned for at least 200 years). As one might expect, the environmental gradient model which describes the vegetation also describes the fuel, since the interplay of both the abiotic environment and vegetation (macro-flora and decomposers) determines fuel loadings, annual buildups, and decomposition rates (*cf.*


Litter
a
150 + years since burn
<1
1
>12
>1
<4
12
4
>4
<12
4
Grass and Forbs
b
150 + years since burn
<1
1
3
>3
3
1
<1
1 Hour Dead and Down
c
150 + years since burn
<.1
.1
1.0
<1.0
> .5
1.0
>1.0
<2.0
10 Hour Dead and Down
d
150 + years since burn
1
<1
2
4
2
>4
<6
2
<2
>1
Elevation in m MSL
Elevation in feet MSL
Bottom-lands
Ravines
Draws
Sheltered slopes
Open slopes
Ridges, peaks, xeric flats
NE
SW

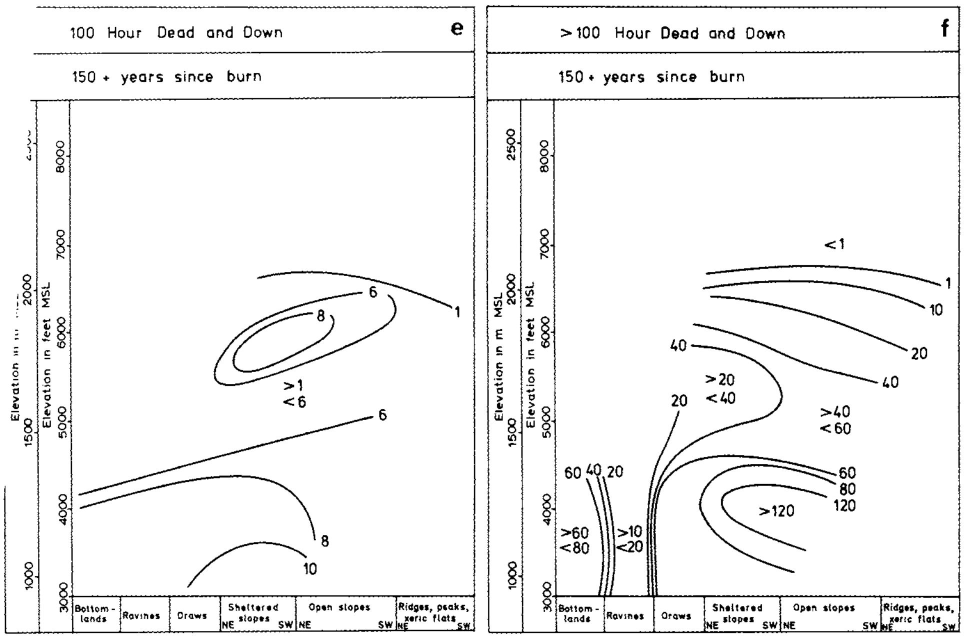


Fig. 17 a-f. Gradient diagrams show the responses of six fuel categories to the elevation and topographic-moisture gradients. Contour lines connect areas of equal fuel loading in metric tons per hectare. All stands are mature and forested. Areas not contoured are combinations of elevation and topography which normally do not support closed forest canopies, or else support a low-elevation "fire climax."

Olson, 1963). These results show that the smaller fuels are most abundant on the higher elevation slopes supporting typical forests, while the larger fuels are most abundant on the low-elevation slopes (cedar-hemlock and spruce communities). Areas not contoured are combinations of elevation and topography which normally do not support closed forest canopies, or else support a low-elevation "fire climax."

Fuels may also be quantified along the time since burn secondary succession gradient, as shown in Figure 18 for slopes at 1000 m elevation. (This is an area where a seral lodgepole canopy with Douglas fir and spruce understory gives way to a cedar-hemlock climax.) Total fuel loadings reach a mode at about 50 years after burn, drop

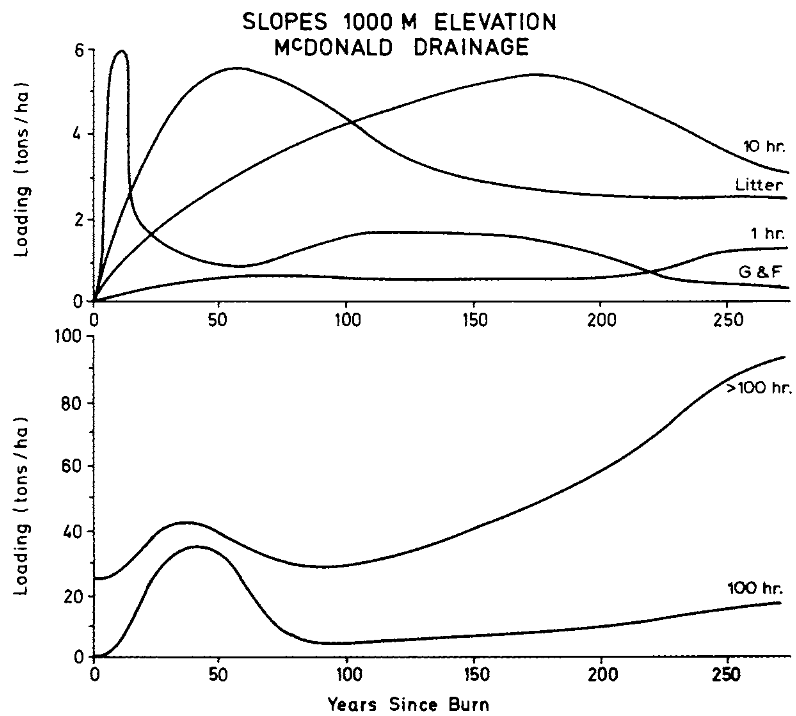


Fig. 18. Responses of six fuel categories to the time since burn gradient. All stands are forested and located in the McDonald drainage; all burns destroyed at least 50% of the canopy.

slightly for the next three decades, and then steadily increase. (Thus, the current "fire prevention" in this area simply increases the fuel loadings, and thus increases the intensity of a fire, when one finally does occur.)

Fuels have also been quantified along the primary succession gradient, as shown in Figure 19. As expected, grass and forbs, and the smaller fuels, show a mode in the meadows. In the Krummholz forests, the loadings drop somewhat (lower understory productivity but similar decomposition rates); they increase again in typical forests in response to the higher productivity.

Fuel distributions are also being quantified in terms of the other

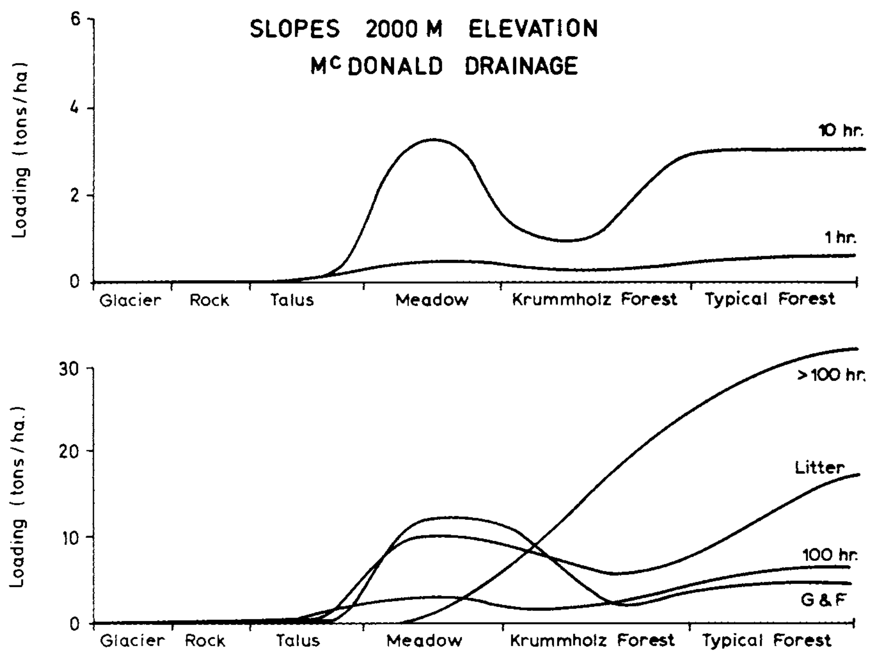


Fig. 19. Responses of six fuel categories to the primary succession gradient. All stands are mature and located in the McDonald drainage.

gradients and categories, but these results are still preliminary and are not presented here. In addition, we measure the spatial distributions of fuels (Kessell, 1976b) in terms of the variance/mean ratio (V) of their relative volumes from one quadrat to the next (using quadrat sizes of .1 x .1 m for litter and duff; .2 x .2 m for 1 hour dead and down; .5 x .5 m for grass and forbs; 1.0 x 1.0 m for brush and 10 hour dead and down; and 5.0 x 5.0 m for 100 hour and greater than 100 hour dead and down). Those results are also preliminary; in general, litter, duff and 1 hour fuels tend to be random (V=1), brush and larger dead and down fuels tend to be clumped, or contagious (V ranging from 3 to 100), and grass and forbs exhibit variation from uniform to clumped (V ranging from near 0 to 20). The use of such measures for fire modeling is described below.

THE HECTARE INVENTORY

In our hypothetical Alpha-Bravo-Charlie ecosystem, the biota responded to two gradients; we thus designed an inventory which described the location of every hectare on each gradient, and used these data to retrieve information on the flora and fuels. We do the same for the Glacier hectare inventory, but with the following modifications:

(1) we must describe the position of each unit of land on each of six gradients and within four categories;
(2) we must permit the description of portions of hectares whenever discontinuities exist;
(3) we must describe localized occurrences of one environmental complex upon another (such as a scattering of meadow and Krummholz forest on a rock outcrop);
(4) we must describe special features, such as rivers, lakes, trails, buildings, and the like;
(5) we must be able to handle exceptions for which the gradient model does not give acceptable accuracy.

The inventory system for Glacier uses one mandatory and two auxillary forms, as shown in Table 2. Form H-101 codes the standard inventory required for every hectare (or fraction thereof, if necessary); up to three entries per hectare are allowed. (Thus if a ravine crosses a sheltered slope, a separate entry is made for each). It includes information on the file structure, UTM coordinates, elevation, topography, aspect, burn history, other disturbances, cover type, primary succession, and watershed location. In addition, for cases where the gradient model does not provide acceptable accuracy, one may adjust the gradient positions (columns 47—65) as necessary to obtain an acceptable prediction. When more than one record is used per hectare, the location and percent cover of each is also recorded (columns 36—45).

If localized formations occur within the larger unit (hectare), these (up to four) are recorded on Form H-111 (otherwise, it is not used). If special features occur within the hectare, then Form H-121 is coded as shown in Table 2.

Table 2. The hectare inventory system for Glacier National Park.

column	abbreviation	Information	
Form H-101	Standard Hectare	Inventory Record	
1	#C	# of records to describe this hectare	
2	S#	sequence # of this record (within hectare)	
3	L	1 if localization (H-111) record follows: otherwise 0	
4	S	1 if special features (H-121) record follows; otherwise 0	
	UTM	Universal Transverse Mercator coordinates	
6-10	N	UTM north in 100's meters (no decimal point)	
11-14	E	UTM east in 100's meters (no decimal point)	
	SITE ACT	Actual site descriptors	
16-20	EL	Elevation in feet MSL	
21	T	Topographic-moisture, where:	
		1=Bottomland	5=Open slope
		2=Ravine	6=Peak / ridge
		3=Draw	7=Xeric flat
		4=Sheltered slope	8=Slope (unspecified)
22	X	Aspect, where:	
		1=N	5=S
		2=NE	6=SW
		3=E	7=W
		4=SE	8=NW
23	B	1 if burned, 0 if mature	
24-26	YSB	Approx. years since last burn (omit if col. 23=0)	
27	I	Intensity of last burn, where:	
		1=full canopy (over 90%)	
		2=mosaic canopy (over 50%)	
		3=partial canopy (under 50%)	
		4=understory only	
		5=available fuel (areas without canopy)	
		(omit if col. 23=0)	
28	OD	Other disturbances, where:	
		2=fellfield / slide	
		3=hydric	
		4=animal grazing	
29	C	Vegetative formation (cover) type, where:	
		0=glacier or perm. snow	
		1=rock	
		2=talus	
		3=talus and meadow	
		4=meadow	
		5=mesic marsh / bog	
		6=xeric or subxeric prairie	
		7=typical forest	
		8=Krummholz forest	
		9=shrub	

Table 2 (continued)

30-31	PR	Primary succession, where: 1=glacier or perm. snow 10=solid rock 20=broken rock 30=boulders and talus 40=talus 50=talus and meadow 60=meadow 70=meadow and Krummholz forest (or shrub) 80=Krummholz forest (or shrub) 90=Krummholz forest (or shrub) to typical forest 99=typical forest
32	ALP	Alpine wind-snow gradient category, where: 1=pass 3=other high wind area 2=near pass 4=perm. snowfield
33-34	DR	2-digit drainage area code
	SPLIT	Location and coverage of this unit in hectare (omit if col. 1=1)
36-37	%	Percentage of hectare covered by this record
38-45	LOC	Grid location of this subunit on scale: 7 8 9 4 5 6 (block=1 hectare) 1 2 3 (north is up)
47-65	SITE FIT	Readjustment of gradient site descriptors; used only when model predictions are inaccurate using true site data. Permits changing any site descriptor included in col. 16-34 such that new descriptors give acceptable predictions. Format per col. 16-34.
66-67	SPLR	Code # of special branch record if used (otherwise O)
Form H-111	Standard Hectare	Inventory Localization Record
1-9	UTM	Same code as col. 6-14 of H-101
	FIRST	First localization type
11	C	Formation (cover) type (same code as col. 29 of H-101)
12-13	PR	Primary succession (same code as col. 30-31 of H-101)
14-15	%	Percentage of area covered by this local type
16-19	CTG	variance/mean contagion ratio on 20 x 20 m grid (default=1.0)
	SECOND	Second localization type
21-29	as above	same format as col. 11-19 above
	THIRD	Third localization type
31-39	as above	same format as col. 11-19 above
	FOURTH	Fourth localization type
41-49	as above	same format as col. 11-19 above
Form H-121	Standard Hectare	Inventory Special Features Record
1-9	UTM	Same code as col. 6-14 of H-101
	FIRST	First special feature

11	T	Type of special feature, where: 1=lake or perm. pond 5=road 2=temp. pond 6=improvement/building(5) 3=stream/river 7=campground 4=trail 8=other
12-15	#	Four-digit identification number
16	DR	If col. 11=3, 4, or 5, direction of "flow" (same code as col. 22 of H-101)
17	DG	If col. 11=3, degree (order) of stream (0=temp.)
	SECOND	Second special feature
19-25	as above	same format as col. 11-17 above
	THIRD	Third special feature
27-33	as above	same format as col. 11-17 above
	FOURTH	Fourth special feature
35-41	as above	same format as col. 11-17 above

The coded information is obtained from 7½ minute USGS topographic maps, stereo vertical black and white photos (scale of 1:15, 840), oblique aerial infrared photos (35 mm transparencies taken by the author), and vegetative formation type maps which we draw as overlays to the 7½ minute topographic maps (using the above aerial photos). The infrared photos are an especially valuable tool, offering much better formation type—primary succession differentiation than is available from black and white or conventional color photos. A black and white print (made from a color infrared photo) and interpretive sketch for the Trout and Rogers Lakes area is shown in Figure 20.

The inventory for a 1 square kilometer (100 hectare) area contains from 100 to 350 records, depending on its diversity, and takes an experienced interpreter from 2 to 5 hours to code. Thus, about 10 to 12 man-weeks are required to code the area covered by a 7½ minute topographic map (about 130 square kilometers).

The inventory alone, even before it is linked to gradient models, provides a multitude of habitat and site information, much more detailed than anything available from current maps or other graphic records. For example, we use Glacier's computer terminal (accessing an IBM System 370/168) to read the inventory from disk and then print 1:4000 scale topographic, site and formation-type maps with 1

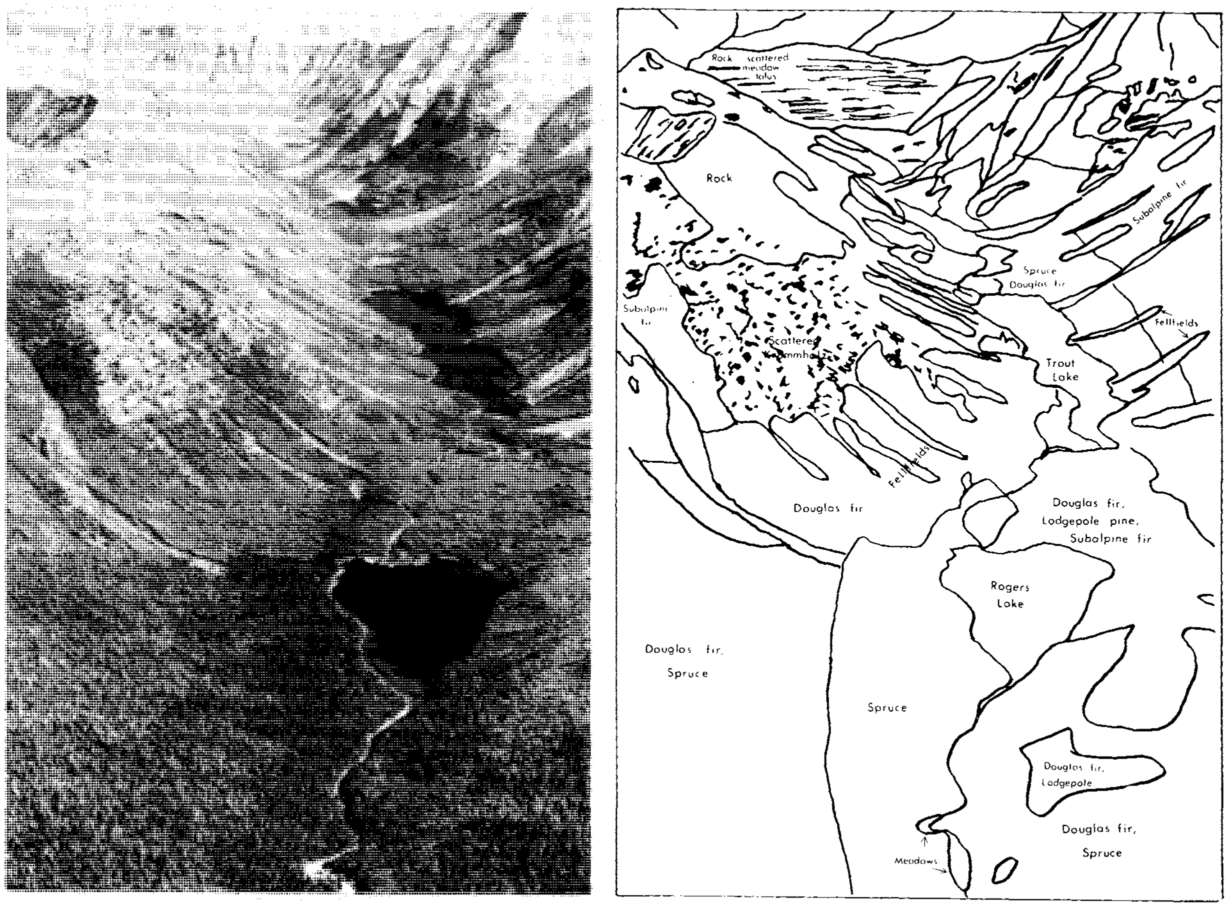


Fig. 20. (a, left) Black and white print (made from a color infrared photo) and (b, right) interpretive sketch for the Trout and Rogers Lakes area.

hectare resolution for 1 kilometer at a time; by changing the scale to 1:2000, we obtain even more detailed information on a ¼ kilometer (25 hectare) area. Finally, of course, we link the gradient models to the inventory to retrieve detailed information on a hectare by hectare basis.

For example, suppose an inventory record informs the program that a given hectare is located in the McDonald valley, is a sheltered slope with northeast aspect at 1200 m elevation, and has a formation-type (and primary succession) of typical forest. We retrieve from the Glacier model the following information:

(1) the relative density of *Pseudotsuga menziesii* is about 8 percent (from Fig. 9a);
(2) the relative density of *Thuja plicata* is about 9 percent (Fig. 9b);
(3) the relative density of *Pinus monticola* is about 1 percent (Fig. 9c);
(4) the relative density of *Picea* is about 18 percent (Fig. 9d);
(5) the relative density of *Abies lasiocarpa* is about 1 percent (Fig. 12d);
(6) the relative density of *Tsuga heterophylla* is about 60 percent (Fig. 13d);
(7) the relative density of other canopy species is about 3 percent $(100-(8+9+1+18+1+60))$;
(8) *Acer glabrum* is abundant (Fig. 10);
(9) treated as a mosaic type, this is a cedar-hemlock forest (Fig. 11);
(10) the litter loading is about 4 tons/hectare (Fig. 17a);
(11) the grass and forbs loading is less than 1 ton/hectare (Fig.17b);
(12) the 1 hour dead and down loading is about 1.2 tons/hectare (Fig. 17c);
(13) the 10 hour dead and down loading is about 3 tons/hectare (Fig. 17d);
(14) the 100 hour dead and down loading is about 8.5 tons/hectare (Fig. 17e);
(15) the greater than 100 hour dead and down loading is about 80 tons/hectare (Fig. 17f); and so forth.

If we desire this information because a fire has just been spotted at this point, all this information, plus other data on ground access, nearby natural fire barriers, and the like, are available just minutes after the fire is reported.

The advantages of such a system over the habitat-type approach appear to be obvious, significant, and highly desirable.

FIRE SPREAD AND EFFECTS MODELING

We may now take the vegetation and fuel information which we have retrieved from the gradient models, combine it with depth and packing information obtained from other gradient models not shown here, add the current weather and fuel moisture, calculate slope (from the elevation and aspect records in the inventory), and enter these data into the Rothermel (1972) combustion model to predict ground fire spread rate and intensity for a fire burning in this hectare on any given day. We may do the same for each adjacent hectare, *ad infinitum* if necessary, and thus predict the behavior of an individual fire burning in a particular place at a particular time.

We still do not have a true real-time model, because we are still assuming that fuels are uniformly distributed throughout the hectare (while in reality they are not), and we still assume that fire spread is a deterministic process, while in fact it is not.

The problem of modeling discontinuous fuels in Glacier has been approached through the development of two new ground fire models. The first is based on the Frandsen hexagonal model which divides the hectare into small cells (usually 4 m across). One assumes that fuel is horizontally uniform within a single cell, but induces stochastic variation in the fuel loadings from cell to cell. This permits the fire to realistically accelerate and decelerate, and to burn around fire barriers or areas of low fuel loadings (Kessell, 1975, 1976b). The second model, developed by Collin Bevins of Gradient Modeling, Inc., permits realistic simulation of vertical fuel discontinuities by dividing the fuel array into five distinct vertical strata; these include the litter stratum, the grass and forbs (with imbedded dead and down branchwood) stratum, the shrub stratum, the ladder fuel stratum, and the canopy stratum (Bevins, in preparation; *cf.* Kessell, 1976b). Both models are operational on a test basis in Glacier National Park.

Once we simulate the most likely burn area, we may then use the gradient model to predict the resulting plant successions, since one gradient is time since burn (modified by the categories of burn intensity). Thus for a full canopy burn of a southeast sheltered slope (1000 m elevation) in the McDonald valley, we expect, after 25 years, relative densities of 2 percent and 40 percent for hemlock and lodgepole, respectively (Fig. 14). After 100 years, we expect relative densities of 60 percent and 10 percent, respectively, for the same two species; at climax, we expect hemlock to have reached a relative density of about 65 percent, with Douglas-fir, red-cedar and spruce showing relative densities of 15 percent, 10 percent and 6 percent, respectively (Fig. 9). We can also predict the development of fuel loadings following the burn by Figure 18.

CONCLUSIONS

Ideally, then, one can use such a model to predict the behavior and results of an individual fire in a natural area, and use these predictions to help a fire manager determine the management policy for that particular fire; a flowchart for such a system is shown in Figure 21. This approach appears to be an attractive and feasible alternative to current "all or nothing" suppression/let burn management policies.

Despite the solid theoretical framework and data base supporting the model and hectare inventory, such an approach encounters many technical obstacles which limit any attempt at real-time fire modeling; these include the difficulty of predicting fire weather, difficulty estimating crowning potential and the resulting increase in fire intensity, difficulty estimating potential spread by crowning or spotting, and the near void of studies of the responses of mammals and other important animal species to environmental gradients. (On this latter point, however, current studies in Glacier suggest that the elk-moose-deer complex apparently follows elevation/topographic-moisture/burn gradients on the winter ranges, the mountain goat/sheep distributions may be described at least in terms of the primary succession gradient (rock *vs.* talus-meadow), and the black/grizzly bear

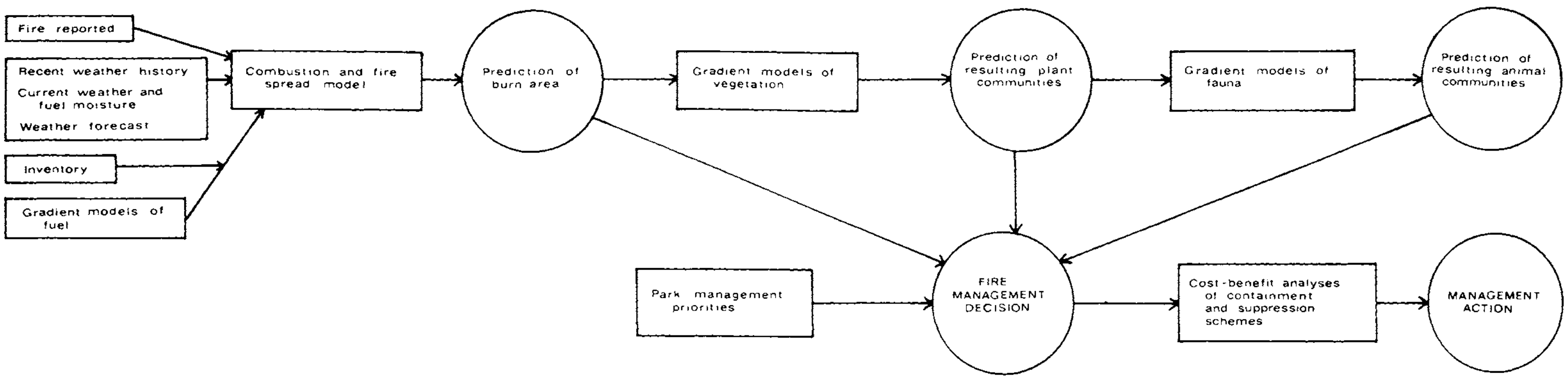


Fig. 21. Flowchart for real-time fire management system based on gradient models and the current Glacier National Park hectare inventory method.

habitats correspond to primary succession and elevation (forested *vs.* alpine)—crude, indeed, but a beginning). Yet despite these limitations, the gradient model approach overcomes many of the problems and limitations inherent in more traditional and less precise methods.

Finally, of course, one must weigh the cost of such an approach (about $1.00 per hectare) compared to less ambitious fire management projects—but I hope administrators and managers will view the cost not only in terms of dollars, but also in terms of management and resource quality, and that fiscal decisions will consider both elements.

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