MODELING FOREST PRODUCTIVITY OF THE BOREAL FOREST IN WEST-CENTRAL CANADA UNDER CLIMATE CHANGE CONDITIONS

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ABSTRACT

Global circulation models predict an increase of 2-4°C in the next 50-100 years in the boreal region of western Canada. Forest productivity - soil water capacity, carbon and nitrogen cycling models are needed to answer the questions related to effects on tree growth under climate change. Preliminary results of using a model derived from LINKAGES indicate that with the onset of warming in the southern boreal region white spruce (*Picea glauca* Moench [Voss]), growth is enhanced in loamy soil but declines in sandy soil. For jack pine (*Pinus banksiana*), growth is intensified in sandy soil but decreases in loamy soil. Aspen (*Populus tremuloides* Michx.) growth is augmented in both soil types. In certain fringe species such as sugar maple (*Acer saccharum*), red pine (*Pinus resinosa*), and white cedar (*Thuja occidentalis*), growth may be slightly enhanced. Overall, higher productivity of all species occurred on loamy soil because of higher fertility. Thus local soil conditions are crucial in determining the productivity response to climate change. But fire was assumed not to occur during the simulation period. There is considerable evidence that fire cannot be ignored in our region and must be included in our eventual model. For this reason, fire succession models such as FIRESUM are being considered for this important process.

RÉSUMÉ

D'après les prévisions établies à partir de modèles de circulation à l'échelle du globe, la région boréale de l'ouest du Canada connaîtra une augmentation de température de 2-4 °C au cours des 50 à 100 prochaines années. Des modèles de la productivité forestière, de la capacité de l'eau du sol et du cycle du carbone et de l'azote sont nécessaires afin de pouvoir répondre aux questions touchant les effets du changement climatique sur la croissance des arbres. Les résultats préliminaires d'un modèle dérivé de LINKAGES indiquent que, avec le début du réchauffement dans le sud de la région boréale, la croissance de l'épinette blanche [*Picea glauca* Moench (Voss)] serait plus marquée dans les sols limoneux mais réduite dans les sols sableux. Dans le cas du pin gris (*Pinus banksiana*), elle s'intensifierait dans les sols sableux mais diminuerait dans les sols limoneux. La croissance du peuplier faux-tremble

(*Populus tremuloides* Michx.) augmenterait dans les deux types de sols, tandis que celle de certaines essences d'importance secondaire, comme l'érable à sucre (*Acer saccharum*), le pin rouge (*Pinus resinosa*) et le thuya occidental (*Thuja occidentalis*), pourrait s'améliorer légèrement. Dans l'ensemble, la productivité de toutes les essences serait plus élevée dans les sols limoneux en raison de la plus grande fertilité de ceux-ci. Les conditions pédologiques locales sont donc cruciales pour déterminer, sur le plan de la productivité, la réaction des forêts au changement climatique. Cependant, on a supposé qu'il n'y aurait pas d'incendies pendant la période de simulation. Or, il existe de nombreuses preuves à l'effet que les incendies sont une réalité dans notre région et qu'ils doivent être inclus dans nos modèles éventuels. C'est pourquoi on se penche sur des modèles de succession chronologique des incendies, comme FIRESUM, pour tenir compte de cet important processus.

FOREST GROWTH MODELS - FOR CLIMATE CHANGE EFFECTS

Types/Approaches of Forest Models

There is a multitude of modeling strategies for forest ecosystems: spatial or not (distance dependent or distance independent); single species or mixed; even or all-age stand, dimensionality: one-dimensional, two-dimensional, or three-dimensional; trees or aggregate stand; discrete or continuous time steps; and landscape attributes.

Unfortunately there is no "best" approach to modeling forest ecosystems. Traditional growth and yield models have no *a priori* assumptions about how climate affects tree growth. Holdaway (1990) for example looked at the residuals of the STEMS model and correlated them to climate variables. Hence Holdaway (1990) could model the effects of climate on tree growth in an indirect or *a posteriori* way because after the variations were explained by tree growth, site, competition, the remaining source of variation would include climate. However, this is not a cause-and-effect way to model climate change influence on tree growth. Gap models are more appropriate for climate change because of underlying *a priori* assumptions of how temperature and precipitation influences on ecosystem function and forest growth and yield. Thus gap models are much better suited for the purpose.

Gap Models

Gap models simulate the establishment, annual diameter growth, and mortality of each tree on a small 100-1000 m^2 model plot. By nature, they can handle mixed-species, mixed-age(d) forest development. The merit of gap models is that they describe the dynamics of a gap in detail.

The first gap model JABOWA was developed by Botkin *et al.* (1972). A proliferation of variations were developed since JABOWA and its immediate successor FORET (Shugart 1984). Over thirty models have been documented. Figure 1 shows the genealogy of major gap models. The variety of models represent various adaptation and detail of ecological processes represented. The models developed covered divergent forest species, types, biomes and regions (Urban and Shugart 1992). In order to develop a model to suit a region, the major processes inherent in that region must be represented and incorporated in it.

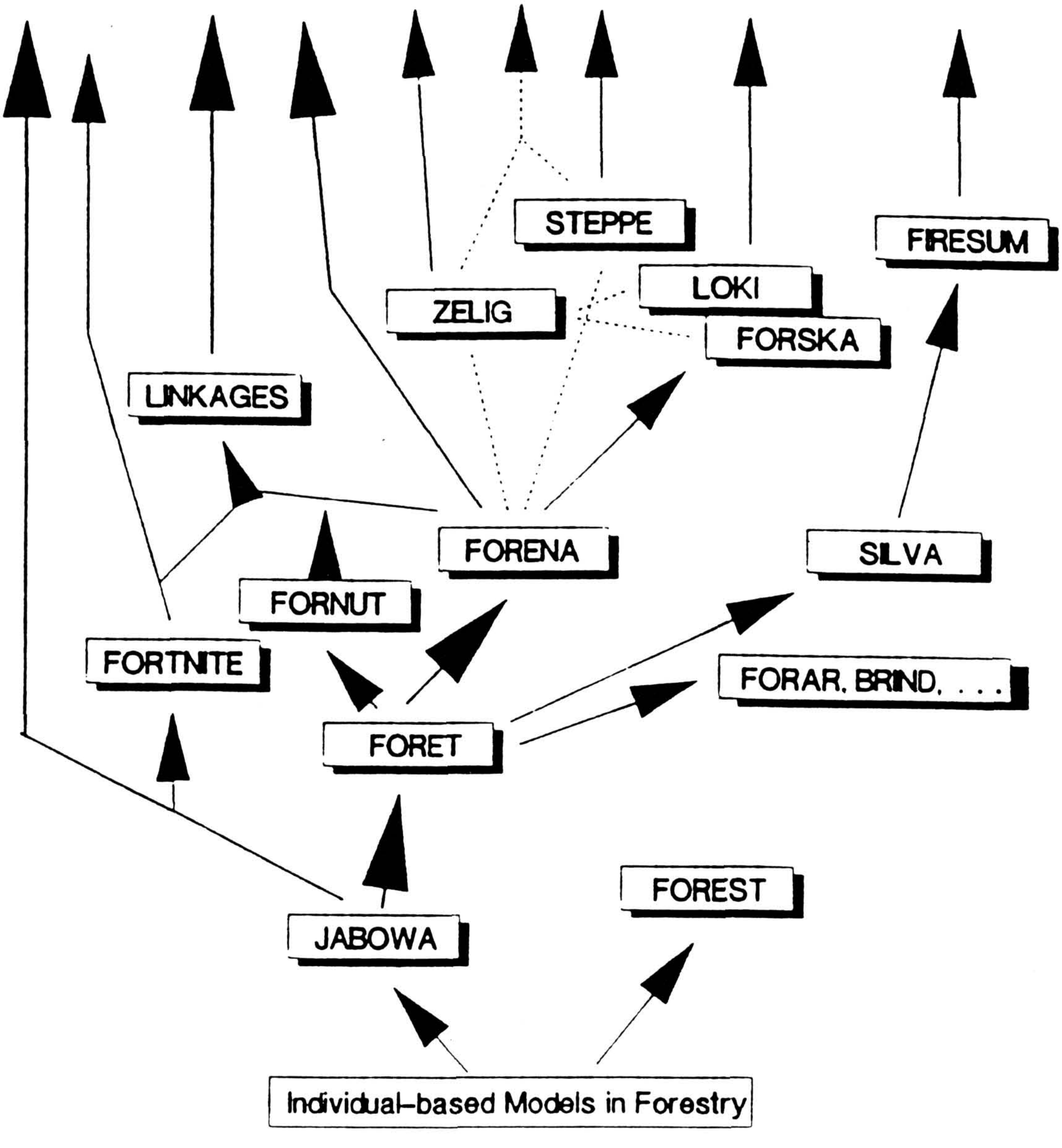

Figure 1. The genealogy of major gap models (After Urban and Shugart 1992)

LINKAGES

LINKAGES (Pastor and Post 1985) was chosen for preliminary analysis because it has the same tree species found in the north central region of Canada, and it explicitly treats nutrient cycling. LINKAGES is a very useful model since its soil subsystem seems to be sufficiently simple to be used in long term simulations. It also includes temperature, soil moisture and the quality of substrate as factors controlling decomposition.

Preliminary results with using LINKAGES (Pastor and Post 1985) on the low boreal (about 55 degree latitude) was attempted. The scenario considered is a warming of 4 degrees over a 100 year period after 200 year of steady present climate conditions, and then followed by 200 years at the elevated temperature. Precipitation remains the same as predicted by most global circulation models (Grewal 1991). Table 1 shows the comparison of productivity (biomass yield) trends as a result of warming for local tree species in two contrasting soil types - sand and loam.

Table 1 Effect of climate warming on the forest species of low boreal west-central Canada using LINKAGES

Species	Soil Texture	
	Sandy	Loam
Jack Pine	+	-
White Spruce	-	+
Aspen	+	+
Birch	-	-
Balsam Fir	-	+
Black Spruce	-	+
Cedar	negl.	negl.
Larch	negl.	negl.
Sugar Maple	negl.	negl.
Red Pine	negl.	negl.

Legend: + = positive effect - increase in biomass; - = negative effect - decrease in biomass; negl. = negligible in magnitude shift due to climate change and in amount of biomass

For the lower boreal jack pine is favoured by climatic warming in sandy soil but biomass productivity actually decreased in loamy soil (Table 1). Aspen growth increased as a result of warming in both sandy and loamy soils. White spruce is positively affected in loamy soils but negatively in sandy soil (Table 1). The apparent decrease of white birch in both soil types could be due to the lack of fire in the simulation. Balsam fir and black spruce are relatively low in amounts but seemed to be positively affected in loam and negatively in sand. In general the minor species such as cedar, larch, sugar maple, white and red pine are slightly affected but their magnitude and their biomass are negligibly small.

These predictions are plausible with the present understanding of boreal species. Soil texture is an important factor to consider in modeling growth and yield under climatic change conditions. LINKAGES is particularly concerned about the feedback between tree population dynamics and C and N cycling. LINKAGES tracks the feedback mechanism between decomposition i.e. litter types, decomposition rates, climate conditions, and nutrient pools. Important considerations in the model are that tree species respond differentially to nutrient availability, species have different litter quality and moisture content determines decomposition and N mineralization rates.

Kellomaki *et al.* (1988) used a modified version of LINKAGES (Pastor and Post 1985) to predict climate change effects on Finnish forests productivity and silvicultural operations and raised similar concerns. Kellomaki added a module to simulate winter dormancy of trees and gives more explicit information on how the year-round changes in temperature will affect the survival and growth of trees. He has also adapted LINKAGES for simulation of forest ground vegetation in boreal conditions in Finland (Kellomaki and Vaisanen 1991).

From the stand point of growth and yield, it could be expected that the effects of climate change could be beneficial and increase the productivity of the forest ecosystem by: a) the increase in the growth of local tree species, b) improved possibility to introduce exotic tree species of high productivity. c) migration of southern hardwoods.

However, with climate warming comes uncertainties. Warming could change the annual growth rhythm of the local tree species causes subsequent de-hardening in the fall, late flushing and frost damage. Also, it could change the population of pathogenic fungi and insects, to which local tree species are adapted. More epidemic of insects and diseases could lead to loss of growth and yield.

LINKAGES (Pastor and Post 1985) assumes that fire does not occur. Boreal forests are often the target of fire and predictions ignoring fire may be unrealistic. Fire is a major process in the boreal forest ecosystem and should must be included in our modeling effort.

Forest fires is a major uncertainty to productivity prediction. Fire frequency and intensity may increase as a consequence of climatic warming. Sirois and Payette (1991) conclude after studying Northern Quebec's recent fire history that low postfire regeneration that returned during the 20th century warming is likely to result in decreased productivity in Northern Quebec and likely to result in southward expansion of the forest tundra. Other uncertainties include insect and disease infestation, which may increase in the boreal forests because of warming and drying of soils.

FOREST FIRE

Many gap models either ignore fire or assume that it does not occur during the course of the simulation period. Those that do include fire do so as a random kill of all trees in the plots with a fixed probability of occurrence. However, fire is an integral part of the boreal forest region of Canada. The lack of its realistic representation would limit a model's subsequent credibility and usefulness. Moreover, fire frequency is expected to increase because global circulation models indicate substantial CO_2 warming in the high latitudes. In the last century the region of northwestern forests had experienced a statistically significant overall warming of 1.3 degree C, second only to the Mackenzie District in the country (Environment Canada 1992). In my review of available gap models worldwide the important ones that incorporate fire process are - 1) BRIND (Shugart and Noble 1981), an Australian model, 2) CLIMAX (Dale and Hemstrom 1984) from northern California; 3) SILVA (Kercher and Axelrod 1982) for the Sierra Nevada; and 4) FIRESUM (Keane *et al.* 1989) from the US Intermountain region. Of the four the one that has the most explicit representation of fire behaviour and its ecological effects is FIRESUM.

FIRESUM

FIRESUM is an ecological successional process model developed for northern Rocky Mountains. It is an offspring of SILVA. The model lineage can be traced back to FORET (Shugart 1984). FIRESUM models fire and its effects elaborately and realistically; much better than SILVA and for that matter any other gap model that I have seen.

FIRESUM has detailed feedback loops between stand conditions, fire intensity, tree mortality and forest regeneration, thus it is uniquely suited to studying disturbance due to fire (both natural and management related). The code of the model was obtained from Dr. Bob Keane of the Intermountain Forest Experiment Station of the U.S. Forest Service. The program was modified to run on a 386/40MHz computer using Microsoft Fortran (version 5.0).

FIRESUM has potential processes for incorporation into our ultimate regional climate change model. FIRESUM models woody fuel build-up, fire intensity, tree regeneration, tree mortality and tree growth - and includes processes that were added or significantly improved over SILVA. Figure 2 is a schematic diagram of the model showing major relationships of components.

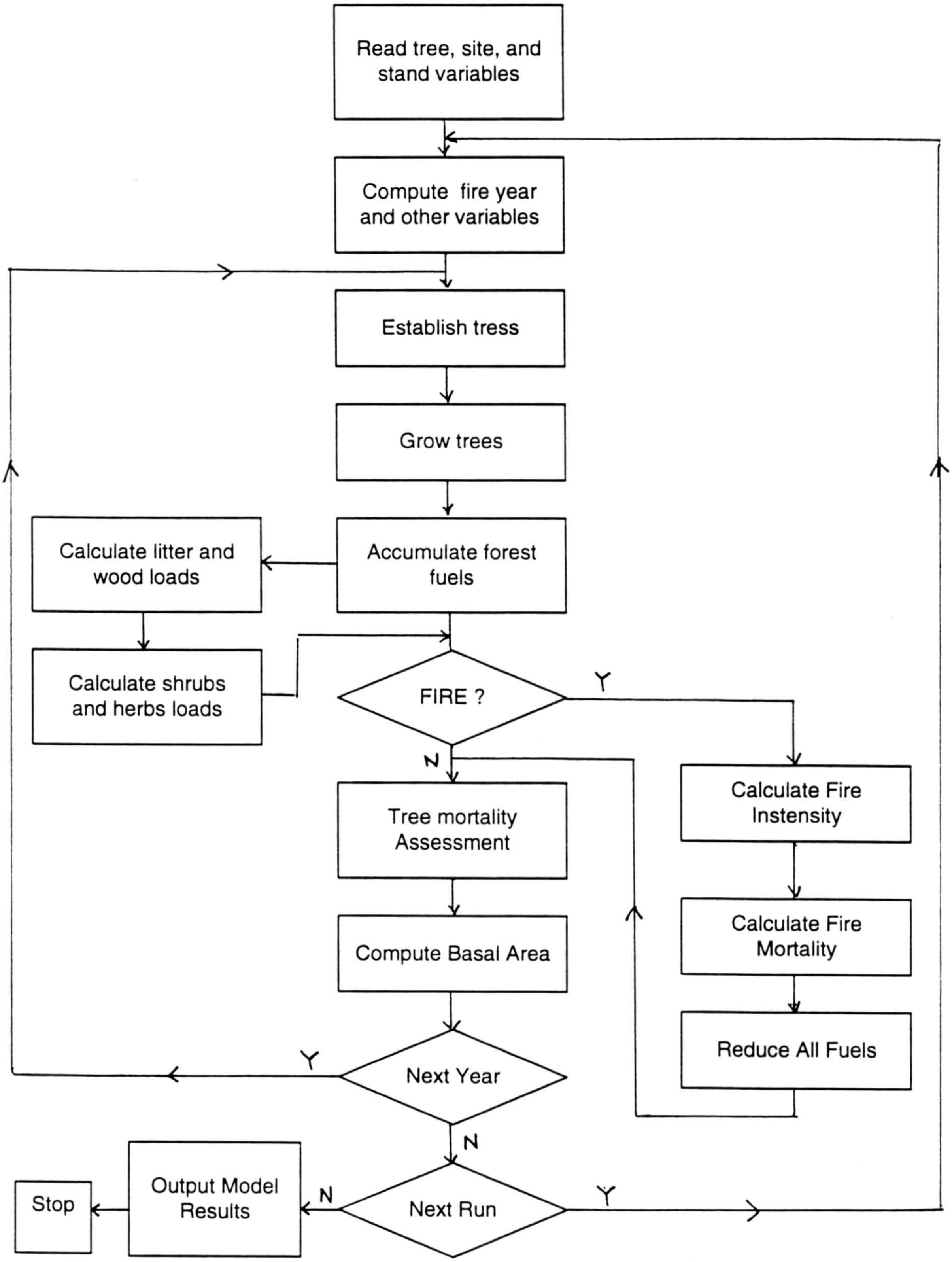

Figure 2. Schematic diagram of program logic of the simulation process model FIRESUM

Main Processes represented in FIRESUM

Growth Process

Tree growth is modeled by annual increase in tree diameter (at breast height 1.3 metres) using a difference equation that is a saturating function dependent on maximum attainable diameter, height , and age of each tree. An optimal diameter increase for a tree species is reduced by 4 growth reduction factors:- shading, crowding, water stress, and growing season warmth (degree days) on tree growth.

Regeneration Process

Trees are established on the simulation plot if the following two climatic conditions were met 1) Degree days had exceeded a minimum of degree days for a species under consideration. 2) The actual to potential evapotranspiration ratio had to be greater than the minimum value for the species. If met the size of the cone crop was then evaluated. Each year a species can have a good or poor cone crop and trees are established only in the year following good cone crops. Cone crop years are computed stochastically using Monte Carlo techniques. Maximum number of seeding survival is a function of duff depth, distance to seed source, and seed dispersal. All trees are established as a sapling of 1 cm diameter at breast height.

Mortality Process

There are four types of mortality modeled as an annual probability of death. 1) random or background mortality (i.e. endemic perturbations such as windthrow). 2) stress mortality over long periods of limited light, water, or crowding. 3) Fire - when a fire occurs trees are killed by scorching foliage and killing cambium. FIRESUM uses percentage crown scorched and bark thickness as independent variables to predict the probability of death after one year. 4) Insect and disease epidemics account for the last type of mortality. Currently FIRESUM simulates only mountain pine beetle and rust infestation. The year in which beetle or rust infestation starts is defined by the user.

Fuel and Fire Process

Fuel loadings are annually estimated and the information is used if a fire is initiated. Six dead and two live fuel components are modeled in FIRESUM (Table 2). The dead fuel consists of litter, downed woody branchwood (in diameter classes), shrub and herbaceous fuel. The live fuels are live shrub and live herbaceous. Loadings for these components are computed annually and used to determine fire intensity. Litter and duff loadings are dynamically modeled using compartments.

Table 2 Fuel components included in FIRESUM

Number	Fuel Component	Description
	Dead Fuel	
		Litter Fuel
1	Litter	Downed tree foliage, no duff material contributes to fire
		Downed Woody Branchwood
2	1-hour time lag	Twigs and branches 0 to 1/4 inch diameter
3	10-hour time lag	Twigs and branches 1/4 to 1 inch diameter
4	100-hour time lag	Twigs and branches 1 to 3 inch diameter
		Shrubs and Herbaceous Fuel
5	Shrub	Shrub stemwood 0 to 1 inch diameter
6	Herbaceous	Grass and forbs
	Live Fuel	
		Shrub and Herbaceous Fuel
7	Shrub	Foliage and small stemwood on live shrubs
8	Herbaceous	Grass and forbs living on forest floor

Fires are simulated in FIRESUM by computing fire intensity, flame length, scorch height from fuel loadings and weather conditions. Fire weather conditions and fuel moisture are also input to the model and influence fire intensity. Fire behaviour characteristics are then computed. Fire occurrence may by supplied by the user 1) at a certain year, 2) selected fire intervals 3) stochastically chosen intervals. Subsequent tree mortality from fire is estimated. After a fire occurs duff, litter, and woody fuel loadings are reduced using regression equations. Woody fuel from dead trees are added to the fuel bed.

Because of the many simulation parameters differ by stand composition and site (e.g. maximum basal area, extinction coefficient) it was necessary to stratify these parameters by a forest or site classification. Fire groups are thus used - groups of similar habitat types, potential natural vegetation based on simulation in stand composition and fire history.

Input

The user defined site, tree species, and run parameters of FIRESUM are read into the program from data files. Thus allowing efficient modification of parameters without altering program code. Three input files containing data on tree species specific parameters, site specific parameters and simulation run parameters.

Output

Six output files from the model include details on echoed and calculated model parameters, basal area accumulation per species per year, woody and duff fuel loadings, number of seedlings established per species per year, brush fuel loadings, and fire behaviour statistics.

CONCLUSION

We need a process modelling approach to study yield predictions under a climate change scenario (Grewal 1991, Grewal 1992) because process models use *a priori* assumptions as to how climate and other factors affect tree growth. There is a multitude of process-oriented "gap-dynamic" or "gap-phase" models developed, with genealogy traceable to JABOWA (Botkin *et al.* 1972) and one of its immediate successors FORET (Shugart 1984). Gap models are being examined to select the best processes for inclusion into our regional model. Because of the importance of fire in the boreal forest the fire process models such as FIRESUM, CLIMAX and BRIND are being examined. FIRESUM has the best potential because of its elaborate treatment of fuel loadings and fire behaviour simulation.

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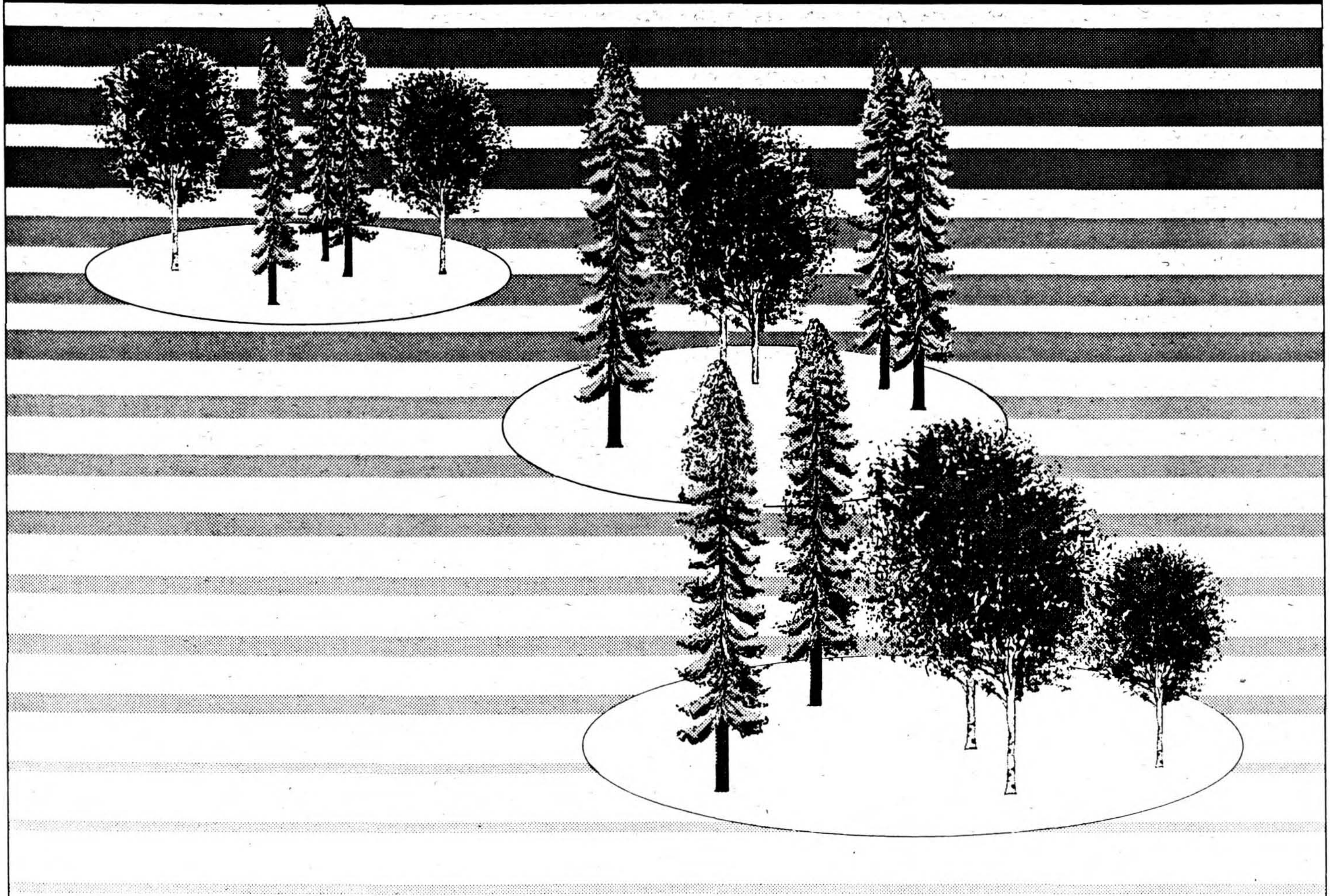

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