PREDICTING FOREST COVER TYPE CHANGES
FOR A REGION OF NORTHEASTERN MINNESOTA

March, 1979

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ABSTRACT

This paper reports on a study conducted for the Regional Copper-Nickel Study to predict the change in area covered by defined forest types in 64,000-hectare region in northeastern Minnesota after a 100-year period. Two forms of a general Markov model proposed in an earlier paper (Sloss, 1977) were used to obtain these predictions.

Model predictions were to be validated by comparing the results obtained from simulations using qualitatively derived parameters with results simulations using parameters quantitatively derived. The latter parameters were to have been determined from changes in forest types seen on aerial photographs taken of the same area at different times. Because of the youthfulness of forests in the area chosen for study and inconsistencies in USFS cover-typing over the years, realistic quantitative parameters could not be obtained by this method. Therefore the model was not tested and its merit depends on the validity of model assumptions. A discussion of these assumptions and the derivation of the qualitative model parameters is provided.

After definition of forest types and the initial distribution vector (which gives the amount of area assigned to each age-class of each type), two models were applied with the aid of a computer. These additive and multiplicative models similar results. Both predicted, in 100 years, significant coverage increases in red pine, upland black spruce, planted white spruce, and in a fir-spruce-deciduous type and decrease in the area occupied by aspen-birch and jack pine. The simulations also predicted a shortage of harvestable red pine 60 to 80 years from now.

Finally, this report discusses the unsefulness of the Markov models and

their predictions. The report concludes by examining problems with the technique used to validate the model and suggests improvements that might allow the model to be tested in the future.

Programs written for this project are presented in Appendix III and are available from _____ stored on _______.

INTRODUCTION

The State Legislature established the Regional Copper-Nickel Study to assess potential social, economic, and environmental impacts of any future mining in the Duluth Gabbro Complex of northeastern Minnesota. Such assessment includes characterizing the area's present and future terrestial life. Of particular importance in determining not only the fate of wild life but also future timber yields is the study's success in predicting change in the area's forests. Such change depends on numerous factors, including the type of soils and forests, age of the forests, previous treatment of stands and other unidentifiable variable all of which are extremely difficult to quantify. With the aid of a Markov model nevertheless this report attempts to obtain valid predictions of future cover type distributions over a region.

An earlier paper (Sloss, 1977), discussed the suitability of various successional models found in the literature for predicting cover type changes over a large region and concluded that the model of Shugart, Crow, and Hett (1973), although having the highest potential, was inappropriate for this task. This differential equation model had not been tested to check if the unrealistic assumptions inherent in the model were acceptable.

Instead, that paper proposed and recommended that a Markov model be used by the Regional Copper-Nickel Study to predict future forest cover type distributions over a large region. This new model, composed of difference equations, is conceptually simplier and easier to work with than the Shugart et al. (1973) model because it reconizes age-insead of size-classes. In addition, forest management strategies are easily modeled for forested area broken into age~~s~~-classes (Gould, 1977). The flexibility of this Markov model, which recognizes age-classes, enables the user to easily express when forests are harvested and the extent that a forest type is regenerated as the same or

Figure 1.

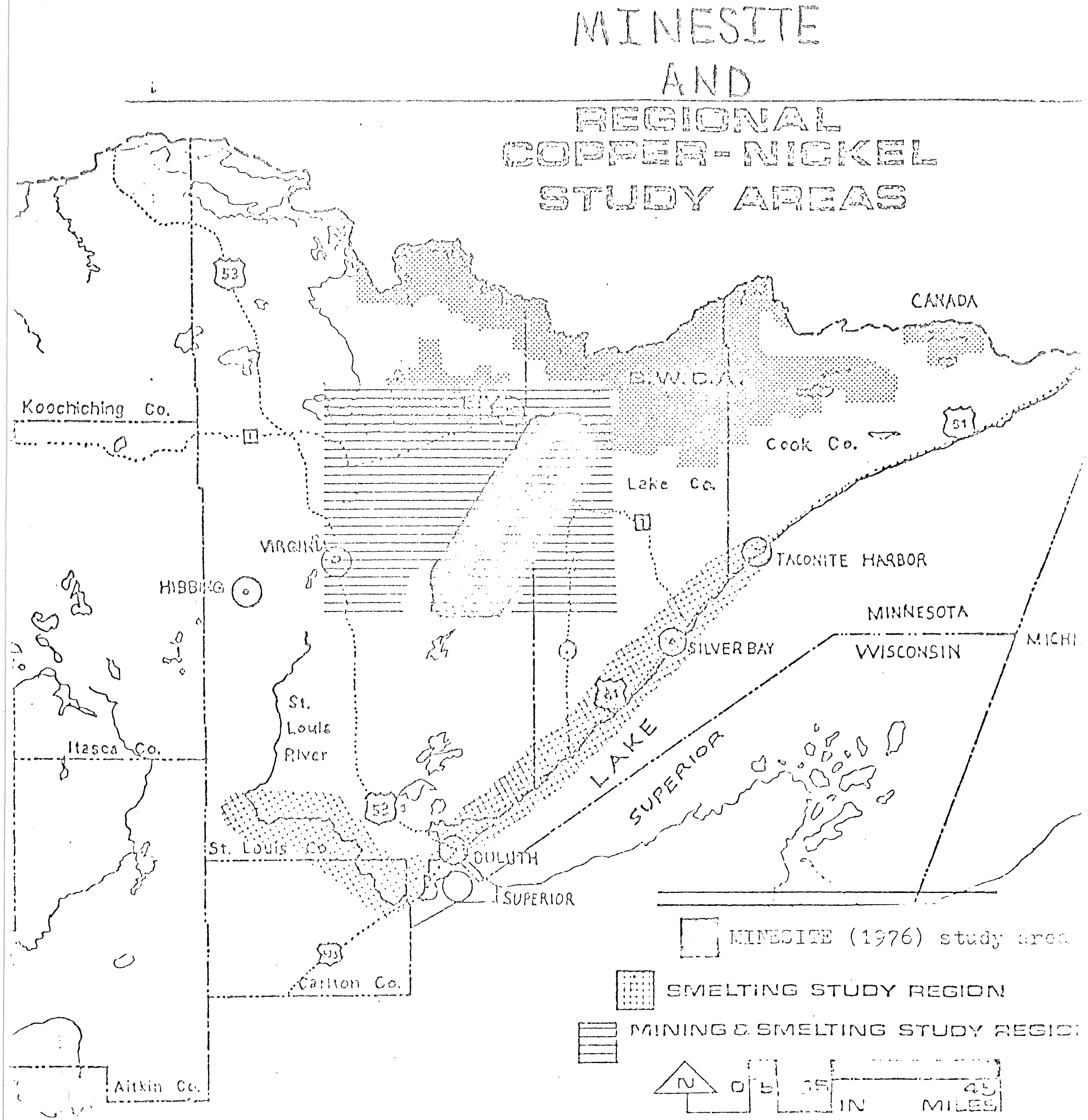
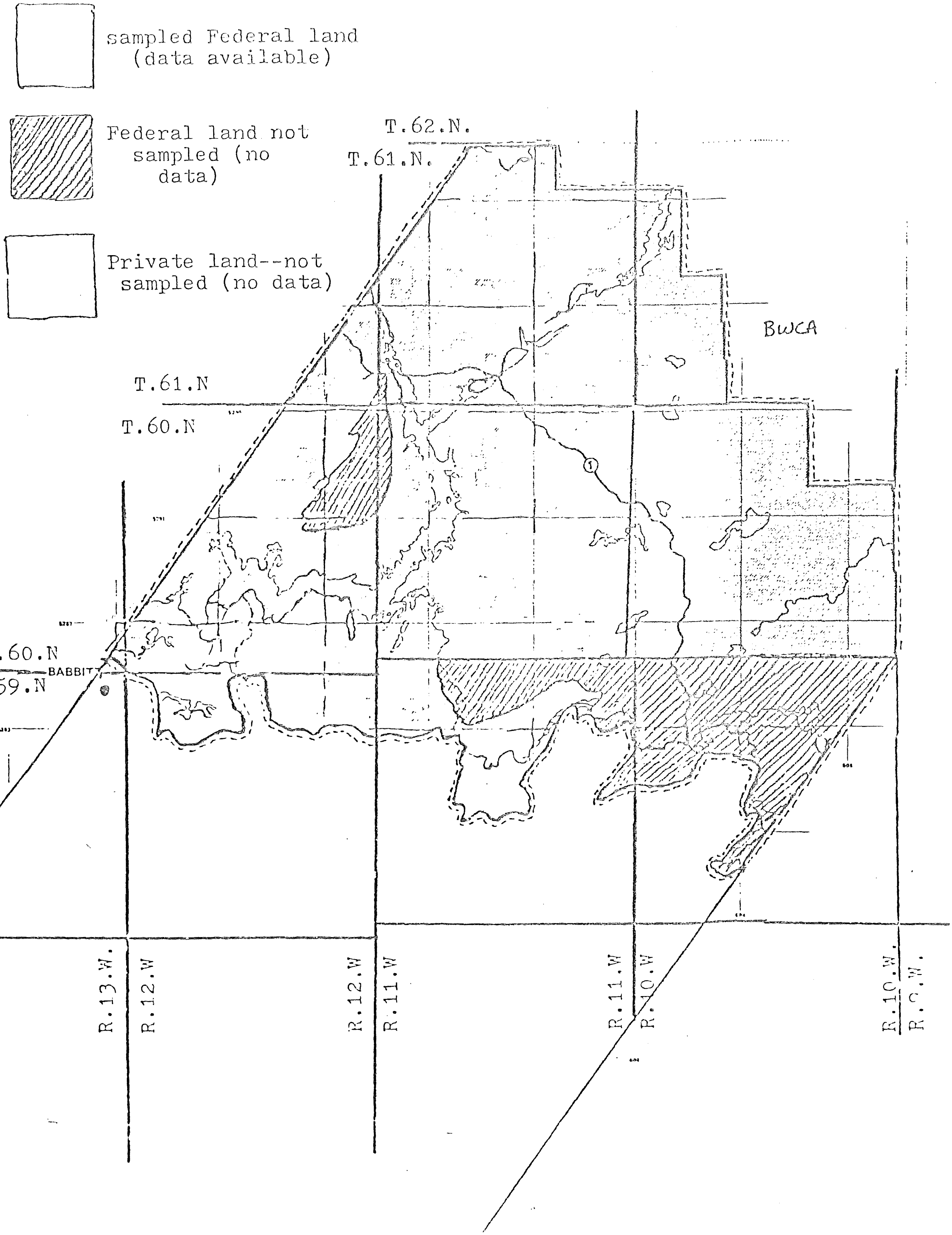

MINESITE AND REGIONAL COPPER-NICKEL STUDY AREAS
CANADA
B.W.C.A.
53
Koochiching Co.
1
61
Cook Co.
Lake Co.
1
VIRGINIA
HIBBING
TACONITE HARBOR
MINNESOTA
WISCONSIN
MICHI
SILVER BAY
61
St. Louis River
Itasca Co.
LAKE SUPERIOR
52
St. Louis Co.
DULUTH
SUPERIOR
53
Carlton Co.
Aitkin Co.
MINESITE (1976) study are
SMELTING STUDY REGION
MINING & SMELTING STUDY REGI
N
0 5 15 45
IN MILES

Figure 2.

The study area-- in the Birch Lake Kawishiwi area.



or some other type. Because the forested region, over which the model will be applied, is intensively managed. it is essential that the model used have such flexibility.

SUCCESSION STUDY AREA

This study focused on the area lying northeast of Birch Lake near the greatest known concentration of copper-nickel mineralization and adjacent to the Boundary Waters Canoe Area (BWCA). The southern border of this Study Area is defined by watershed boundaries. This region was investigated for the following reasons:

1) results of vegetation studies done within the BWCA can more reasonably be extrapolated to this adjacent area,

2) a large portion of the area (about 85 percent) is Federally owned and managed by the Forest Service as part of the Superior National Forest (in addition to keeping adequate records, the Forest Service practices predictable forest management),

3) extensive cutting of the area has left the forests even-aged and easily typeable--prerequisites for the modeling approach used in this study,

4) the area not only includes the greatest known copper nickel resource but also is probably the most sensitive to potential mining within the Regional Copper Nickel Study Area,

5) a previous study conducted by the MDNR's MINESITE project provides an inventory of several variables including,

Single space

forest type, forest size, density, age and soil type classes on the basis of 1 hectare cells. PP Table 1 summarizes, for those cells falling within the successional study region total areas occupied by forest types of varying ages. Description of these commonly used timber classes accompanies the table.[2] Interpretation of aerial photos taken in 1970 was used by the MINESITE project in cover typing the area, and interpretation of photos taken in 1937, 1948, 1961, as well as in 1970 allowed determination of the approximate date of stands' origin.

Table 1.

An age distribution based on timber cutting history for the forests occupying the northern third of the MINESITE (1976) area.[3] Definitions of MINESITE vegetation types follow the table.

TYPE	1977 AGE (years): 0-6	7-15	16-28	29-40	41+	Virgin	1961 Fire	Open Water	Total
	AREA IN HECTARES								
jack pine	0	200	102	384	1523	306	0	2	2515
aspen-birch	0	1400	2548	3264	20684	1453	0	53	29402
upland mixed	0	38	176	416	1023	142	0	5	1800
spruce-fir	0	104	263	461	2810	436	0	4	4078
red pine	0	136	85	93	496	154	0	0	964
white pine	0	5	0	0	10	0	0	7	22
plantation	2121	1211	601	0	0	0	0	0	3933
harvested	770	100	21	0	0	0	0	0	891
upland brush	0	43	41	5	53	0	1	0	143
grassland	0	2	7	0	44	1	0	0	54
marsh	0	14	26	64	235	241	0	11	591
lowland brush	0	103	191	132	1968	599	5	26	3024
tamarack	0	0	0	0	57	3	0	1	61
black spruce	0	113	223	295	2501	1056	0	2	4190
conifer swamp	10	112	294	572	2691	927	0	4	4610
swamp hardwoods	0	1	0	0	62	1	0	26	90
white cedar	0	0	9	19	51	20	0	1	100
* nonproductive swamp	0	13	125	119	305	482	0	3	1047
* open water	0	3	0	10	250	49	0	5232	5544
* farm	0	0	0	0	14	73	0	0	87
* residential	0	298	201	0	171	9	0	0	679
total	2891	3894	4913	5834	34948	5962	6	5377	63825

Type	Symbol (for later use)	Definition (after MINESITE (1976))
jack pine	JACK P	---more than 50 percent pine with jack pine outweighing white and red pine.
aspen-birch	ASP-B	---more than 50 percent trembling aspen, large tooth aspen, Balm of Gilead and paper birch.

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[3] Specifically, the table is a summation of MINESITE T16 and [illegible] cross-tabulations for the following MINESITE watersheds: Kawishiwi River, South Kawishiwi, Bear Island, Denley Creek, Stoney River, and [illegible].

* not used in simulations

Definition of MINESITE vegetation types (continued).

Type	Symbol	Definition
upland mixed		---natural or logged upland areas containing a mix of aspen, birch, pines and spruce. May also contain red maple and balsam fir.
spruce-fir	FIRSD or UBLKS	---A mixed hardwood-coniferous type composed of more than 50 percent white (and/or black)[4] spruce and balsam fir.
red pine	RED P	---more than 50 percent pine with red pine outweighin white and jack pine.
white pine	WHT P	---more than 50 percent pine with white pine outweighing red and jack pine.
plantation		---areas that have been planted but species cannot be identified on the aerial photographs.
harvested		---only one growing season elapsed since area harvested.
upland brush	BRUSH	---upland shrubs (hazel, pin cherry, etc.) with less than 10 percent stocked commercial tree species.
grassland	BRUSH	---all upland open areas of grass with less than 10 percent stocked commercial tree species.
marsh	SEDGE	---marsh (grass, sedges, and some lowland brush), bog or open muskeg.
lowland brush	LSHRB	---lowland shrubs (alder, (leatherleaf, Labrador tea,)[4] etc.) with less than 10 percent stocked commercial tree species.
tamarack	LARCH	---more than 50 percent swamp conifers with tamarack outweighing other species.
black spruce	LBLKS	---more than 50 percent swamp conifers with black spruce outweighing other species.
conifer swamp	MCBOG	---spruce, cedar, balsam, and tamarack comprising more than 50 percent of the stand.
swamp hardwoods	SHWDS	---more than 50 percent composed of bottomland hardwoods (ash, elm, Balm of Gilead, red maple).
white cedar	CEDAR	---more than 50 percent swamp conifers with northern white cedar outweighing other species.
nonproductive swamp		---spruce, tamarack, or cedar bog which will not produce trees of pulpwood size in 100 years.
open water		---lakes, ponds, flowage, streams.
farm		---crop, orchard, or pasture, but not farm woodland.
residential		---areas used for industry or residence.

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[4] I've added the terms within the parentheses to aid in understanding the types.

METHODS

Suppose we know from Table 1 that about 250 hectares of the study area are occupied by 'state one'--even-aged jack pine stands 20 years or less in age. In twenty years, barring some catastrophe, this 250 hectares of jack pine will have matured to a second state--even-aged stands 21 to 40 years of age. As the stands mature further, some are cut and regenerate to jack pine (returning some area to state 1) whereas others break down to be replaced by succeeding species (sending area to other states). Suppose we know how all area classified as any forest type is dis~~turbed~~tributed among states or twenty-yeat age-classes. To predict cover type changes we need to know how this initial distribution of the region's area among these many states changes in time. Flow of area from state to state is properly defined by a system of linear difference equations or a Markov process, the mathematics of which will be described later.

Use of a Markov model entails the need for finding a transition matrix--a table of parameters that given the probability that area flows from one to another state after a given time interval. The original intent was to examine merely the role natural forest succession plays in affecting forest cover type changes in the area. Although the transition matrix was to be qualitatively derived from comments in the ecological literature regarding forest dynamics, the same matrix was also to be determined quantitatively using old and more recent aerial photo interpretations by charting the history of forest stands covering randomly selected points within the area. It was hoped that similarity between the qualitatively and quantitatively derived two matricies would produce similar results of model simulations. Thus the model and qualitative observations of successional trends made by

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[1] Personal communication from W.A. Patterson, Copper-Nickel. 1977.

[2] Common and scientific neames of plant species mentioned are given in Appendix I.

plant ecologists could be used as checks against each other.

Area systematically sampled for the identification of transitions is shaded in Figure 2. Because this area is Federally owned, I could use detailed 1948 Forest Service timber survey maps and Forest Service compartment records with associati~~on~~ed maps compiled in the 1970's to tally changes in forest str. that occur at township sections corners, centers, and midpoints along section lines.

As sampling progressed, however, it soon became evident that too few instances of natural succession had occurred during this time interval to validate the qualitatively derived successional trends. Aerial photo interpretation revealed that many stands where natural succession appeared to occur were merely thinned after 1948 or were changed because of an epidemic, a change in drainage patterns, or some other disturbance. Consequently, any qualitative predictions of forest type changes had to account for disturbance if it were to be tested using a transition matrix derived from this sampling process.

It was hoped that forest compartment records, which list stand ages, whether partial cutting occurred, and the past effect of pests, might be used to partition transitions from one type to another into defined groups of disturbance. Although typing scale and recognized cover types in 1948 and in the 1970's are almost identical, different interpret~~at~~ers drew boundaries around forest stands in 1948 and in the 1970's. The major cause for a typing change of forests occupying sample points from 1948 to the 1970's was due either to a typing error or the lumping together on one map of different stands identical in other period. Because of this situation attention was focused on points where the stand boundaries appeared similar on maps compiled for both periods. Although a transition matrix was obtained, data points were so scarce that only a few trends in forest change are evident (all apparently caused by forest management). With the available data, therefore, a comprehensive test of the

ASSUMPTIONS IN LIGHT OF THE TRADITIONAL CONCEPTS OF THE PLANT COMMUNITY AND SUCCESSION

Although the model could not be rigorously tested by the methods described above qualitative predictions were sought on the basis of several assumptions. These assumptions are outlined below in a theoretical context because plant succession is the main driving force in the model.

The vegetation of an area may be treated as being either 1) continuously variable or 2) composed of discrete units. Each approach has utility under contrasting conditions. When applied to vegetation that lacks distinct natural boundaries between plant assembleges, the former approach (known as the "continuum concept" (McIntosh, 1967) allows community composition and species quality to be related to environmental gradients. Examples of analytical techniques that embody this approach include, among others, synecological coordinates (Bakuzis, 1959), direct gradient analysis (Whittaker, 1967), and principle components ordination (see Pielou, 1977). Where vegetation discontinuities do occur, the communities can be assigned to a restricted number of abstract cover types arbitrarily or quantitatively defined. Braun-Blanquet's releve' method (1932) provides an example of arbitrary community classification; Orloci's agglomerative clustering analysis (1967) provides one of quantitative classification. At the very least, this "community concept" allows the simplification of a heterogeneous region.

Another advantage of recognizing discrete communities is that these arbitrary units can be arranged in temporal sequence. This idea originated with Clements (1916) who believed that the development of plant communities is analogous to the development of organisms. Clements' theory of plant succession holds that, for any given region and its associated climate, a community undergoes stages of development where particular plant associations affect their environment in a way that allows an invading plant association to dominate. The process culminates in the "mature" climax state in which members of the final association act to preclude any further invasion. Most importantly, this view implies that the process is predictable and that particular community types may be considered as stages in the development of an area's vegetation that culminate in a climax state.

Gleason (1926) strongly opposed this idea of the plant community and its development. His "individualistic concept" stress that the behavior of a plant assemblege depends only on the individual plants composing the assemblage. Further, the plant composition on a particular site depends on which species are able to migrate to and survive on that site. Because species range limits rarely coincide and environments lack uniformity in space and time, communities with identical plant compositions are almost never observed. Therefore, this view claims that the origin and dynamics of no two communities from the same region can be considered identical.

Although the individualistic concept provided a basis for the continuum school, it offers little opportunity for predicting change in vegetation on a regional basis. The concept maintains that these changes are a stochastic rather that deterministic phenomenon. In the past, ecologists have used stochastic models to simulate tree-by-tree replacement for particular forests (Leak, 1971; Bodkin et al., 1971; and Horn, 1975). However, as the forested area and subsequent environmental heterogeneity of an area increases in such a model, predicting the behavior of individual trees becomes too difficult. For large regions then, it is most feasible to follow Clements (1916) and treat the community type, or the unit area it occupies, as the individual. This choice necessarily leads to the first assumption of this analysis---that the natural replacement of one stand by another is a more or less discrete process rather than a slow continuous one.

The second major assumption made by this analysis claims that stands classified as the same cover type have enough structural similarity that they exhibit identical temporal behavior.

Fire and forest management have historically served to maintain reasonably distinct boundarie~~d~~s between forest stands occupying the study area. Stands can be identified and classified to the dominant canopy species. By using the forest types recognized by the Forest Service and described in the next section, the number of "~~I~~individuals' can be reduced enough to be handled by a model simulation. This arbitrary typing scheme disregards all other structual layers including mosses, herbs, shrubs, understory species and overstory sp~~a~~ecies that do not contribute significantly to the basal area of the stand. For example, a stand of relatively pure overstory black spruce over a blanket of feathermoss and a stand with 51 percent black spruce-49 percent jack pine in the overstory and little moss would both be classified as "upland black spruce types." The functional attributes of these two communities are probably quite different.

Daubenmire (1966), emphasizes that abiotic factors, as well as biotic ones may serve to retard or accelerate the rate of succession on a given site. Properties of the soil, the slop~~w~~e of the land and the variability in local climate ma~~u~~y affect the ability with which succeeding species may compete with those already pr~~ivate~~esent. The third assumption of the succession model is that site characteri~~?~~stics remain fairly constant throughtout the areas occupied by each forest type and through time so that the model parameters represent good averages of when stands "die" and are succeeded by other.

Because of disturbance and problems with the methodology described in the previous section, successional parameters depend entirely on the assumption just outlined. These assumptions, that one stand replaces another at one instant in time and that the rates of replacement are independent of the biotic and abiotic components of the site, are clearly unrealistic, but simplify the task of determining regional changes in vegetation. Effects produced by the unrealistic assumptions may tend to cancel each other so that qualitative predictions of successional trends can be obtained.

DEFINING COVER TYPES AND THE INITIAL DISTRIBUTION VECTOR

The choice of abstract cover types for use in a simulation is not a simple task. Vegetation types for northeastern Minnesota recognized by various authorities are set side by side for comparison in Table 2. Although successional relationships are more easily identified and expressed when using objectively defined communities (Grigal and Ohmann, 1975), the monotypic forest types recognized by the Regional Copper-Nickel Study, the MINESITE project and the Forest Service are most suitable for modeling forest management. Forest Service cover types were used because the study area has been and will be intensively managed. However, an aspen-birch community~~,~~ is recognized in lieu of separate aspen and birch types because such pure stands are infrequent in the study area. In order to establish initial areas in each cover type for use in the model simulation, a map of the succession study area was needed. Such a map must include all lands, regardless of their ownership. The only such map available for the succession study area was that of the DNR MINESITE project.

MINESITE vegetation types are similar to but not identical with the Forest Service types. Using the areas and ages of sample stands, area from MINESITE vegetation classes was prorated to those different types used in the model.

Table 2.

Forest types defined for areas of northeastern Minnesota by authorities cited at the head of columns. The vertical proximity of the types reflects their floristic similarity (as based (very roughly) on the authors' comments and my own impressions gained from comparing different vegetation maps).

Regional Copper-Nickel Study	Society of American Foresters (1954)	MINESITE (1976)	Forest Service in 1948	map symbol	Forest Service after 1970	map symbol	Ohmann and Ream (1971)	Grigal and Ohmann (1975)
succession study area	North America	MINESITE study area	Superior National Forest				BWCA	BWCA
							jack pine (fir)	jack pine (fir)
Jack pine	#1 jack pine	jack pine	jack pine	5	jack pine	J	jack pine (black spruce)	jack pine (black spruce)
							jack pine (oak)	jack pine (oak)
		upland brush			upland brush	U	lichen outcrop	lichen outcrop
			upland brush	1h				
		harvested			open	O		
		grassland	grassland	0				
								maple-oak
red pine	#12 red pine	red pine	red pine	8	red pine	R	red pine	red pine
	#21 white pine	white pine	white pine	9	white pine	W	white pine	aspen-birch-white pine
aspen-birch	#11 aspen-birch	aspen-birch	aspen-birch	A	aspen	A	aspen-birch	aspen-birch
					birch	B		
							maple-aspen-birch	maple-aspen-birch
mixed conifer-deciduous		upland mixed						maple-aspen-birch-fir
							white cedar	white cedar
							fir-birch	fir-birch
					fir	F		
mixed black spruce Jack pine	#4 spruce-fir	spruce-fir	spruce-fir	6	white spruce	G		
			black spruce	7	upland black spruce	I	black spruce (jack pine)	black spr (feathermo
black spruce	#12 black spruce				lowland black spruce	S		
		black spruce						
		conifer swamp	mixed conifer swamp	Br	mixed conifer swamp	Q		

Table 2 (continued).

Regional Copper Nickel Study	SAF (1954)	MINESITE (1976)	Forest Service			
			1948		1970	
tamarack	#38 tamarack	tamarack	tamarack	T	tamarack	T
ash	#39 lowland hardwoods	lowland hardwoods	lowland hardwoods	Ms	lowland hardwoods	E
cedar	#37 white cedar	white cedar	white cedar	4	white cedar	C
		non-productive swamp	non-productive swamp	Sx	non-productive swamp	x
		lowland brush	lowland brush	1s	lowland brush	L
			muskeg	2		
		marsh	marsh	Ψ	marsh	Ψ

Such procedure is described below with the aid of Table 3 through 6.

1. Table 3 shows how 57 percent of MINESITE upland mixed forest was typed by the Forest Service. Notice that age-intervals are 0 to 20 years, 21 to 40, etc. instead of the 0 to 6, 7 to 15, etc. intervals found in Table 1. Here it was assumed that forest younger than 40 years are equally distributed in age and cover so that 5/13 (38 percent) of the area in the 16 to 28 year MINESITE age-interval can be allocated to a 0 to 20 year interval whereas the remaining 8/13 (62 percent) goes to a 21 to 40 year interval.[5]

   To remain consistent with the early age-distribution set out for the upland mixed type by the MINESITE data, prorated areas for age-classes beyond 40 years are somewhat less than the values called for by the precent of sampled area falling in theat age-class (e.g. sample area for 81 to 100-year-old jack pine calls for 9 percent or 169 of the 1800 mixed upland hectares to be prorated to that class. However, only 162 hectars are prorated this way--the other seven are subjectively moved into the 21 to 40-year jack pine age-class to aid in insuring that 572 prorated hectares remain in this age-class overall.

2. MINESITE spruce-fir area is similarly prorated among balsam fir and upland black spruce types as shown in Table 4. Correlation was generally good between these types although some MINESITE spruce-fir was typed as pine, aspen-birch, and lowland black spruce.

3. Plantation and harvested area is prorated to early age-classes of jack pine, aspen-birch, white spruce, and red pine as shown in Table 5. Most of the harvested area occurred in the Stoney River watershed, southernmost in the succession study area. Because few compartment records were obtained for this area. Only a four percent sample could be obtained.

4. Upland brush and grassland areas were combined into an upland non-forested type.

5. Much of the MINESITE mixed-conifer-swamp type was typed by the Forest Service as lowland black spruce. One possible explanation for this inconsistency is that small upland islands or intrusions of pine and fir in black spruce swamps confused those who did the vegetation typing for MINESITE (1976).[6] At any rate, MINESITE mixed conifer area was prorated back to black spruce as indicated in Table 6.

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[5] It was also assumed that those few hectares flooded (or listed under "open water" in Table 1) are properly included with area of the same type in the 0 to 20-year age-class. In addition, virgin stands are all assumed to be older than 40 years.

[6] Personal communication from N.P. Sather, Copper-Nickel. 1978.

Table 3.

Prorating area typed as upland mixed by MINESITE (1976) among the following Forest Service cover types used in the model: jack pine (JACKP), aspen-birch (ASP-B), white spruce (WHT S), upland black spruce (UBLKS), balsam fir (FIRSD), red pine (RED P), and lowland black spruce (LBLKS). For any age-class, values in:

a-columns are hectare areas sampled,
b-columns are percentages of the total sampled area,
and c-columns are prorated areas.

age-class	0-20			21-40			41-60			61-80			81-100			101+			total		
upland mixed	63			572			1165												1800		
column	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
JACKP	0	0	0	30	3	68	8	1	13	67	6	113	90	9	162	7	1	11	208	20	367
ASP-B	20	2	63	20	2	66	116	11	183	149	14	236	55	5	87	0	0	0	360	36	635
WHT S	0	0	0	0	0	0	0	0	0	0	0	0	12	1	19	0	0	0	12	1	19
UBLKS	0	0	0	7	1	98	45	5	54	24	4	24	30	3	30	25	2	25	131	13	231
FIRSD	0	0	0	0	0	89	50	5	50	16	1	16	50	5	50	0	0	0	116	11	205
RED P	0	0	0	125	13	237	0	0	0	20	4	20	0	0	0	0	0	0	145	14	257
LBLKS	0	0	0	0	0	14	15	1	26	13	1	23	0	0	0	21	2	23	149	5	80
total	20	2	63	182	19	572	234	23	326	269	26	432	243	23	348	53	5	59	1021	100	1800

$$\text{area sampled} = \frac{(100)(1021)}{(1800)} = 57\% \text{ of total.}$$

Table 4.

Prorating area typed as spruce-fir by MINESITE (1976) among upland black spruce (UBLKS) and balsam fir (FIRSD). Column headings as above.

age class	0-20			21-40			41+			total		
spruce-fir	218			614			3246			4078		
column	a	b	c	a	b	c	a	b	c	a	b	c
UBLKS	0	0	0	14	1	116	616	64	2421	630	65	2537
FIRSD	67	7	218	60	6	498	210	22	825	337	35	1541
total	67	7	218	74	7	614	826	86	3246	967	100	4078

$$\text{area sampled} = \frac{(100)(967)}{(4078)} = 24\% \text{ of total.}$$

Table 5.

Prorating area typed by MINESITE (1976) as plantation and harvested among types used in the model. Cover type abbreviations are as in Table 3.

age-class	---	---	0-20	21-40	total
plantation	---	---	3582	351	3933
	sample area	percent of total	prorate area	prorate area	prorate area
JACKP	110	12	430	42	472
ASP-B	231	25	896	88	984
WHT S	220	25	895	88	983
RED P	348	38	1361	133	1494
total	909	100	3582	351	3933
harvested	---	---	879	12	891
JACKP	20	53	466	6	472
ASP-B	10	26	228	3	231
RED P	8	21	185	3	188
total	38	100	879	12	891

area sampled $= \frac{(100)(909)}{(3933)}$

= 23% of total plantation area

area sampled $= \frac{(100)(38)}{(891)}$

= 4% of total harvested area

Table 6.

Prorating area typed by MINESITE (1976) as mixed conifer to black spruce so that the distributions of both reflect the sample distribution. Columns headings a, b, and c are as in Table 3. (MCBOG is mixed conifer).

	age-class	0-20	21-40	41+	total
MINESITE	black spruce	208	425	3557	4190
	mixed conifer	249	743	3618	4610
	total	457	1168	7175	8800

column	a	b	c	a	b	c	a	b	c	a	b	c
LBLKS	109	6	441	101	7	1007	1502	76	6190	1712	87	7638
MCBOG	4	0	16	16	1	161	239	13	985	259	13	1162
total	113	6	457	117	8	1168	1741	88	7175	1971	100	8800

area sampled $= \frac{(100)(1971)}{(8800)}$ = 22% of total.

Data in Table 1 indicate that most forested area in the succession study area originated more than 40 years ago. Such area for each type is partitioned into 20-year age-classes again based on the ages and areas of sample stands as shown in Table 7. Finally, all prorated area in Tables 3 through 7 is combined in Table 8 forming an initial distribution vector in the appropriate form for the model described in the following section.

From Table 8 we see that 41 to 60-year-old aspen-birch occupies more area than any other state. Interestingly, this area seems to fill a void in the pine types of this age-class. This distribution may reflect widespread replacement of pine stands by aspen after harvest between 1917 and 1936.

In summary, the distribution in Table 1 has been readjusted to that in Table 8 by more-or-less objective means. The values surely are not exact, particularly those for types occupying small areas, but do ~~not~~ accurately reflect the age-distribution of the forests in the succession study area as they now exist.

MARKOV MODELS FOR SIMULATING COVER TYPE CHANGES

Mathematics..

A model is proposed that may be considered a discrete analouge of Shugart, et al.'s (1973) differential equation model for simulating forest succession over a region. Both models adhere to the assumptions outlined earlier. Instead of utiliz~~y~~ing forest size classes, however, the proposed uses age-classes as mentioned in the introduction.

The form of the model is set of linear difference equations where x represents the acreage occupied by cover state i of an unspecified age at time t and a_{ij} represents the probability that an acre of cover state i becomes one of j during the time-interval t (equation 1, 2, and 3).

Table 7.

Prorating area of most MINESITE vegetation types among 2--year age-classes. Those types found in Table 1 but not list below are not the model were not considered relevant for simulations of cover type change. The large percentages for sampled pine is explained by the Forest Service's liberal typing for conifers in aspen-birch or mixed stands as opposed to MINESITE typing. Column headings a and c are defined in table 3.

age-class	0-20		21-40		41-60		61-80		81-100		101-120		121-140		141-160		sample
column	a	c	a	c	a	c	a	c	a	c	a	c	a	c	a	c	%
JACKP	947	243	874	443	45	62	413	633	344	595	113	219	0	0	0	0	103
ASP-B	1049	2462	1235	4750	2628	13282	874	4427	761	4427	113	0	0	0	0	0	23
UBLKS	0	0	14	116	287	1182	154	629	84	360	91	385	0	0	0	0	---
FIRSD	67	218	60	498	124	487	42	165	44	173	0	0	0	0	0	0	---
RED P	498	171	425	143	0	0	170	557	28	93	0	0	0	0	0	0	116
WHT P	0	12	0	0	0	0	1	1	53	8	0	0	0	0	12	1	300
BRUSH	---	66	---	33	---	50	---	48	---	0	---	0	---	0	---	0	---
SEDGE	---	38	---	79	---	158	---	158	---	158	---	0	---	0	---	0	---
LSHRB	---	214	---	243	---	1284	---	1284	---	0	---	0	---	0	---	0	---
LARCH	0	0	12	1	16	10	40	24	44	26	0	0	0	0	0	0	184
LBLKS	109	441	101	1007	259	1076	259	1076	526	2187	404	1052	12	50	40	169	---
MCBOG	4	16	16	161	57	223	69	271	77	303	28	112	4	16	4	16	---
SHWDS	0	21	8	6	20	23	32	36	4	4	0	0	0	0	0	0	64
CEDAR	0	5	0	24	0	0	0	0	16	34	0	0	0	0	11	37	71

Table 8

The initial distribution vector obtained by summing prorated areas in all preceeding tables.

age-class	0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	total
JACKP	1138.	560.	105.	936.	857.	230.	0	0	0	3826
ASP-B	3702.	4907.	13465.	4664.	4514.	0	0	0	0	31252
WHT S	896.	87.	0	0	19.	0	0	0	0	1002
UBLKS	0	214.	1182.	629.	360.	383.	0	0	0	2768
FIRSD	218.	587.	537.	181.	223.	0	0	0	0	1764
RED P	1717.	516.	0	577.	93.	0	0	0	0	2903
WHT P	12.	0	0	1.	8.	0	0	1.	0	22
BRUSH	66.	33.	50.	48.	0	0	0	0	0	197
SEDGE	38.	79.	158.	158.	158.	0	0	0	0	591
LSHRB	214.	243.	1284.	1283.	0	0	0	0	0	3024
LARCH	0	1.	10.	24.	26.	0	0	0	0	61
LBLKS	441.	1021.	1102.	1099.	2187.	1705.	50.	169.	0	7774
MCBOG	16.	161.	223.	271.	303.	112.	16.	16.	0	1118
SHWDC	21.	6.	23.	36.	4.	0	0	0	0	90
CEDAR	5.	24.	0	0	34.	0	0	37.	0	100

$$\begin{aligned} x_{11}&=a_{11}x_{10}+a_{12}x_{20}+\ldots+a_{1n}x_{n0} \\ x_{21}&=a_{21}x_{10}+a_{22}x_{20}+\ldots+a_{2n}x_{n0} \\ &\vdots \\ x_{n1}&=a_{n1}x_{10}+a_{n2}x_{20}+\ldots+a_{nn}x_{no} \end{aligned} \qquad \text{in algebraic form,} \qquad (1)$$

$$\text{or} \quad \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{vmatrix}_{t=1} = \begin{vmatrix} a_{11} & a_{12}\cdots a_{1n} \\ a_{21} & a_{22}\cdots a_{2n} \\ \vdots & \vdots \\ a_{n1} & a_{n2}\cdots a_{nn} \end{vmatrix} \cdot \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{vmatrix}_{t=0} \qquad \text{in matrix form,} \qquad (2)$$

$$\text{or} \quad \overline{X}_{t=1}=(T)(\overline{X}_{t=0}) \qquad \text{in vector form.} \qquad (3)$$

The state of the region at t=1 ($\overline{X}_{t=1}$) is a linear function of the state at t=0 ($\overline{X}_{t=0}$). If I assume that $\overline{X}_{t=1}$ always depends only on $\overline{X}_t$ (i.e. that T, transition matrix, is constant for all t), equation 3 can be solved by repeated iteration and substitution yielding:

$$\overline{X}_{t=n}=(T^n)\ (\overline{X}_{t=0}) \qquad \text{a Markov process.} \qquad (4)$$

To incorporate age-structure into this multi-species model, groups of x_{it} variable are assigned to each forest type--a number that depends on the selection of t, the time-step-interval. Though smaller time-step intervals would have allowed more frequent examination of a more detailed distribution vector during a simulation, an interval of 20 years was used to minimize the number of equations needed in the model. Area is thus prorated among the fifteen cover types into 20-year age-classes as shown in Table 8. For bookkeeping purposes, ten age-classes were assigned to each of these types. This yields n=(10 age-classes)x(15 cover types)=150 equations for use in a simulation. Ten age-classes per type also permits area of any type to reach a maximum age of 200 years. Maintaining the order of types listed in Table 8, the x_i variables are assigned to cover states as follows: x_1 through x_{10} are jack pine age-classes 0 to 20 through 181 to 200 respectively; x_{11} through x_{20} likewise are aspen-birch age-classes; the process continues this way until finally, x_{141} through x_{150} become cedar age-classes.

A major task in this project is finding the appropriate values that fill the n-by-n transition matrix T. As indicated earlier, qualitative derivations of T should be performed considering all factors, including disturbance as well as natural succession, which affect change in cover type distribution. In order to more easily assess the impact of the factors, each one must be considered separately from the rest. These impacts are somehow brought together in the final analysis.

One approach used in this study is embodied by the following interesting though relatively unrealistic system:

$$\overline{X}_{t+1}=((I-bI+bB)((I-aI-aA)((I-mI+mM)((S)\overline{X}_t)))) \qquad (5)$$

where S=the forest growth and succession transition matrix,
M=the forest management transition matrix,
A=the abiotic disturbance transition matrix,
B=the biotic disturbance transition matrix,
identity I=the n-by-n idently matrix,
and m,a,b=fractions of the entire area that are affected by management, abiotic, and biotic disturbances, respectively.

This model is not as complicated as it appears. The equation merely states that after every time-step, area in $\overline{X}_t$ is redistributed when $\overline{X}_t$ is multiplied in sequence by a successional transition matrix followed by management, abiotic, and biotic disturbance transition matrices. This model is henceforth required to as the "multiplicative" model. The lower case variables are used to insure that not all of $\overline{X}_t$ is affected by a disturbance matrix (e.g. if a=0.05, then 5 percent of the area is burned or affected by some other abiotic disturbance during each time-step). If m=a=b=1.0, the sytem reduces to:

$$\overline{X}_{t+1}=(B(A(M(S)\overline{X}_t)))). \qquad (6)$$

The advantage of this model is that it utilizes intact transition matrices that are easily constructed. Because the time variable is discrete, however, results depend upon the order in which these matrices are used to redistribute area in $\overline{X}_t$. This is a major disadvantage.

Equation 7 defined a second additive and a more realistic model also used here.

$$\overline{X}_{t+1}=(S+M+A+B)\overline{X}_t \qquad (7)$$

where S, M, A, and B are as above
but, $S+M+A+B=T$.

The matrices are not transitional but rather, sum to a transition matrix. Although model results do not depend on the arrangement of S, M, A, and B in equation 7 as in the previous model,[7] these matices are not easily constructed.

With intial conditions shown in Table 8 and transition matrices qualitatively derived, both models were used to simulate cover type changes after a 100-year period or five time-steps. In addition, if a valid T could have been derived from the sampling procedure, equation 3 could have been used in a 100-year simulation period to obtain a third set of results. Unfortunately the sampling procedure failed to produce a valid T so this third set of results couldn't be used to support the predictions of the first two sets.

Computer Programs.

Two computer programs written in Minnesota FORTRAN (MNF) and run on the University Computer Center's Cyber 74 are listed in Appendix III. The first program, CTYPEC (cover type change), computes the results of a simulation whereas the second, CTCOP (cover type change output), prints the results in the proper form. Additional programs that set up or listed various files

[7] Matrices are communative under addition but not multiplication (Bradely, 1975 (page 43)).

used by these two main programs, including one that stored the transition matrices, are not included with this report.

As shown CTYPEC applies the multiplicative model given by equation 5 by printing, onto a file, new distribution that result each time old distributions are multiplied by (all or a fraction of) S, M, A, or B. Depending on the the detail required by the user, CTCOP analyzes and prints out the results in forms ranging from a lengthy list of how each factor affected each age-class of each type after each time-step to a small table that merely summarizes the simulation.

the
With yhr few minor alterations shown boxed on the left in Appendix III, the programs can apply the system described by equation 7, the additive model also, when m,a, and b (denoted in CTYPEC as U,L(i=2,4) are all set to zero, the programs can apply equation 3 (where S=T).

The dimensions of each transition matrix in a linear model with 150 equations requires 22,500 storage locations of computer memory per matrix--near or beyond the loading capabilities of many systems. To conserve core space, transition matrices were stored in a random access file so that CTYPEC, which is only able to handle one matrix at a time, could read in any matrix when it was needed.

As a consequence of the model's structure, the transition matrices are sparce (i.e. they contain few non-zero terms). Sparce matrices can be efficiently packed for storage using the principle of "linked lists" (Tewarson, 1973). Although I handle the matrices in bulk here, users should know that this packing process exists and could significantly reduce computer costs.

QUALITATIVE DERIVATION OF SUCCESSIONAL PROBABILITIES

As previously indicated, parameters that fill the successional transition matrix, S, could only be determined qualitatively. It was hoped that information obtained solely from the ecological and silvicultural literature could be used to derive the constants. However, even the comprehensive vegetational studies of Ohmann and Ream (1971), Heinselman (1973), and Grigal and Ohmann (1975) fail to provide sufficient appropriate evidence for the derivation of these parameters.

According to the model's structure, only three pieces of information are needed for each potential cover type succession:

(1) the age of the pioneer when it breaks down.

(2) the probability that a particular cover type replaces the first type, and (3) the age of the succeeding type when it replaces the first.

These values can be organized and arranged in diagrams or "model topologies" like those shown in Appendix II,[8]. To gather information in addition to that gleaned from the literature, copies of the letter in Appendix II were sent for review to those qualified to make judgements regarding forest dynamics in northeastern Minnesota. The values used in these topologies were determined from the literature.

The reasoning presented below was used to produce the final successional parameters oraganized into the model topology shown in Figure 3. Assumption were based on fifteen returned letters and the literature.

1. Jack Pine (JackP).

Even-aged stands of jack pine break down at ages from 60 to 100 years depending on site conditions (Fowells 1965). Most reviewers agreed with my determination

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retrospect

[8] Because a time-step of twenty years is used in the model, the ages should be multiples of twenty. In res~~pect~~, however, it appears that use of the

pivotal

pivtal ages, 10, 30, 50, etc. would have been more appropriate for the age of the successor at the time of replacement instead of the ages 20, 40, 60 etc., which fall on the border between two-age classes.

of 80 years as the replacement-age of an average jack pine stand.[9] Some however, felt this value should be higher and indeed, jack pine stands over 100 years of age (usually along lake shores or roads) were sampled as part of this study. In the BWCA, Heinselman (1973) also sampled many stands dominated by jack pines over 100 years in age. For these reasons, succeeding forest types were assumed to replace all jack pine stands of ages over 120 years.

Because of the species' intolerance of shade, jack pine cannot regenerate itself in the absence of disturbance except on very dry, nutrient-poor soils. It initially appeared that shade-tolerant black spruce would replace jack pine with high probability (0.8) on good sites because black spruce was a significant understory component in about 80 percent of Ohmann and Ream's (1971) sampled jack pine stands within the BWCA. In addition, black spruce seems to gain dominance earlier than balsam fir in Heinselman's (1973) study and shares dominance with jack pine in one of the Regional Copper-Nickel Study's community types (Sather, 1979). However, reviewers unanimously agreed that jack pine succession to spruce-fir-birch occurs much more frequently than succession to upland black spruce.[10] Reasons for this include:

1) black spruce, with its semiserotinous cones, largely depends on periodic fire for its occurrance on the uplands (LeBarron, 1948) and, since the early 1900's most of the study area hasn't burned.

and 2) the establishment of fir seedlings is prolific in the absence of fire.

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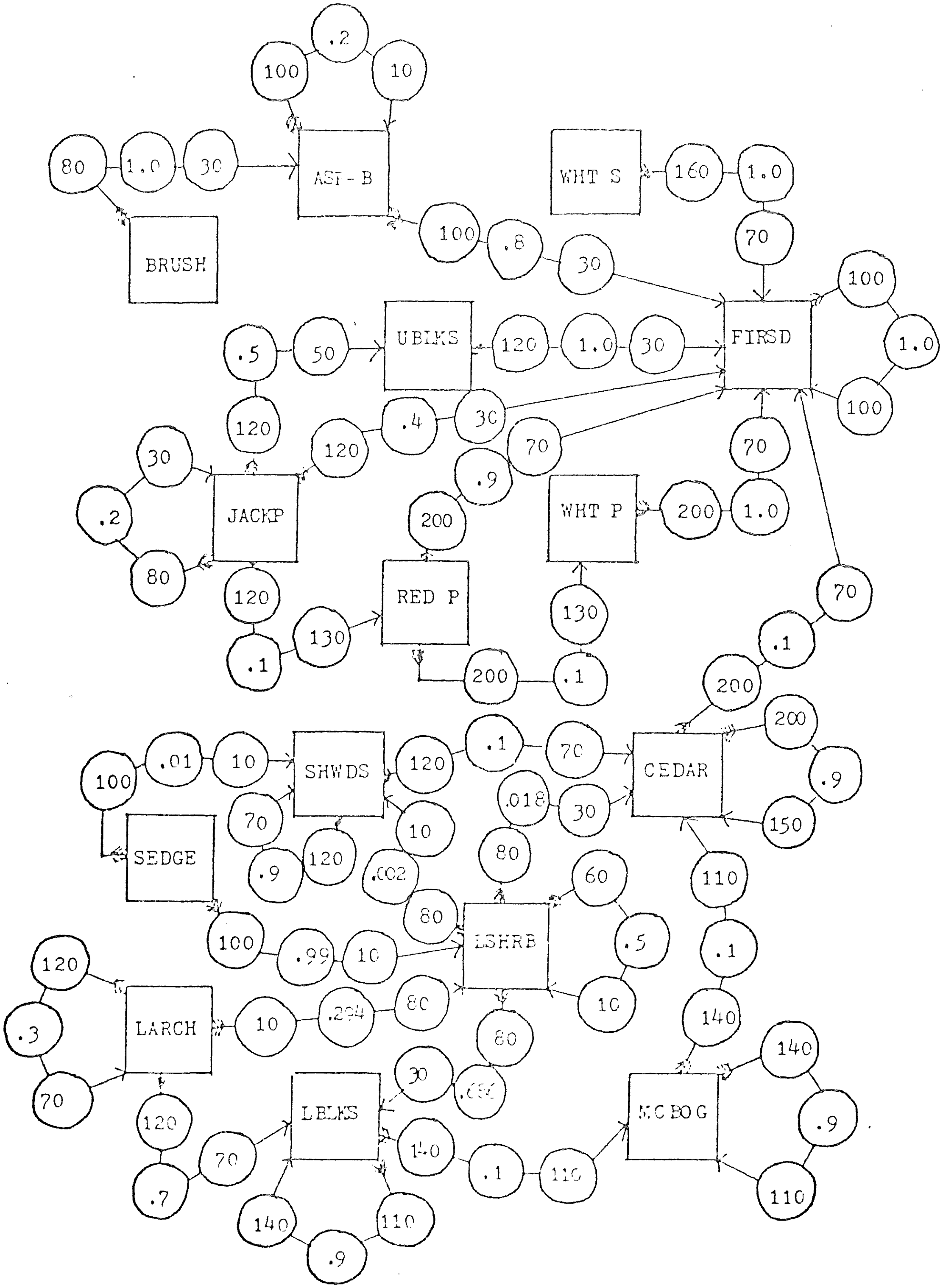
[9] Replacement-age is defined as the age of the pioneer when the dominance of basal area shifts over from that of the pioneer to the succeeding species.

[10] Lewis Ohmann in his review of the successional schemes even suggested a 1.0 probability for jack pine succession to spruce-fir-birch.

Figure 3. Non-zero parameters of the successional transition matrix arranged diagrammatically like those in Appendix II.



Despite these arguments, it was believed that most jack pine stands are first dominated by upland black spruce before succeeding to spruce-fir-birch because many more of the stands sampled in the study contained more measurable amounts of spruce than fir. To adjust for the opinions of reviewers probabilities were equalized assuming that jack pine is replaced by 41 to 60-year old upland black spruce with probability (S(33,6)=) 0.5 and by a fir dominated community with probability (S(43,6)=) 0.4. Placement of succeeding stands in an age-class is quite arbitrary. Although understory elements may behave as younger trees once released, they are often merely suppressed individuals of the same age as trees in the canopy (Heinsleman, 1973).

N. Sather (personal communication) suggested that up to 30 percent of the jack pine in the study area occuppies sites too poor to support the more mesic species. Because of the open character of these stands, jack pine can regenerate itself free from competition. Such land is most ptoperly handled in a simulation by assigning its area to another cover type presumably called "xeric jack pine." Because the number of feasible cover types is limited for modeling reasons, a feedback loop was incorporated within the jack pine cover type to account for this phenomenon. Because they occur on poor sites, these stands were assumed to break down at age 60 and are replaced with probability (S(4,3)=0.8; S(2,3)=) 0.2 by 21 to 40-year old jack pine.

The reamining 10 percent of the jack pine stands were assumed to break down at age 120 and are replaced by red pine of the next age-class (S(57,6)=0.1). This successional trend was suggested by a number of reviewers and also is indicated by Ohmann and Ream (1971). The trend is incorporated however, as an artifact of forest management. Plantations in the area often contain significant amounts of both jack pine and red pine. If the jack pine is left to decay in such a plantation, red pine of the same age will eventually succeed.

Aspen-birch(ASP-B).

According to Kittredge and Gevorkiantz (1929), aspen stands break down after 60 years, whereas associated aspen-birch or pure birch stands break down at about 80 years of age on average sites. A replacement of 100 years was selected for aspen-birch stands, however, because:

1) Many of the sampled stands were typed aspen or birch and assigned ages over 80 years,

and 2) some reviewers suggested that the replacement age of 60 years shown in Appendix II should be raised.

Two pieces of evidence suggest that aspen-birch communities do not succeed immediately to "climax types." First, Heinselman (1954) in his study of immediate replacement of aspen-birch stands concluded that successor reproduction was insufficient for replacement in most Minnesota stands. Second, aspen and birch poles dominated about 80 percent of the understory in Ohmann and Ream's (1971) aspen-birch type even though fir and spruce dominated the seedling class. The upland scheme in Appendix II contains a delaying mechanisms for aspen-birch succession to a fir community--most aspen-birch area enroute to the climax spruce-fir-birch type flows to a mixed type (still dominated by aspen-birch but containing a significant amount of conifers). Although such a mixed cover type was not used as one of the intial distribution vectors it is recognized as a spearate community type by both ~~the~~ Minesite (1976) and the Regional Copper-Nickel Study (Sather, 1979).

Because aspen and birch are both extremely intolerant of shade, aspen-birch succeeding aspen-birch seems improbable regardless of the above arguments. Aspen-birch poles in such stands are probably suppressed individuals that lack vigor needed to replace dying trees in the canopy.

Instead, W.A. Patterson (personal communication) suggested a more probable trend--on certain sites, aspen-birch regenerates itself because canopies break up so quickly that light reaching the forest floor becomes sufficient to stimulate the growth of aspen suckers. The number of sites capable of sustaining such a trend is probably small compared to the percentage of sites where canopy break-down is slow. As shown in Figure 3, 20 percent of aspen-birch is assumed to be affected in this way (S(11,15)=0.2).

Balsam fir and spruce undoubtedly/ should replace the remaining 80 percent of aspen-birch type having canopies that break up slowly (S(42,15)=0.8). Studies of Kittredge and Gevorkiantz (1929), Ohmann and Ream (1971), Heinselman (1973) and the Regional Copper-Nickel Study (Sather, 1979) support this assertion.

White Spruce (WHT S).

Stands dominated by w White spruce occur in the study area ~~northeastern Minnesota~~ only as plantations. Becaused the species generally is long-lived (Wilde, et al., 1940), 160 years was selected as the age when such stands break down. In the rare cases when white spruce escapes logging, a fir-dominated community should succeed (S(44,28)=1.0).

Upland Balck Spruce (UBLKS).

Black spruce is shorter-lived on the uplands, succumbing after 80 years of growth instead of 140 or 160 years for lowland black spruce on average sites (LeBarron, 1948). Many upland black spruce stands over 100 years of age were sampled. For this reason, all black spruce stands were assumed to a balsam fir-dominated community after 120 years (S(42,36)=1.0).

Black spruce's ability to survive in dense shade suggests that this type might have temporal stability. Ohmann and Ream (1971) and Heinselman (1973) elaborate on potential successions of other types to a blck spruce-jack pine (or a blck spruce(-feathermoss)) type having poorly developed shrub and herb layers but a well developed moss layer. Apparently, black spruce maintains its presence in this type through layering, whereas a poor seeded afforded by the moss deters the establishment of fir seedlings. Upland balck spruce stands in the succession study area lack luxurian moss cover (Sather , 1979). Therefore, fir reproduction should be sufficient to allow succession of upland black spruce stands to fir-dominated stands after one generation.

Balsam fir (FIRSD).

The spruce-fir type of Cooper (1913) or the spruce-fir-birch type of Buell and Niering (1957) are generally accepted as the climax communities for this region. Buell and Nering (1957) support calims of the latter community's persistance with the following observations:

1) balsam fir reporduction was abundant and where an opening in the canopy occurred, the seedlings grew rapidly forming thickets of fir,

2) though its reproductive potential was poor, white spruce could remain a minor component in the type because of its longevity,

and 3) paper birch, though shade intolerant, could maintain its presence once established on a site by sending up fast-growing basal sprouts from a felled parent.

Using the advice of C.F. Algren (communication by letter), aspen was recognized as a minor component of this type because of its abundance and persistence in the succession study area. Based on these considerations, this fir community was named FIRSD--a climac cover type dominated by balsam fir and containing lesser amounts of spruce and deciduous trees.

The model parameters are derived by considering the ecology of balsam fir only. Although the species may attain ages of 200 years, windfall and butt rot reduce the average longevity of fir to 80 or 90 years (Fowells, 1965; Morris, 1948). All even-aged fir stands were assumed to reach 100 years of age and remain in the 81 ro 100-year age-class as they become uneven-aged (S(45,45)=1.0).

Red Pine (RED P).

Red pine and the stands in which it dominates are very long-lived. Therefore red pine stands that escape logging were assumed to break down at the maximum age allowed for a type in the model--200 years.

The topology in the appendix shows red pine succeeding with equal probability to either white pine or spruce-fir-birch. White pine replacement of red pine (1) has been documented by Kittredge (1934), (2) is supported by the understory composition of Ohmann and Ream's (1971) red pine type, and (3) is clearly shown by Heinselman's (1973) Table 9, which gives the "structure by species and age ranges for a 283-year-old red pine stand" in the BWCA. However, most of the red pine in the succession study area has been planted, and because seed sources of white pine have been drastically depleted by logging and blister rust, succession of red pine to the fir type is more likely than succession to white pine. As shown in Figure 3, all red pine over 200 years of age is replaced in the model by fir with probability (S(44,60)=) 0.9 and by white pine with probability (S(67,60)=0.1.

White Pine (WHT P).

The longevity of white pine is even greater than that of red pine. Shade tolerance fir and spruce should replace all white pine over 200 years of age with probability (S(44,70)= 1.0 as is illustrated by Heinselman (1973) by the structure of a 360 year old white pine stand with dense fir and spruce understory.

Upland Brush (BRUSH).

Although few stands were observed, upland brush stands that occur in the succession study area are replaced in the model by aspen-birch after 80 years of development (S(12,75)=1.0. This trend might be realized when aspen root systems invade adjacent areas of brush.

Lowland Types

Only one previous study (Dean, 1971) was available for wetlands near the study area and very little feedback was received from reviewers regarding possible successional trends in wetalnds.

The lowland model topology in the appendix is based on wetlands sampled as part of the Regional Copper-Nickel Study (1979) and successional trends are quite speculative. Almost all lowland area in the model is tied up in nutrient deficient communities. The model may overestimate the intial area of nutrient poor communities because used of Heisnelman's (1970) indicator species to define netrient status of study area wetlands suggest that most are not ~~of~~ nutrient poor rather (RCNS, 1979). According to the topology, successional trends to the more nutrient-rich types occur very slowly.

Because no area flows into sedge type (SEDGE) from mats invading areas of open water, the topology assumes that all sledge area, after 100 years, flows to lowland shrubs (LSHRB) with probability (S(91,85)= 0.9 or to swamp hardwoods (SHWDS) with probability (S(131,85)=) 0.1. This modeling approach is unrealistic and should have been modified because the model did not allow for disturbances (e.g. by beavers) that would allow area to return to the sedge type.

In contrast, area is fed back to the low land shrub community in Figure, 3, thus accounting for changes caused by fluctuations in water levels (S(91,93)= S(94,93)=0.5). Note that the two lowland shrub communities of the lowland topology in Appendix II are combined in Figure 3.

Because alder carr comprises only about two percent of the area currently in LSRF, the magnitude of the successional arrows to tamarack (LARCH) and lowland black spruce (LBLKS) remains esentially the same, whereas those to swamp hardwoods and northern white cedar (CEDAR) are greatly reduced. After 80 years all lowland-shrub area not recycled to the type is modeled to be replaced by tamarack with probability (S(101,94)=) .98x.3=0.294, by black spruce with ptobability (S(112,94)=) .98x.7=0.686, by swamp hardwoods with probability (S(131,94)=).02x.1=0.002, and by cedar with probability (S(124,94)=) .02x.9=0.018.

Tamarack, intolerant of shade, is succeeded by more tolerant black spruce except on sites too poor to close the canopy and shade out tamarack reproduction. In Figure 3, 30 percent of the tamarack is assumed to occupy poor sites whereas the remaining 70 percent is replaced by black spruce after 120 years (S(104,106)=.3, S(114,106)=0.7).

Natural succession should not appreciably affect the remaining four stable cover types. As shown in the topology in Figure 3, it is assumed that 10 percent of the stands of replacement-age[11] succeed to different types, whereas the remaining 90 percent stays in that type in an earlier age-class. Fir slowly increases in black spruce bogs to allow some area to flow to the mixed conifer bog type (S(126,117)=0.1, S(116,117)=0.9). In this mixed type (MCBOG) as well as in the swamp hardwoods type, cedar, the most shade tolerant species found in the region (Baker, 1949), will increase and allow some area in these types to flow into CEDAR (S(146,136)=0.1, S(134,136)=0.9). Finally, as suggested by two reviewers, area is modeled to flow from the cedar type to FIRSD linking the upland and lowland topologies in Figure 3 that were separated in Appendix II (S(44,150)=0.1, S(148,150)=0.9).

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[11] Replacement-ages for the lowland forested types are derived from Fowells (1965).

Growth

If not already evident, growth is realized in the model by setting some matrix entries below the diagonal to 1.0 (S(i+1,i)=0.1). Values for S(i+1,i) remain zero is i corresponds to an age-class greater than or equal to the replacement-age.

MANAGEMENT PROBABILITIES

In Figure 4, parameters that fill the management transition matrix, M, are shown in a topology as before. The topology embodies rotation ages and regeneration practices currently used by the Forest Service in its management of the Superior National Forest.

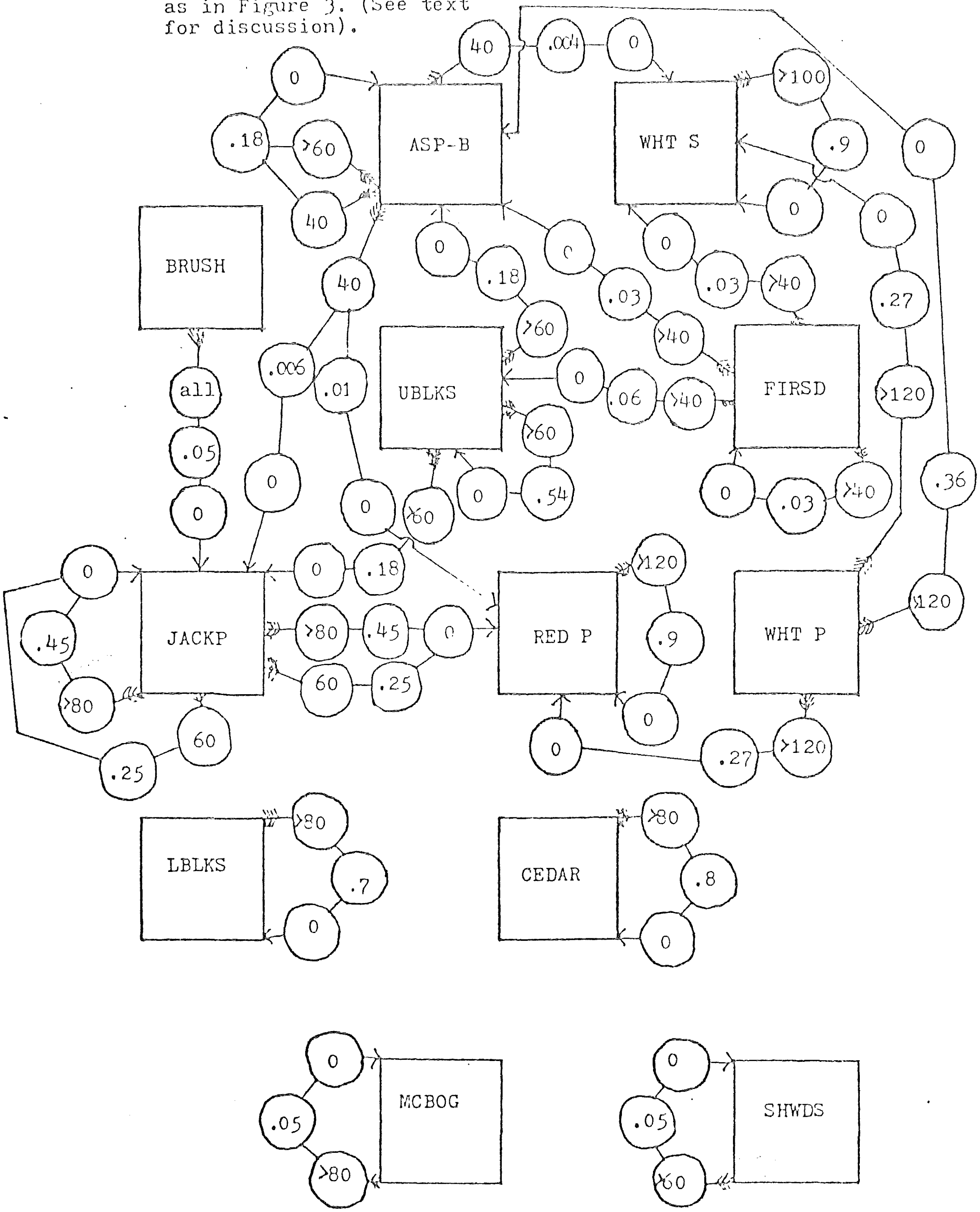
Jack Pine

The topology shows that half of the jack pine area is harvested after 60 years, whereas 90 percent of that remaining is harvested in later years. That area escaping management corresponds to jack pine held in reserve areas around lakes or along roads. Where~~e~~ver possible, the Forest Service has trie~~s~~d to regenerate harvested jack pine stands to red pine. A success rate of conversion of 50 percent is assumed for modeling purposes.

Aspen-birch

Largely because aspen-birch covers so much of the study area, only about 20 percent of the type is assumed to be managed at-and-beyond rotation age. After 40 years of growth, most of the aspen harvested is now regenerated as aspen-birch in contrast to the practices of the 1950's and 1960's when the Forest Service consistently attempted to regenerate conifer stands (predominately red pine) from plantations on converted sites. In Figure 4, only five percent of harvested aspen-birch is converted by the model in this manner. After 60 to 70 years of growth, Hypoxylon canker is assumed to

Figure '. Non-zero parameters of the management transition matrix arranged as in Figure 3. (See text for discussion).



reduce the economic value of 90 percent of the aspen trees on average sites. Currently, these stands are clearcut (leaving the timber on the site) and aspen-birch is allowed to regenerate by suckering. In Figure 4, 18 percent of the aspen-birch older than 60 years is modeled to regenerate in this way.

White Spruce

In the model 90 percent of the white spruce type is harvested from each age-class older than the rotation age of 100 years and all harvested stands are regenerated to white spruce.

Upland Black Spruce

According to LeBarron (1948), harvested black spruce stands often do not grow as black spruce but rather as aspen-birch or jack pine as is assumed in Figure 4. As was the case with white spruce 90 percent of the area in each age-class over the raotation age of 60 years is harvested in the model.

Balsam Fir

Because of the disastrous effect that the spruce budworm (*Choristoneura fumiferana* Clem.) has on balsam fir, only 15 percent of each age-class over the rotation age of 40 years is harvested. For the same reason, more than half of the harvested area is converted to spruce.

Red Pine

Red pine is treated exactly as white spruce except that a rotation age of 120 years is used for red pine vs 100 years for white spruce.

White Pine

Although white pine produces valuable timber, the Forest Service finds managinq sites for white pine ujeconomical because of white pine blister rust caused by Cronartium ribicola. Therefore, assume that 90 percent of the white pine in age-classes older than 120 years is harvested and converted in the model to more disease resistant types. Most of the conversion is directed in the model into the aspen-birch compartment because ~~further~~ if white pine is selectively removed, aspen-birch will remain; if while pine is clear cut, aspen-birch regeneration is cheapest.

Upland Brush

The Forest Service will probably spend little effort managing this type. Transfer functions used in the model assume some conversion to jack pine.

Lowland Types

The four lowland types shown at the bottom of Figure 4 are harvested by the Forest Service using the strip-cut method. Because of this practice, seed sources are assumed to be sufficient to regenerate each type after harvest as shown in Figure 4. Percentages of the area harvested, also shown in the figure, reflect the value of the timber in each type.

ABIOTIC AND BIOTIC DISTURBANCE PROBABILITIES: FIRE AND EPIDEMICS

Upland fire, spruce budworm epidemics, and white pine blister rust are incorporated into the model as the major natural disturbances affecting cover type changes in this region. More types of disturbances could and should have been modeled. These three at least provide examples of how disturbances can be incorporated into a linear system.

The following assumptions is made inregard to upland forest fires--types burn in proportion to the fraction of the region's area they occupy at the time of the fire. Lowland forest fires are not included in the model.

Figure 5.

Non-zero paramaters of the fire (abiotic disturbance) transition matrix arranged diagrammatically as before assuming all area burns. Area of all types less than 21-years goes 5 percent to upland brush, 95 percent to aspen-birch.

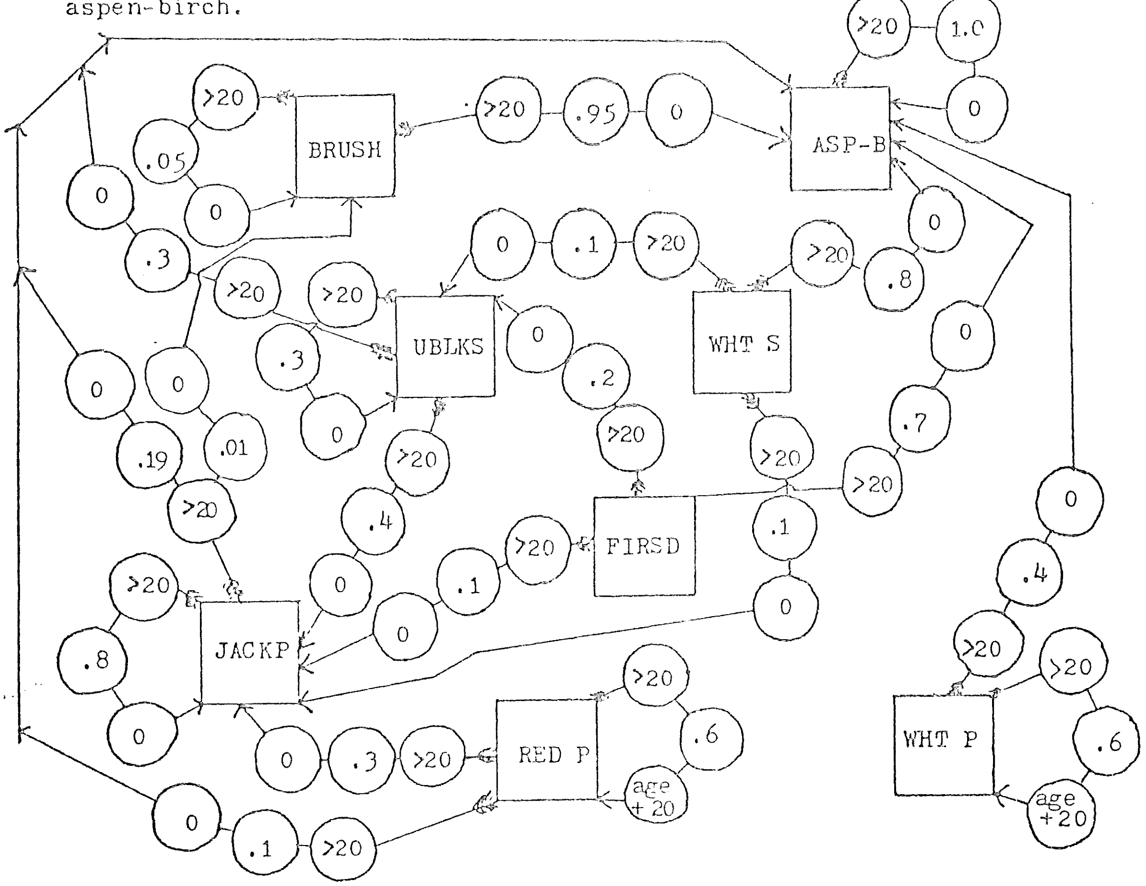
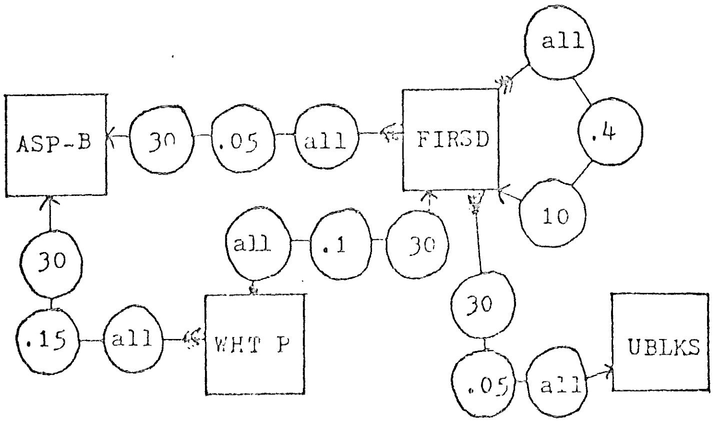


Figure 6.

Non-zero parameters of the epidemic (biotic disturbance) transition matrix arranged diagrammatically as before assuming that only 50 percent of fir and 25 percent of white pine type area is affected.



In Figure 5, a topology is provided that shows trends initiated when the entire region burns. The following comments justify these trends.

1). Area of all types less than 21 years of age flows 95 percent to aspen-birch and 5 percent to upland brush because conifers (in conifers-dominated types) do not produce seed after 20 years of age.

2). Aspen and birch with their suckering or and stump sprouting abilities ~~respectively~~ and light seeds, are better adapted for regeneration after fire than the conifers. ~~My~~ Systematic aerial photo sampling of the area around Cherokee Lake before and after wildfire (using maps provided in Ohmann, et al.'s (1973) Figure 9) supported this assertion. With a sample size of 129, about 30 percent of the points within conifer stands before the fire became aspe-birch after the fire, whereas only 8 percent of the points falling within hardwood stands before were dominated by jack pine after fire. The topology in Figure 5 likewise allows aspen-birch to more or less replace conifer-dominated area after fire.

3). Jack pine (Roe, 1963) and black spruce (LeBarron, 1939) are both adapted to fire by having persistent serotinous and semiserotinous cones that are induced to open by a fire's heat and subsequently sprinkle seeds onto seedbeds cleared by the fire. For this reason, assume that much conifer-dominated area flows to these two types after fire.

4). The thick fire-resistant bark of red and white pine allows these types to survive all but the most severe crown fires. Trends in Figure 5 account for this phenomenon.

In the simulations, five percent of the area burns each time-step. A more likely scenario would postulate a random occurrence of a few large fires over the simulation period (e.g. see Heinselamn's (1973) Table 2). However the mathematics are kept simple and the results are more easily interpretable if the area is allowed to burn each time is held constant.

Little is known of the effects that epidemics have on community structure. Because Ohmann and Ream's (1971) budworm-disturbed community contained sufficient fir reproduction to regenerate the stand, ~~that~~ 80 percent of the budworm-disturbed fir is modeled to ~~tin~~ remain in the fir type, as shown in Figure 6. Otherwise, area flows to the types dominated by important associates of fir in FIRSD--aspen-birch and black spruce. Blister rust should move disturbed area out of the white pine type as arbitrarily assumed in Figure 6. In the model, 50 percent of the area in each age-class of FIRSD becomes infested with the spruce budworm; this was the approximate proportion of sampled fir stands that a search of compartment records indicated has sustained heavy budworm damage. 25 percent of the white pine type is assumed to be destroyed by blister rust.

USING THE TOPOLOGIES FOR DIFFERENT QUALITATIVE MODELS

The topologies can be correctly transcribed into the matrices used in either the multiplicative or additive model if one remembers: 1) that the elements in each column of each matrix must sum to one in the multiplicative model, and 2) the elements of each column in all the matrices together must sum to one in the additive model.

For the mulplicative model, probabilities shown in the successional topology are in the correct form for placement into the matrix because those leaving a box for a given age-class sum to one. In the other three topologies, however, disgonal elements must be assigned values that will insure that all column elements in M, A, and B sum to one. For example, the diagonal element M(3,3) must be set to 0.5 (i.e. management doesn't affect half of the area in the 41 to 40-year jack pine age-class) so that $\sum_{i=i}^{150} M(i,3) = 1.0$.

On the other hand, the successional topology probabilities are the only ones that need modification for use in the additive model. These values must be reduced to the portion of the area in the type not disturbed. Using 101 to 120-year old jack pine as an example, only five percent of the cover-state area under-goes succession in the additive model because 90 percent is harvested and five percent burns. Therefore, the successional probabilities for 101 to 120-year old jack pine must be multiplied by 0.5 before incorporation into S for the additive model. Problems occur when disturbance probabilities sum to more than one as is the case for white pine where 90 percent is managed, five percent burns, and 25 percent is destroyed by blister rust. Here, the levels of disturbance must be changed to accomodate the additive model. Thus 63 percent of the white pine area in age-class over 120 years is modeled as managed area whereas seven percent undergoes continued growth and succession.

RESULTS

Tables 10 and 11 list the area in each age-class of each type after every time-step as predicted by the multiplicative and the additive models respectively. From these data, the graphs in Figure 7 are constructed. These graphs show how the total area occupied by the more important cover types changes over the 100-year simulation period. To aid in the following discussion of disturbance and succession, graphs (Figure 8) were constructed to show the area of important forest types harvested after each time-step. Because predictions of the mulplicative and additive models are similar in most respects (particularly in regard to the total area occupied by each type), the two are treated as a single case.

Jack pine

The qualitative simulations (Figures 7a) predict a gradual decrease in the area occupied by jack pine. This drop of about 1500 total hectares is caused by the conversion of harvested jack pine to red pine. The loss in area accounted for by succession is offset by gains due to fire. The drop in the harvest curve (Figure 8) after the 21 to 40-year interval corresponds to the time when what little 41 to 60 year old jack pine now occuring in the study area reaches rotation age.

Table 10.

Change in the initial distribution vector (Table 8) over a 100-year simulation period as predicted by the multiplicative model (equation 5).

TYPE	AGE IN YEARS 0-20	20-40	40-60	60-80	80-100	100-120	120+	TOTAL
AT T= 0 YEARS,								
JACKP	1138.0	560.0	105.0	936.0	857.0	230.0	0	3826.0
ASP-B	3702.0	4907.0	13465.0	4664.0	4514.0	0	0	31252.0
WHT S	896.0	87.0	0	0	19.0	0	0	1002.0
UBLKS	0	214.0	1182.0	629.0	360.0	383.0	0	2768.0
FIRSD	218.0	587.0	537.0	181.0	223.0	0	0	1746.0
RED P	1717.0	516.0	0	577.0	93.0	0	0	2903.0
WHT P	12.0	0	0	1.0	8.0	0	1.0	22.0
BRUSH	66.0	33.0	50.0	48.0	0	0	0	197.0
SEDGE	38.0	79.0	158.0	158.0	158.0	0	0	591.0
LSHRB	214.0	243.0	1284.0	1283.0	0	0	0	3024.0
LARCH	0	1.0	10.0	24.0	26.0	0	0	61.0
LBLKS	441.0	1021.0	1102.0	1099.0	2187.0	1705.0	219.0	7774.0
MCBOG	16.0	161.0	223.0	271.0	303.0	112.0	32.0	1118.0
SHWDS	21.0	6.0	23.0	36.0	4.0	0	0	90.0
CEDAR	5.0	24.0	0	0	34.0	0	37.0	100.0
AT T= 20 YEARS,								
JACKP	1417.0	1258.9	292.6	10.0	71.1	81.4	0	3131.0
ASP-B	7057.0	3833.9	3729.3	10489.2	3633.3	0	0	28742.8
WHT S	78.7	851.2	82.7	0	0	1.8	0	1014.4
UBLKS	1270.0	268.3	312.5	112.3	59.8	34.2	0	2057.1
FIRSD	2168.3	2046.6	237.0	216.8	163.1	0	0	4831.8
RED P	917.6	1682.7	505.7	0	565.5	91.1	2.3	3764.8
WHT P	0	8.8	0	0	.7	5.9	.1	15.5
BRUSH	24.2	59.6	29.8	45.1	0	0	0	158.6
SEDGE	0	38.0	79.0	158.0	158.0	0	0	433.0
LSHRB	798.4	214.0	243.0	642.0	0	0	0	1897.4
LARCH	377.2	0	1.0	10.0	24.0	26.0	0	438.2
LBLKS	3635.2	1321.1	1021.0	1102.0	329.7	701.7	526.5	8637.2
MCBOG	36.7	16.0	161.0	223.0	257.4	317.6	121.6	1133.3
SHWDS	7.3	21.0	6.0	21.8	34.2	3.8	0	94.1
CEDAR	56.8	28.1	24.0	1.6	0	6.8	7.4	124.7
AT T= 40 YEARS,								
JACKP	753.9	1348.0	657.8	27.8	.8	6.8	0	2795.0
ASP-B	5677.7	7104.1	2913.8	2905.1	8171.1	0	0	26771.9
WHT S	93.5	74.8	808.6	78.5	0	0	.2	1055.6
UBLKS	503.9	1562.0	293.6	29.7	10.7	5.7	0	2405.6
FIRSD	2882.5	2443.3	826.3	95.7	153.4	0	0	6401.2
RED P	552.8	899.3	1649.0	495.6	0	554.2	10.0	4160.7
WHT P	0	0	6.5	0	0	.5	.4	7.5
BRUSH	16.1	21.8	53.8	26.9	0	0	0	118.5
SEDGE	0	0	38.0	79.0	158.0	0	0	275.0
LSHRB	277.9	798.4	214.0	121.5	0	0	0	1411.8
LARCH	188.7	377.2	0	8.8	10.0	24.0	0	608.8
LBLKS	1860.9	4075.6	1321.1	1039.2	330.6	103.0	364.0	9094.4
MCBOG	46.0	36.7	16.0	161.0	211.8	259.0	402.8	1133.3
SHWDS	6.1	7.3	21.0	8.9	20.8	32.5	0	96.6
CEDAR	12.6	68.4	28.1	25.9	.3	0	2.8	138.1

Table 10.

(continued)

TYPE	AGE IN YEARS 0-20	20-40	40-60	60-80	80-100	100-120	120+	TOTAL
AT T= 60 YEARS,								
JACKP	908.1	721.5	704.3	62.5	2.1	.1	0	2398.6
ASP-B	5590.4	6015.3	5399.1	2269.8	2263.1	0	0	21537.7
WHT S	127.7	88.9	71.0	768.2	74.6	0	.0	1130.4
UBLKS	532.9	1073.7	1487.1	27.9	2.8	1.0	0	3125.4
FIRSD	4809.4	4478.8	986.5	333.7	100.6	0	0	10708.9
RED P	1129.8	541.7	881.3	1616.0	485.7	0	55.3	4709.8
WHT P	0	0	0	4.8	0	0	.1	4.8
BRUSH	17.7	14.5	19.7	48.5	0	0	0	100.4
SEDGE	0	0	0	38.0	79.0	0	0	117.0
LSHRB	263.4	277.9	798.4	107.0	0	0	0	1446.8
LARCH	35.7	188.7	377.2	7.2	8.8	10.0	0	627.7
LBLKS	1275.0	1944.3	4075.6	1337.9	311.8	140.6	94.0	9179.2
HCBOG	52.0	46.0	36.7	16.0	152.9	302.3	532.7	1138.5
SHWDS	5.8	6.1	7.3	47.7	8.5	19.7	0	95.2
CEDAR	23.1	14.8	68.4	41.5	5.2	.1	.5	153.5
AT T= 80 YEARS,								
JACKP	998.2	874.6	377.0	66.9	4.7	.2	0	2321.6
ASP-B	4854.4	5918.8	4571.6	4205.9	1768.2	0	0	21318.9
WHT S	254.8	121.3	84.4	67.5	729.8	7.1	.0	1264.9
UBLKS	1263.0	1067.3	1020.0	141.3	2.6	.3	0	3494.5
FIRSD	4572.9	3145.4	1808.3	398.3	175.3	0	0	10100.2
RED P	582.1	1107.2	530.9	863.6	1583.7	475.9	5.4	5148.9
WHT P	0	0	0	0	3.5	0	.0	3.5
BRUSH	16.9	15.9	13.1	17.8	0	0	0	63.7
SEDGE	0	0	0	0	38.0	0	0	38.0
LSHRB	477.4	263.4	277.9	399.2	0	0	0	1418.0
LARCH	31.5	35.7	188.7	380.2	7.2	8.8	0	652.1
LBLKS	1314.6	1348.4	1944.3	4082.6	401.4	110.6	51.4	9253.2
HCBOG	49.1	52.0	46.0	36.7	15.2	396.4	520.9	1116.2
SHWDS	5.1	5.8	6.1	23.8	45.3	8.1	0	94.2
CEDAR	37.8	25.1	14.8	99.0	8.3	1.0	.1	186.1
AT T=100 YEARS,								
JACKP	845.5	961.0	457.0	35.8	5.1	.5	0	2304.8
ASP-B	4847.6	5144.5	4498.3	3561.3	3276.4	0	0	21328.1
WHT S	810.1	242.1	115.2	80.2	64.1	69.3	.7	1381.7
UBLKS	1058.7	1715.3	1014.1	96.9	13.4	.3	0	3898.7
FIRSD	4202.5	2844.5	1270.0	730.1	231.6	0	0	9278.6
RED P	840.8	570.5	1085.1	520.3	846.4	1552.0	47.2	5462.2
WHT P	0	0	0	0	0	2.6	.0	2.6
BRUSH	18.1	15.2	14.4	11.8	0	0	0	59.5
SEDGE	0	0	0	0	0	0	0	0
LSHRB	176.6	477.4	263.4	139.0	0	0	0	1056.4
LARCH	117.4	31.5	35.7	191.4	380.2	7.2	0	763.3
LBLKS	3251.5	1588.5	1348.4	1950.4	1224.8	122.9	45.8	9532.3
HCBOG	47.3	49.1	52.0	46.0	34.8	215.2	649.3	1093.7
SHWDS	5.3	5.1	5.8	12.7	22.6	43.1	0	94.6
CEDAR	86.7	45.0	25.1	39.0	19.8	1.7	.2	217.5

Table 11.

Change in the initial distribution vector (Table 8) over a 100-year simulation period as predicted by the additive model (equation 7). [illegible]s identify values which greatly disagree with those in Table 10. See Text for discussion.

TYPE	AGE IN YEARS 0-20	20-40	40-60	60-80	80-100	100-120	120+	TOTAL
AT T= 0 YEARS,								
JACKP	1138.0	560.0	105.0	936.0	857.0	230.0	0	3826.0
ASP-B	3702.0	4907.0	13465.0	4664.0	4514.0	0	0	31252.0
WHT S	896.0	87.0	0	0	19.0	0	0	1002.0
UBLKS	0	214.0	1182.0	629.0	360.0	383.0	0	2768.0
FIRSD	298.0	507.0	537.0	181.0	223.0	0	0	1746.0
RED P	1717.0	516.0	0	577.0	93.0	0	0	2903.0
WHT P	12.0	0	0	1.0	8.0	0	1.0	22.0
BRUSH	66.0	33.0	50.0	48.0	0	0	0	197.0
SEDGE	38.0	79.0	158.0	158.0	158.0	0	0	591.0
LSHRB	214.0	243.0	1284.0	1283.0	0	0	0	3024.0
LARCH	0	1.0	10.0	24.0	26.0	0	0	61.0
LBLKS	441.0	1021.0	1102.0	1099.0	2187.0	1705.0	219.0	7774.0
MCBUG	16.0	161.0	223.0	271.0	303.0	112.0	32.0	1118.0
SHWDS	21.0	6.0	23.0	36.0	4.0	0	0	90.0
CEDAR	5.0	24.0	0	0	34.0	0	37.0	100.0
AT T= 20 YEARS,								
JACKP	1460.4	1090.5	532.0	52.5	37.4	42.8	0	3215.7
ASP-B	6929.0	3650.7	4661.6	10098.8	3591.3	0	0	28931.4
WHT S	82.3	851.2	82.6	0	0	18.0	0	1034.2
UBLKS	854.7	87.3	209.0	1122.9	31.5	18.0	0	2323.4
FIRSD	726.6	2904.7	264.1	161.1	121.2	0	0	4177.8
RED P	1068.8	1631.1	505.7	0	565.5	91.1	1.1	3863.4
WHT P	0	8.4	0	0	.7	5.8	.1	15.1
BRUSH	21.0	59.4	29.7	45.0	0	0	0	155.1
SEDGE	0	38.0	79.0	158.0	158.0	0	0	433.0
LSHRB	798.4	214.0	243.0	642.0	0	0	0	1897.4
LARCH	377.2	0	1.0	10.0	24.0	26.0	0	438.2
LBLKS	2877.7	1321.1	1021.0	1102.0	1099.0	701.7	526.5	8649.1
MCBUG	22.3	16.0	161.0	223.0	271.0	306.6	121.6	1121.5
SHWDS	6.1	21.0	6.0	23.0	34.2	3.8	0	94.1
CEDAR	56.8	28.1	24.0	1.5	0	6.8	7.4	124.6
AT T= 40 YEARS,								
JACKP	589.7	1387.9	1035.9	266.0	2.1	1.9	0	3283.6
ASP-B	5931.4	6834.2	3468.2	3496.2	7776.0	0	0	27506.1
WHT S	51.3	78.2	808.6	78.5	0	0	.9	1017.5
UBLKS	727.2	1020.8	84.0	198.6	56.1	1.6	0	2088.3
FIRSD	1687.5	2542.5	1307.1	79.2	84.7	0	0	5701.0
RED P	227.1	1015.4	1598.5	495.6	0	554.2	89.6	3980.4
WHT P	0	0	6.1	0	0	.5	4.3	10.9
BRUSH	29.1	18.9	53.5	26.7	0	0	0	128.2
SEDGE	0	0	38.0	79.0	158.0	0	0	275.0
LSHRB	277.9	798.4	214.0	121.5	0	0	0	1411.8
LARCH	188.7	377.2	0	8.8	10.0	24.0	0	608.8
LBLKS	1629.1	3318.1	1321.1	1039.2	1102.0	333.8	364.0	9107.2
MCBUG	35.0	22.3	16.0	161.0	223.0	270.9	392.3	1120.6
SHWDS	5.9	6.1	21.0	9.2	21.8	32.5	0	96.6
CEDAR	11.4	68.4	28.1	25.8	1.5	0	2.8	138.0

Table 11.

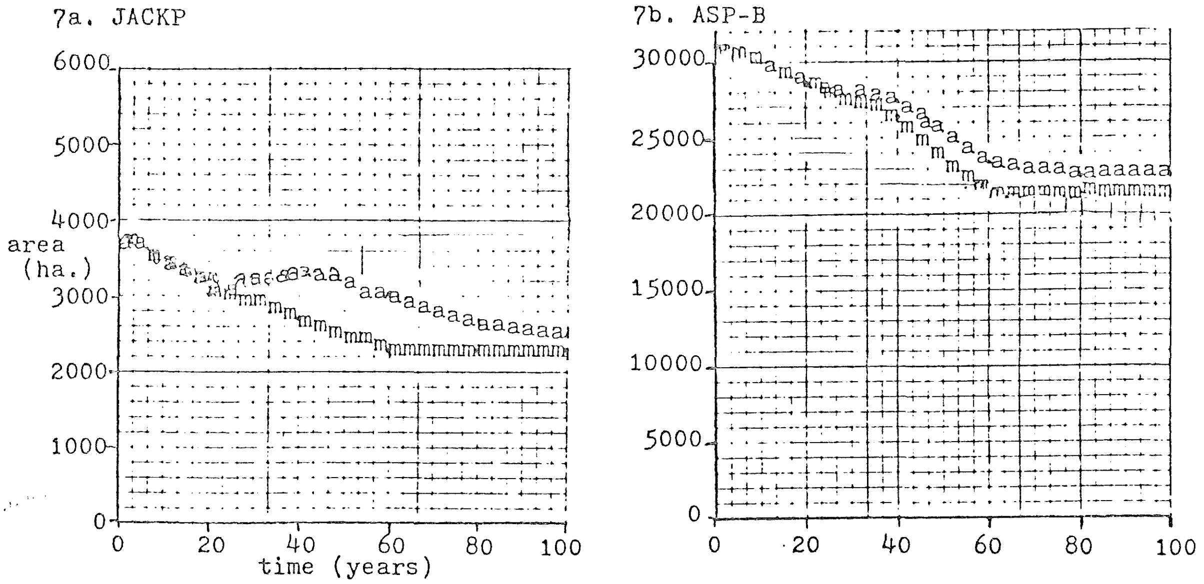
(continued)

TYPE	AGE IN YEARS 0-20	20-40	40-60	60-80	80-100	100-120	120+	TOTAL
AT T= 60 YEARS,								
JACKP	644.1	562.9	1318.5	518.0	10.6	.1	0	3054.2
ASP-B	5708.7	5945.6	6492.5	2601.1	2692.1	0	0	23440.1
WHT S	59.6	46.7	74.3	768.2	74.6	0	.0	1025.5
UBLKS	292.1	975.8	969.8	79.8	9.9	2.8	0	2330.3
FIRSD	2324.5	5550.6	1144.1	392.2	49.2	0	0	9460.6
RED P	470.7	215.8	995.1	1566.6	465.7	0	550.2	4284.0
WHT P	0	0	0	4.5	0	0	.8	5.3
BRUSH	24.7	26.2	17.0	48.1	0	0	0	116.0
SEDGE	0	0	0	38.0	79.0	0	0	117.0
LSHRB	263.4	277.9	798.4	107.0	0	0	0	1446.8
LARCH	35.7	188.7	377.2	7.2	8.8	10.0	0	627.7
LBLKS	1259.8	1712.4	3318.1	1337.9	1039.2	372.0	163.3	9202.8
MCBOG	44.3	35.0	22.3	16.0	161.0	302.9	534.1	1115.6
SHWDS	5.0	5.9	6.1	48.8	8.8	20.8	0	95.4
CEDAR	3.5	13.5	68.4	40.8	25.8	.3	.5	152.8
AT T= 80 YEARS,								
JACKP	830.9	617.1	534.8	659.3	20.7	.5	0	2663.2
ASP-B	4304.8	5940.4	5648.3	4869.4	2002.9	0	0	22765.8
WHT S	73.7	56.6	46.3	70.5	729.8	70.9	.0	1047.9
UBLKS	251.9	750.5	927.1	921.3	4.0	.5	0	2855.2
FIRSD	3831.8	2705.0	2497.8	343.2	132.4	0	0	9510.3
RED P	1094.9	447.2	211.5	975.2	1535.2	475.9	44.0	4783.9
WHT P	0	0	0	0	3.3	0	.1	3.3
BRUSH	25.2	22.2	23.5	15.3	0	0	0	86.4
SEDGE	0	0	0	0	38.0	0	0	38.0
LSHRB	477.4	263.4	277.9	399.2	0	0	0	1418.0
LARCH	31.5	35.7	188.7	380.2	7.2	8.8	0	652.1
LBLKS	1102.2	1333.2	1712.4	3325.1	1337.9	328.8	141.6	9281.3
MCBOG	49.9	44.3	35.0	22.3	16.0	391.4	532.2	1091.2
SHWDS	4.9	5.0	5.9	23.9	46.3	8.3	0	94.4
CEDAR	21.3	5.4	13.5	96.6	40.8	5.2	.2	183.0
AT T=100 YEARS,								
JACKP	845.4	795.9	586.2	267.4	26.4	1.0	0	2522.3
ASP-B	4551.3	4579.4	5643.4	4236.2	3749.4	0	0	22759.8
WHT S	175.6	70.0	53.8	44.0	67.0	693.3	3.5	1107.3
UBLKS	779.1	714.8	713.0	880.7	46.1	.2	0	3133.8
FIRSD	3893.3	2958.4	1217.3	749.3	142.7	0	0	8961.1
RED P	522.7	1040.1	438.2	207.2	955.7	1504.5	469.9	5138.4
WHT P	0	0	0	0	0	2.4	.0	2.4
BRUSH	27.1	22.7	20.0	21.2	0	0	0	91.0
SEDGE	0	0	0	0	0	0	0	0
LSHRB	176.6	477.4	263.4	139.0	0	0	0	1056.4
LARCH	117.4	31.5	35.7	191.4	380.2	7.2	0	763.3
LBLKS	1265.9	1376.0	1333.2	1718.6	3325.1	409.5	132.1	9560.4
MCBOG	47.0	49.9	44.3	35.0	22.3	225.1	645.2	1068.8
SHWDS	5.1	4.9	5.0	13.1	22.7	44.0	0	94.8
CEDAR	36.9	28.5	5.4	37.6	96.6	8.2	1.1	214.2

Figure 7.

Results of three simulations graphed separately for each type in 7a through 7i, where

mmmmmmmmmmmmmmm--identifies results of the multiplicative model (equation 5),
aaaaaaaaaaaaaa--identifies results of the additive model (equation 7).


7a. JACKP
7b. ASP-B

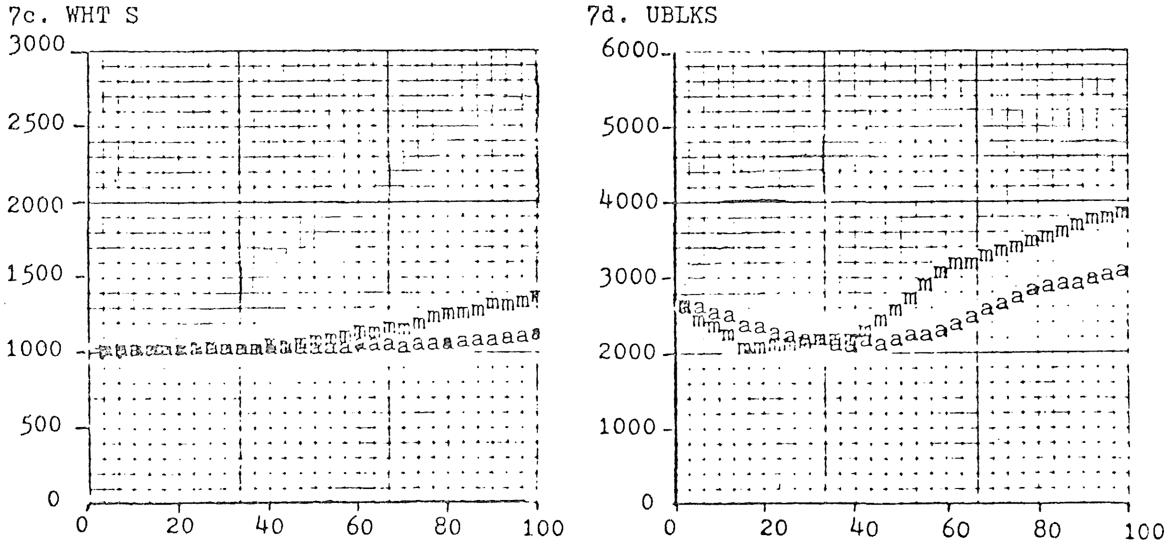

7c. WHT S
7d. UBLKS

Figure 7 (continued)

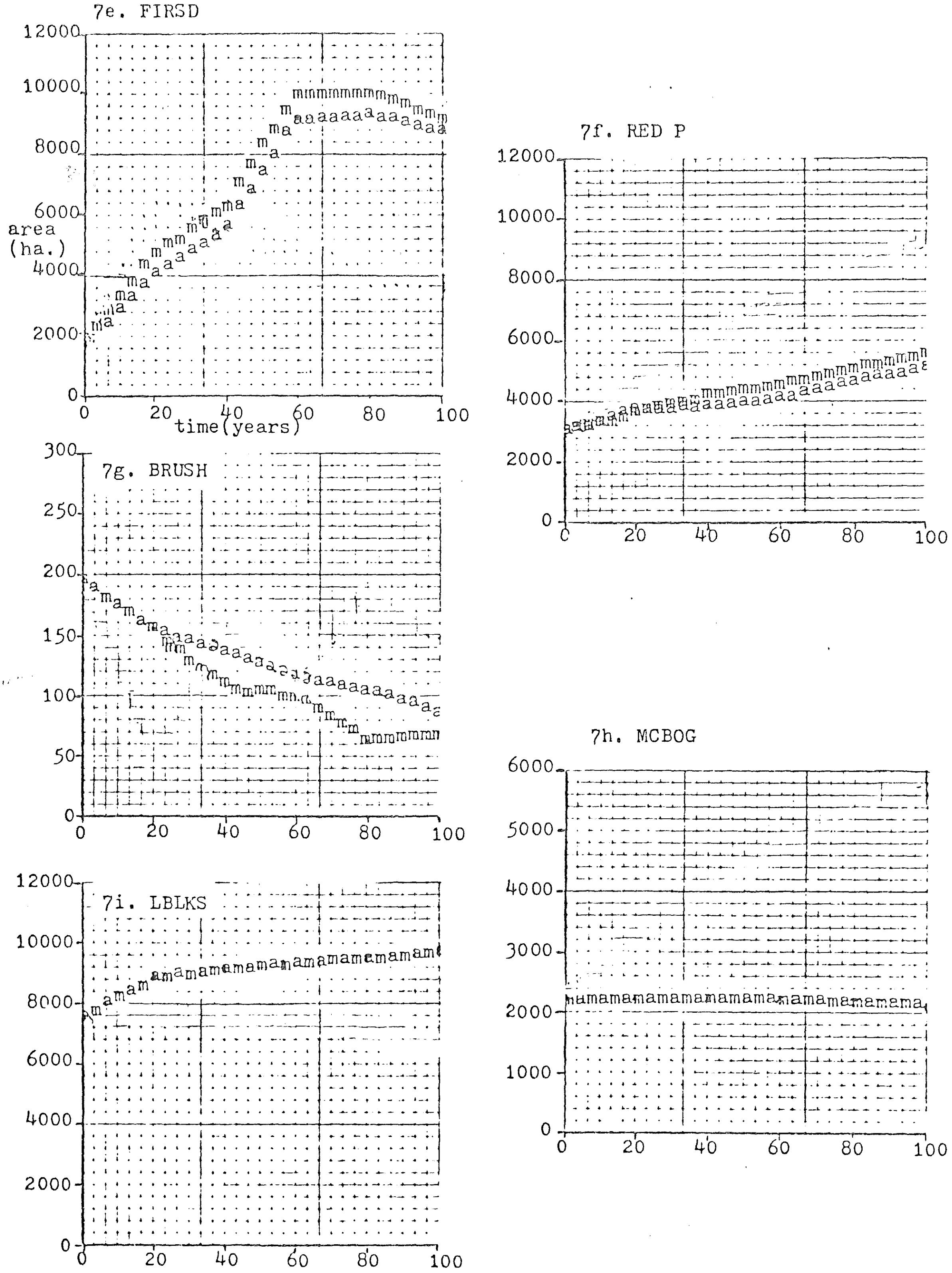
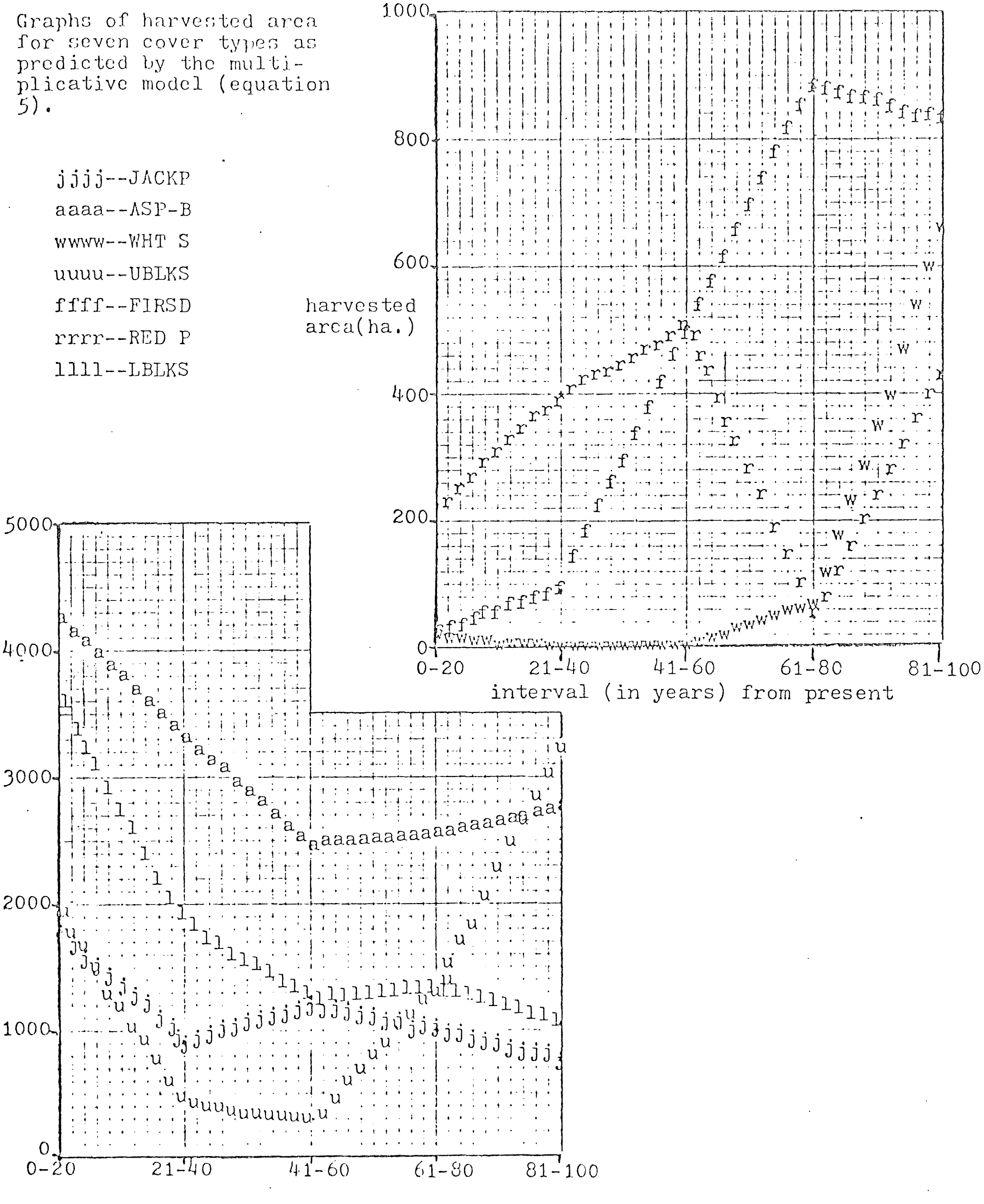


Figure 8.

Graphs of harvested area for seven cover types as predicted by the multiplicative model (equation 5).



White Spruce and Red Pine

The qualitative simulations predict a gradual increase in the area occupied by both of these types (Figures 7c and 7f). Intensive management converts some harvested jack pine and aspen-birch area to white spruce and red pine and also keeps area within these long-lived types preventing succession to fir. The lack of area in the red pine 41 to 60 age-class causes a drastic decline in the area harvested 61 to 80 years in the future. After this period, harvest of both red pine and white spruce increases as plantations originating in the 1950's and 60's reach rotation ages.

Aspen-birch

Area occupied by this type (Figure 7b) declines because succession to fir is not offset by gains caused by epidemics and fire. This effect is particularly noticeable between 41 and 60 years into the simulation when 13,465 hectares of aspen-birch reach replacement-age.

Upland Black Spruce

Area is intially lost from this type because harvested black spruce is regenerated to other types (Figure 7d). However, in time area builds up in the lower age-class as it enters from the fir type that is disturbed by the spruce budowrm. This inputted area produces an increase in harvested upland black spruce (Figure 8) when it reaches rotation age at 80 years into the simulation.

Balsam Fir

The drastic increase in fir (Figure 7e) is undoubtedly caused by succession from aspen-birch. The increase stops 60 years into the simulation as losses caused by harvest, fire, and budworm damage all offset inputs from succession.

Lowland Black Spruce and Mixed Conifer Bog

The qualitative models predict little areal change in these types because succession is slow and management prevents area from leaving the types. Black spruce increases in area because area entering from its replacement of tamarack and lowland shrub stands remains black spruce.

Upland Brush

On an areal basis, upland brush is not an important type in the succession study area. Upland brush is considered here to illustrate the difference between the multiplicative and additive models. Area flows into this type only when a fire burns area in the 0 to 20-year age-class of other upland types because inadequate seed sources or poorly developed suckering root systems are assumed in these areas after fire. In the mulplicative model, little or no area enters the brush type because ~~mulplicative~~ multiplication of the distribution vector by S moves all area out of the y~~p~~oung age-class before it can be acted upon by A. The additive model lacks this problem. Thus ~~the~~ Thus, as shown in Figure 7g, the additive model predicts more area for upland brush than the mulplicative model. The gap between the two curves isn't as large as one would initially think because succession feeds much area into the 0 to 20-year aspen-birch age-class before multiplication of $\overline{X}$ by I-(0.05) I+(0.05)A in the multiplicative model.

Although the mulplicative and additive models both predict nearly equal amounts of total area occupied by each cover type, some individual cover state predictions vary greatly. Differences are most pronounced in age-classes that follow a type's rotation age (compare values in Table 11, identified by asterisks, with the corresponding values in Table 10). In the intensively managed forest types such as pine and white spruce, the mulplicative model never allows much area to pass beyond rotation age. This is so because most area, that is moved into this class (such as the 121 to 140-year class for red pine, which has a rotation age of 120 years) when $\overline{X}$ is multiplied by S, is later harvested when $\overline{X}$ is multiplied by M during any time-step. The area in this case is harvested in the additive model. At the same time, however, area in the preceding age-class (101 to 120 years for red pine) matures and replaces the harvested area. For this reason, forests are harvested at an earlier age in the mulplicative model. The difference in results between the two models illustrates the importance in the mulplicative model of the order in which transition matricies are selected to repartition area in $\overline{X}$ during each time-step. Final age-distributions for the pines and white spruce as predicted by both models would have been more similar had $\overline{X}$ been multiplied by M before S during a time-step in the multplicative model.

DISCUSSION

Multiplicative and additive model curves in Figure 7 tend to level off near the end of the 100 year simulation period. Because the matrices are held constant, the vector probably approaches a stabel age distribution as the simulation continues.[12] Certainly one would never expect a stable distribution of cover states to actually occur in this region. Therefore, unless random components are incorporated into the model (such as allowing portions of the region disturbed by factors to vary), accurate or reasonable predictions of cover type change cannot be obtained for simulation periods that extend far into the future. Interestingly, Shugart et al (1973) calim the opposite for their model--their system of differential equations cannot be used to predict cover type changes over short time intervals.

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[12] This feature ~~at~~ of the ~~mines~~ model can be proven mathematically (Bradely, 1975).

Two valid criticisms of the model approach can be recognized. First, the models used are complicated and expensive devices that merely corroborate much of what is actually common sense. Certainly, one can predict that a shortage of red pine will exist in 60 years after glancing at the age-distribution of the type in Table 8. Second, the models attempt to "do more than the current state of knowledge allows."[13] Surely successional transition probabilities and replacement-ages are not "common knowledge." However, the models present an easy and logical way to bring together all that is known about a system. Furthermore, because of the models' mathematical simplicity, new factors are easily incorporated when they become apparent as a study proceeds. Indeed, the Regional Copper-Nickel Study is presently using the multiplicative model to assess the potential impacts of sulfur dioxide emissions ~~from~~ from smelters. With ease, the models can be used to compare the effects of each factor, in isolation, on the region's vegetation. The model's greatest advantage lies in its ability to integrate the effects of all factors. For example, results of simulations performed here predict an increase in upland black spruce because much aspen-birch area succeeds to fir which in turn is affected by the spruce budworm.

SUGGESTIONS FOR FURTHER STUDY

The best way to test the models used in this report is to compare the results of a simulation against real-world changes in forest cover type distribution. On the other hand, the indirect approach attempted as part this study by using aerial photo interpretations taken at successive dates to confirm successional trends could have been useful if comparable cover typing from successive areas had been available. The transition matrix, obtained here

[13] Quoted from E. Gorham's review of the succession schemes. 1978.

by comparing stands outlined on different maps by different interpreters is suspect.

In the future, workers experienced in photo interpretation should themselves interpret randomly sampled unit areas on photography taken at different periods. In addition to reducing biases to those of individual interpreter, this procedure would allow the owrkers to recognize his own community types. Cover type maps compiled at different times by different interpreters can be used to check the interpretations or as an aid in finding scarce types. Howeverm these maps should not be used as the primary source of information ~~however.~~

Successional trends might become evident when comparing aerial photos taken of the more remote BWCA from 1937 to 1976 than in the succession study area because man has prevented forest fires from natually disturbing the region. According to Heinselman (1973), however, fire exclusion has merely allowed another disturbance, the spruce budworm, to increase in importance. In addition, periodic drought significanlty disturbes forest ecosystems in this area (although this feature was not handled by the model).

Conditions brought on by the 1976 drought were severe enough to kill much of the spruce and fir regeneration on well drained soils.[14] To summarize because "disturbance is the rule rather than the exception,"[15] in northeastern Minnesota, successional trends may not be clearly observed over any time interval--40 years or otherwise.

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[14] Personal communication from W.A. Patterson, Copper-Nickel, 1978

[15] Quoted from L.E. Ahlgren's review of my succesional schemes. 1978.

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APPENDIX I.

Common and scientific names of plant species mentioned in the report. Classification is based on Fernald (1950).

Common Name	Scientific Name
tree species	
jack pine	*Pinus banksiana* Lamb.
trembling aspen	*Populus tremuloides* Michx.
large tooth aspen	*Populus grandidentata* Michx.
balsam poplar ~~Balm of Gilead~~	*Populus balsamifera* L.
paper birch	*Betula papyrifera* Marsh.
red pine	*Pinus resinosa* Ait.
white pine	*Pinus strobus* L.
balsam fir	*Abies balsamea* (L.) Mill.
red maple	*Acer rubrum* L.
tamarack	*Larix laricina* (DuRoi) K.Koch.
black spruce	*Picea mariana* (Mill) B.S.P.
white spruce	*Picea glauca* (Moench.) Voss.
(black) ash	*Fraxinus nigra* Marsh.
(american) elm	*Ulmus americana* L.
northern white cedar	*Thuja occidentalis* L.
shrub species	
(beaked) hazel	*Corylus cornuta* Marsh.
pin cherry	*Prunus pennsylvanica* L.F.
alder	*Alnus rugosa* (Puroi) Spreng.
leather leaf	*Chamaedaphne calyculata* (L.) Moench.
Labrador tea	*Ledum groenlandicum* Cedar

APPENDIX II.

A three page letter sent out to those qualified to judge the merit of the successional schemes provided on the following two pages.

I am an undergraduate at the University of Minnesota working with the MEQB's Copper-Nickel Study on predicting forest cover type changes for a 200-square-mile region southeast of Ely, Minnesota (centered about T61N, R11W). Most of this area lies within the Superior National Forest and is heavily disturbed.

To predict cover type changes in the absence of biotic and abiotic disturbances, I invoke a model that explicitly states (1) at what age the average stand of a particular cover type succumbs to succession, (2) the probability that a particular cover type replaces the first type, and (3) the age of the succeeding type at the hypothetical instant it replaces the pioneer. I recognize the extremely important role that disturbance plays in affecting forest development in the area and will incorporate disturbance into the model later.

Each box in the upland and lowland successional diagrams attached to this letter represents one of the cover types I recognize. The arrows between the boxes represent the direction of succession --an arrow's point directed toward the cover type that replaces the cover type at the arrow's tail. Along each arrow, values that correspond to the parameters described above are circled. I determined these values as best I could from the ecological and silvicultural literature.

I would greatly appreciate your review of these schemes. I'd like you to scrutinize each value along the arrows by blackening in the circle if the value within appears reasonable, placing an "X" over the value if it is unreasonable, or leaving the circle blank if you're undecided. If you can replace any value with a more suitable one, place the new value aside the X'ed circle.

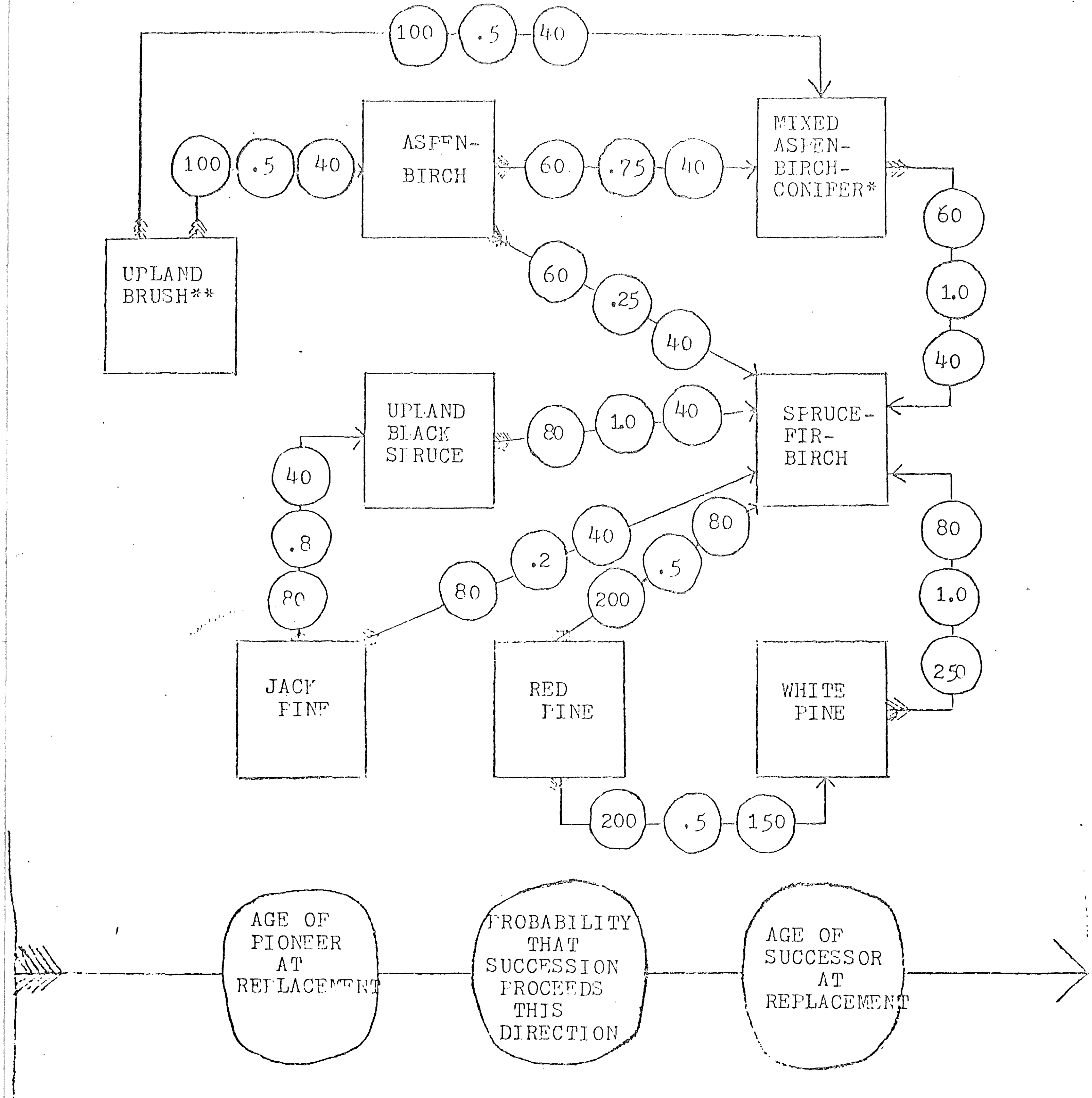
I would also greatly appreciate any additional comments you might wish to give me on the back of either diagram. Please enclose the diagrams in the envelope provided and mail the return letter at your convenience. Thank you for your time.

Sincerely,

Reed Sloss

Appendix 11 (continued) | UPLAND SUCCESSIONAL TRENDS

--for a 200-square-mile region in northeastern Minnesota in the absence of biotic and abiotic disturbances.



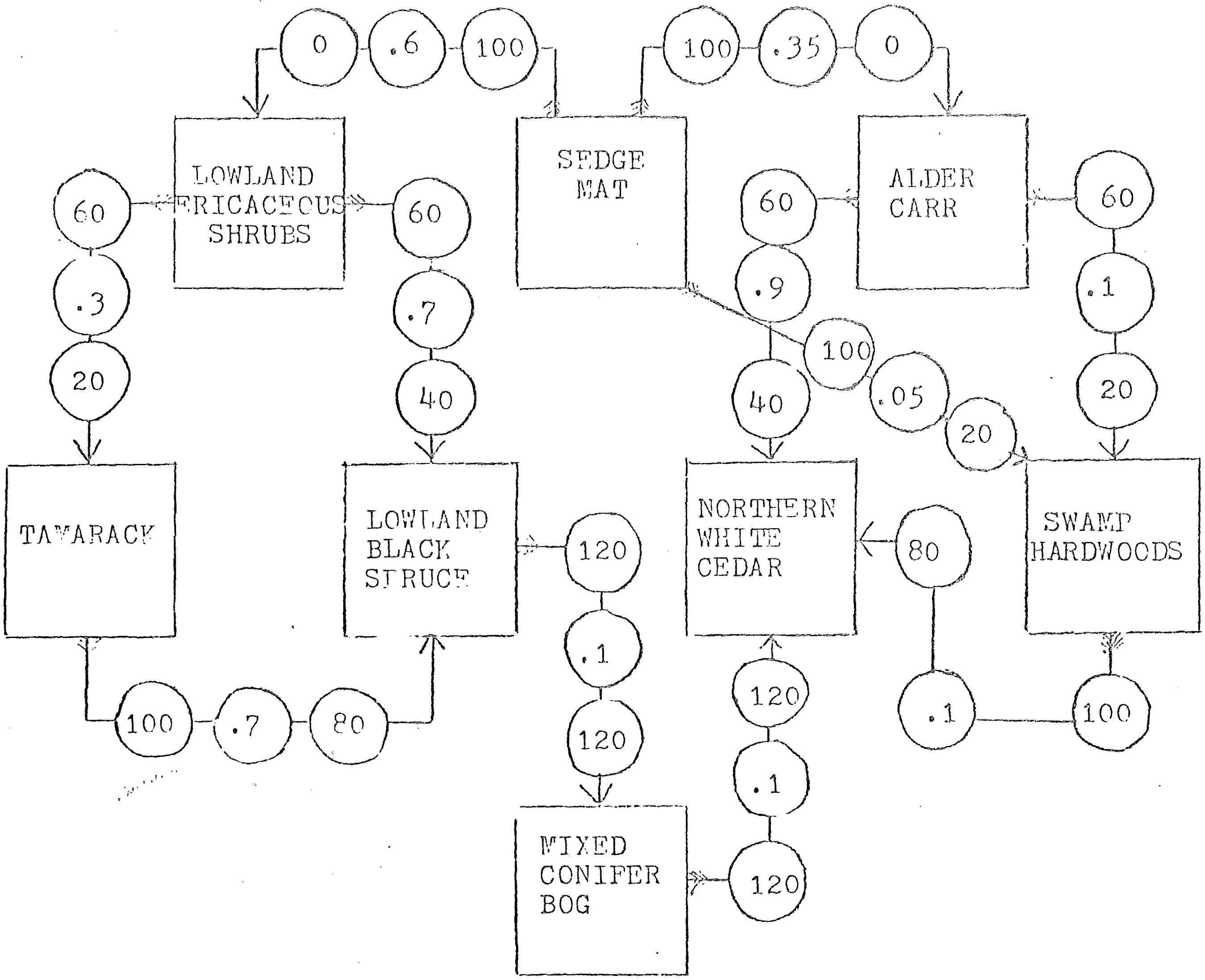
* Natural or logged upland areas containing a mix of aspen, birch, pines, and spruce. May also contain red maple and balsam fir.

** Upland shrubs (hazel, pin cherry, etc.) with less than 10% stocked commercial tree species.

Appendix II (continued)

LOWLAND SUCCESSIONAL TRENDS

(same circumstances and format)



Appendix III.

A listing of two computer programs used to simulate changes in cover types over a region. The first, CTYPEC, stores results on a file. The second, CTCOP, reads the file and prints out the results in an appropriate form. As written, the programs apply the model defined by equation 5. With the modifications shown boxed on the left, the program can be changed to apply the model defined by equation 7.

A. A listing of CTYPEC written in MNF with appropriate comments included.

```
78/05/23. 19.46.05.
MNF       PROGRAM   CTYPEC

      PROGRAM CTYPEC (TSTACK,RESULT,INRJS,OUTPUT,TAPE10=TSTACK,
+     TAPE11=RESULT,TAPE5=INRJS,TAPE6=OUTPUT)
C
C
C
C***THIS PROGRAM SIMULATES FOREST COVER TYPE CHANGES BY USING THE MODEL:
C***    X(T=TSTEP)=((I-(BU,BL)I+ (BU,BL)B)·
C***               ((I-(AU,AL)I+ (AU,AL)A)·
C***               ((I-(MU,ML)I+ (MU,ML)M)·((S)X(T=TSTEP-1))))
C***WHERE:  X=THE COVER STATE DISTRIBUTION VECTOR AFTER SOME TIME-STEP,
C***        I=THE IDENTITY MATRIX
C***        M,A,B(U,L)=FRACTIONS OF THE ENTIRE UPLAND (U) OR LOWLAND (L)
C***                   AREA THAT ARE AFFECTED BY MANAGEMENT, ABIOTIC, AND
C***                   BIOTIC DISTURBANCE RESPECTIVELY,
C***        S=THE FOREST GROWTH AND SUCCESSION TRANSITION MATRIX,
C***        M=THE MANAGEMENT TRANSITION MATRIX,
C***        A=THE ABIOTIC DISTURBANCE TRANSITION MATRIX,
C***    AND B=THE BIOTIC DISTURBANCE TRANSITION MATRIX.
C
C***THIS MODEL IS REALIZED IN THE PROGRAM WHEN THE INITIAL DISTRIBUTION
C***(OLDX) OR ITS PORTION (U,L(I)) IS MULTIPLIED IN SEQUENCE BY S, M, A,
C***AND B (T(I),I=1 TO 4) RESPECTIVELY FOR EACH TIME-STEP. THESE FOUR
C***GIANT MATRICIES ARE STACKED IN SEQUENCE IN A RANDOM ACCESS FILE ABOVE
C***THE INITIAL COVER STATE DISTRIBUTION VECTOR. AFTER EVERY MATRIX
C***MULTIPLICATION, THE RESULTING DISTRIBUTION VECTOR (NEWX) IS THEN
C***STORED IN ANOTHER FILE (#11). THE PROGRAM CAN ACCOMMODATE UP TO 20
C***COVER TYPES AND A SIMULATION PERIOD OF TEN TIME-STEPS.
C
C
      INTEGER UTYPES,LTYPES,TOTALT,XTOTAL,TSTEP,INDEX(6),NTYPES
      REAL OLDX(150),NEWX(150),XHOLD(150),T(150,150),U(4),L(4)
C
C
C***THE USER MUST FIRST PROVIDE THE COMPUTER WITH THE NUMBER OF UPLAND
C***AND LOWLAND COVER TYPES (U,LTYPES), THE NUMBER OF TIME-STEPS OR
C***ITERATIONS OF THE MODEL DESIRED, AND THE "DISTURBANCE PROBABILITIES"
C***WHERE U,L(I=2) ARE THOSE FOR MANAGEMENT, U,L(I=3) ARE THOSE FOR
C***ABIOTIC DISTURBANCE, AND U,L(I=4) ARE THOSE FOR BIOTIC DISTURBANCE.
C
      READ (5,10) UTYPES,LTYPES,TOTALT,(U(I),L(I),I=2,4)
   10 FORMAT (3(I2,1X),6(F4.2,1X))
C
```

Appendix III A--program CTYPEC (continued)

```
00520C
00530C***SO THAT ALL THE AREA EXPERIENCES GROWTH AND SUCCESSION EACH TIME-STEP,
00540C***U,L(I-1) ARE BOTH SET TO 1.0.  "XTOTAL", OR THE NUMBER OF COVER STATES
00550C***IS CALCULATED FOR USE IN THE LOOP BELOW.  THOSE VALUES USED IN THE
00560C***OUTPUT PROGRAM ARE STORED AS THE FIRST RECORD ON TAPE 11.
00570C
00580C
00590      U(1)=L(1)=1.0
00600      NTYPES=UTYPES+LTYPES
00610      UTYPES=10*UTYPES
00620      XTOTAL=10*NTYPES
00630      WRITE (11) NTYPES, XTOTAL, TOTALT
00640C
00650C
00660C***THE INITIAL COVER STATE DISTRIBUTION VECTOR IS READ FROM THE BOTTOM
00670C***OF THE STACK FROM THE RANDOM-ACCESS FILE AND STORED AS THE SECOND
00680C***RECORD ON TAPE 11.
00690C
00700C
00710      CALL OPENMS (10,INDEX,6,0)
00720      CALL READMS (10,OLDX,150,5)
00730      WRITE (11) (OLDX(I),I=1,XTOTAL)
00740C
00750C
```

```
00731C
00732      DO 15 I=1,XTOTAL
00733      XHOLD(I)=0.0
00734   15 CONTINUE
00735C
```

```
00760C***FOR EVERY TIME-STEP, THE DISTRIBUTION VECTOR, OR THAT PORTION OF IT
00770C***CALCULATED IN FRACTD, IS MULTIPLIED IN SEQUENCE BY EACH OF THE
00780C***TRANSITION MATRICIES T(I),I=1 TO 4.  IF NECESSARY, THE AREA NOT
00790C***EFFECTED EACH STEP (XHOLD) IS ADDED BACK TO THE EFFECTED AREA (NEWX).
00800C***AFTER BEING STORED ON TAPE 11, NEWX BECOMES OLDX FOR THE NEXT STEP.
00810C
00820C
00830      DO 100 TSTEP=1,TOTALT
00840          DO 80 I=1,4
00850          IF ((U(I).NE.1.0).OR.(L(I).NE.1.0)) CALL FRACTD (OLDX,XHOLD,
00860+                                             XTOTAL,UTYPES,U,L,I)
00870          CALL READMS (10,T,22500,I)
00880          CALL TXMULT (OLDX,T,NEWX,XTOTAL)
00890          IF ((U(I).EQ.1.0).AND.(L(I).EQ.1.0)) GO TO 40
00900              DO 20 J=1,XTOTAL
00910              NEWX(J)=NEWX(J)+XHOLD(J)
00920   20         CONTINUE
00930   40     WRITE (11) (NEWX(J),J=1,XTOTAL)
00940              DO 60 J=1,XTOTAL
00950              OLDX(J)=NEWX(J)
00960   60         CONTINUE
00970   80     CONTINUE
00980 100  CONTINUE
00990C
01000C
01010      STOP
01020      END
01030C
01040C
01050C***************************************************************
01060C
```

```
00950                  XHOLD(J)=XHOLD(J)+NEWX(J)
00960   60              CONTINUE
00970   80         CONTINUE
00972          WRITE (11) (XHOLD(J),J=1,XTOTAL)
00974              DO 90 J=1,XTOTAL
00976              OLDX(J)=XHOLD(J)
00978              XHOLD(J)=0.0
00979   90         CONTINUE
```

```
01070C
01080C
01090      SUBROUTINE FRACTD (OLDX,XHOLD,XTOTAL,UTYPES,U,L,I)
01100C
01110C
01120C***THIS SUBROUTINE CALCULATES THE FRACTION (U,L(I)) OF THE DISTRIBUTION
01130C***VECTOR (OLDX)THAT IS TO BE MULTIPLIED BY T(I) IN THE MAIN PROGRAM.
01140C***THAT FRACTION NOT LIKEWISE EFFECTED IS HELD IN HOLDX.  "VALUE" IS
01150C***USED TO SAVE PROCESSING TIME.
01160C
01170C
01180      INTEGER XTOTAL,UTYPES,STARTL
01190      REAL OLDX(150),XHOLD(150),U(4),L(4),VALUE
01200C
01210C
01220          DO 200 J=1,UTYPES
01230          VALUE=U(I)*OLDX(J)
01240          XHOLD(J)=OLDX(J)-VALUE
01250          OLDX(J)=VALUE
01260 200      CONTINUE
01270C
01280C
01290      STARTL=UTYPES+1
01300C
01310C
01320          DO 250 J=STARTL,XTOTAL
01330          VALUE=L(I)*OLDX(J)
01340          XHOLD(J)=OLDX(J)-VALUE
01350          OLDX(J)=VALUE
01360 250      CONTINUE
01370C
01380C
01390      RETURN
01400      END
01410C
01420C
01430C*********************************************************************
01440C
01450C
01460C
01470      SUBROUTINE TXMULT (OLDX,T,NEWX,XTOTAL)
01480C
01490C
01500      INTEGER XTOTAL
01510      REAL OLDX(150),NEWX(150),T(150,150)
01520C
01530C
01540          DO 260 I=1,XTOTAL
01550          NEWX(I)=0.0
01560 260      CONTINUE
01570C
01580C
01590          DO 300 I=1,XTOTAL
01600              DO 280 J=1,XTOTAL
01610              NEWX(I)=NEWX(I)+OLDX(J)*T(I,J)
01620 280          CONTINUE
01630 300      CONTINUE
01640C
01650C
01660      RETURN
01670      END
01680C
01690C
01700C********************************************************************
```

Appendix III (continued)

B. A listing of CTCOP written in MNF but lacking comments. The user need only know how the program's behavior depends on the selection of OPSCHE (output scheme). The table below illustrates this.

	Format of Output						
	lists area in each age-class				only lists area in each cover type		
	shows effect of all factors		lists area only				
selected OPSCHE	after each time-step	after last time-step only	after each time-step	after last time-step only	after each time-step	after last time-step only	summary table
1	X						X
2			X*				X
3		X					X
4				X			X
5					X		X
6						X	X
any other integer							X

*Tables 10 through 12 are examples of this output format.

Appendix III B--program CTCOP (continued)

```
 76/05/25. 18.34.55.
 MNF       PROGRAM   CTCOP

00100      PROGRAM CTCOP (RESULT,CTNAME,INPUT,OUTPUT,TAPE11=RESULT,
00110+                    TAPE12=CTNAME,TAPE5=INPUT,TAPE6=OUTPUT)
00120C
00130C
00140C
00150C
00160C
00170C
00180      INTEGER OPSCHE,NTYPES,TOTALT,TSTEP,ANS,TYPE,AGE
00190      INTEGER NAME(15),ANAME,DNAME(5),XTOTAL
00200      REAL FIRSTX(150),STOREX(15,10),HOLD(10),EXCESS
00210      REAL MDATA(150,4,10),CTS(15,6),TCTS(15,6),TCSS(15,6,10)
00270C
00280      READ (11) NTYPES, XTOTAL, TOTALT             MDATA(150,6,10)
00290      READ (11) (FIRSTX(I),I=1,XTOTAL)
00300C
00310C
00330C
00340C
00350      READ (12,15) (NAME(I),I=1,NTYPES)
00360   15 FORMAT (20(A5,1X))
00370C
00380C
00390C
00400      IF (OPSCHE.GT.4) GO TO 20
00410      DNAME(1)=5HS,G
00420      DNAME(2)=5HMGT
00430      DNAME(3)=5HADI
00440      DNAME(4)=5HBDI
00450      DNAME(5)=5HNTC
00460C
00470C
00480   20 IF ((OPSCHE.NE.4).AND.(OPSCHE.LE.6)) CALL TABLEH (OPSCHE)
00490C
00500      IF (ANS.EQ.3HYES) CALL INCOND(OPSCHE,FIRSTX,NAME,NTYPES)
00510C
00520         DO 100 TYPE=1,NTYPES
00530            DO 80 K=1,6
00540            TCTS(TYPE,K)=0.0
00550               DO 40 AGE=1,10
00560               TCSS(TYPE,K,AGE)=0.0
00570   40          CONTINUE
00580   80       CONTINUE
00590 100     CONTINUE
00600C
00610C
00620      I=1
00630         DO 110 TYPE=1,NTYPES
```

Appendix III B--program CTCOP (continued)

```
              DO 105 AGE=1,10
              STOREX(TYPE,AGE)=FIRSTX(I)
              I=I+1
      105     CONTINUE
      110   CONTINUE
C
          DO 390 TSTEP=1,TOTALT
            DO 120 K=1,4
            READ (11) ((MDATA(TYPE,K,AGE),AGE=1,10),TYPE=1,NTYPES)
      120   CONTINUE
C
C
            DO 180 TYPE=1,NTYPES
              DO 160 K=1,6
              CTS(TYPE,K)=0.0
      160     CONTINUE
      180   CONTINUE
C
C
            DO 360 TYPE=1,NTYPES
              DO 350 K=1,6
              IF (K.EQ.1) RNAME=NAME(TYPE)
              IF (K.NE.1) RNAME=DNAME(K-1)
              EXCESS=0.0
                DO 340 AGE=1,10
                IF (K.NE.1) GO TO 260
                  HOLD(AGE)=MDATA(TYPE,4,AGE)
                  GO TO 320
      260       IF ((K.NE.2).AND.(K.NE.6)) GO TO 300
                  IF (K.EQ.6) GO TO 280
                  HOLD(AGE)=MDATA(TYPE,K-1,AGE)-STOREX(TYPE,AGE)
                  GO TO 320
      280         HOLD(AGE)=MDATA(TYPE,K-2,AGE)-STOREX(TYPE,AGE)
                  GO TO 320
      300       HOLD(AGE)=MDATA(TYPE,K-1,AGE)-MDATA(TYPE,K-2,AGE)
C                 HOLD(AGE)=MDATA(TYPE,K-1,AGE
C
      320       CTS(TYPE,K)=CTS(TYPE,K)+HOLD(AGE)
                TCTS(TYPE,K)=TCTS(TYPE,K)+HOLD(AGE)
                TCSS(TYPE,K,AGE)=TCSS(TYPE,K,AGE)+HOLD(AGE)
C
                IF (((OFSCHE.GT.3).OR.(AGE.LE.6)).OR.((OFSCHE.EQ.2).AND.
+                 (K.NE.1))) GO TO 340
                EXCESS=EXCESS+HOLD(AGE)
      340       CONTINUE
              IF ((OFSCHE.EQ.1).OR.((OFSCHE.EQ.2).AND.(K.EQ.1)).OR.
+               ((OFSCHE.EQ.3).AND.(TSTEP.EQ.TOTALT)))
+             CALL ALLDAT (HOLD,EXCESS,CTS,RNAME,K,TYPE,TSTEP,TOTALT)
      350     CONTINUE
      360   CONTINUE
              DO 380 TYPE=1,NTYPES
                DO 370 AGE=1,10
                STOREX(TYPE,AGE)=MDATA(TYPE,4,AGE)
      370       CONTINUE
      380     CONTINUE
          IF ((OFSCHE.EQ.5).OR.((OFSCHE.EQ.6).AND.(TSTEP.EQ.TOTALT)))
+           CALL SUMDAT (CTS,NAME,NTYPES,TSTEP,TOTALT)
      390 CONTINUE
C
C
C
          TSTEP=TOTALT+1
C
          WRITE (6,400)
      400 FORMAT (/,/,*SUMMARY OF SIMULATION*)
C
```

Appendix III B--program CTCOP (continued)

```
C
C************************************************************************
C
C
C
    SUBROUTINE INCOND (OFSCHE,FIRSTX,NAME,NTYPES)
C
C
    INTEGER OFSCHE,NAME(15),NTYPES
    REAL FIRSTX(150),EXCESS,TOTAL
C
C
C
    WRITE (6,600)
600 FORMAT (1X,/,1X,*AT T=   0 YEARS*,/)
C
C
   IF (OFSCHE.GT.4) GO TO 700
C
        DO 680 I=1,NTYPES
        TOTAL=EXCESS=0
            DO 640 J=1,10
            TOTAL=TOTAL+FIRSTX(J+10*(I-1))
            IF (J.GT.6) EXCESS=EXCESS+FIRSTX(J+10*(I-1))
640         CONTINUE
        WRITE (6,660) NAME(I), (FIRSTX(J+10*(I-1)),J=1,6),
+                    EXCESS, TOTAL
660     FORMAT (1X,A5,7(F9.1)1X,F9.1)
680     CONTINUE
C
C
    RETURN
C
C
700     DO 760 I=1,NTYPES
        TOTAL=0.0
            DO 720 J=1,10
            TOTAL=TOTAL+FIRSTX(J)
720         CONTINUE
        WRITE (6,740) NAME(I), TOTAL
740     FORMAT (1X,A5,3X,F9.1)
760     CONTINUE
C
C
    RETURN
    END
C
C
C************************************************************************
C
C
C
    SUBROUTINE ALLDAT (HOLD,EXCESS,CTS,RNAME,K,TYPE,TSTEP,TOTALT)
C
C
C
C
    INTEGER NAME(15),K,TSTEP,RNAME,TYPE,TOTALT
    REAL HOLD(10),EXCESS,CTS(15,6)
C
C
C
    IF (TSTEP.GT.TOTALT) GO TO 810
    IF ((K.EQ.1).AND.(TYPE.EQ.1)) WRITE (6,800) TSTEP*20
800 FORMAT (1X,/,1X,*AT T-*,I3,* YEARS*,*,/)
C
```

Appendix III B--program CTCOP (continued)

```
01300C
01310     CALL TABLEH (OPSCHE)
01320C
01330C
01340         IF (OPSCHE.LE.4) GO TO 420
01350         CALL SOMDAT (TCTS,NAME,NTYPES,TSTEP,TOTALT)
01351         GO TO 505
01380C
01390 420  DO 500 TYPE=1,NTYPES
01400             DO 480 K=1,6
01410             IF (K.EQ.1) RNAME=NAME(TYPE)
01420             IF (K.NE.1) RNAME=DNAME(K-1)
01430             EXCESS=0.0
01440                 DO 440 AGE=1,6
01450                 HOLD(AGE)=TCSS(TYPE,K,AGE)
01460 440             CONTINUE
01470C
01480                 DO 460 AGE=7,10
01490                 EXCESS=EXCESS+TCSS(TYPE,K,AGE)
01500 460             CONTINUE
01510             CALL ALLDAT (HOLD,EXCESS,TCTS,RNAME,K,TYPE,TSTEP,TOTALT)
01520 480         CONTINUE
01530 500     CONTINUE
01540C
01544C
01545C
01547 502 CONTINUE
01550C
01560 505 STOP
01570     END
01580C
01590C
01600C*********************************************************************
01610C
01620C
01630C
01640     SUBROUTINE TABLEH (OPSCHE)
01650C
01660C
01670C
01680C
01690     INTEGER OPSCHE
01700C
01710C
01720C
01730     IF (OPSCHE.GT.4) GO TO 520
01740C
01750C
01760     WRITE (6,510)
01770 510 FORMAT (/,/,7X,*AGE IN YEARS*,/,1X,*TYPE*,6X,*0-20*,4X,
01775+            *20-40*,4X,*40-60*,4X,*60-80*,
01780+            3X,*80-100*,3X,*100-120*,4X,*120+*,4X,*TOTAL*,/)
01790C
01800     RETURN
01810C
01820C
01830 520 WRITE (6,530)
01840 530 FORMAT (1X,*COVER*,7X,*AREA*,8X,*LOSS OR GAIN DUE TO:*,2X,
01845+            *ABIOTIC*,5X,*BIOTIC*,7X,
01850+            *NET-*,/,1X,*TYPE*,8X,*(HA.)*,4X,*SUCCESSION  *,
01860+            *MANAGEMENT  DISTURBANCE DISTURBANCE   CHANGE*)
01870C
01880C
01890     RETURN
01900     END
01910C
```

Appendix III B--program CTCOP (continued)

```
C
  810 WRITE (6,820) RNAME, (HOLD(J),J=1,6), EXCESS, CTS(TYPE,K)
  820 FORMAT (1X,A5,7(F9.1),1X,F9.1)
      IF (K.EQ.6) WRITE (6,840)
  840 FORMAT (1X,/)
C
C
C
      RETURN
      END
C
C
C*********************************************************************
C
C
C
      SUBROUTINE SOMDAT (CTS,NAME,NTYPES,TSTEP,TOTALT)
C
C
C
      INTEGER NAME(15),NTYPES,TSTEP,TOTALT
      REAL CTS(15,6)
C
C
      IF (TSTEP.GT.TOTALT) GO TO 885
      WRITE (6,870) TSTEP*20
  870 FORMAT (1X,/,/,1X,*AT T=*,I3,* YEARS,*,/)
C
C
  885    DO 940 I=1,NTYPES
         WRITE (6,880) NAME(I), (CTS(I,J),J=1,6)
  880    FORMAT (1X,A5,6(3X,F9.1))
  940    CONTINUE
C
C
C
      RETURN
      END
C
C
C************************************************************************
READY.
```