FORCYTE-11: AN EXAMPLE OF THE HYBRID SIMULATION APPROACH TO PREDICTING THE CONSEQUENCES FOR PRODUCTION, YIELD, ECONOMICS, SOIL FERTILITY, NUTRIENT AND ORGANIC MATTER RESERVES, AND ENERGY EFFIENCY OF ALTERNATIVE CROP PRODUCTION SYSTEMS

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ABSTRACT. The eleventh version of the FORCYTE series of models is a flexible, ecosystem-level modelling framework capable of simulating most aspects of single or mixed-species even-aged forest or agroforestry crop production systems. FORCYTE-11 simulates both nutrient cycling and nutrient feedback on growth, and within-canopy light intensity profiles and the effects of shading on the production efficiency of foliage. The hybrid approach to yield prediction is explained and the model is briefly described. The application of FORCYTE-11 in tropical agroforestry is discussed as an example of the model's capabilities. Future development of FORCYTE will include an explicit treatment of moisture as a limiting factor, and improvements in the resolution of events that occur in the early years of stand establishment to make the model more useful as a vegetation management research tool.

INTRODUCTION

Predictions of future forest growth have traditionally been based on an "historical bioassay": the growth achieved over the past rotation. This is probably the best approach to yield prediction if the future growing conditions are the same as those of the past. The record of past growth integrates the effects of all the factors that have influenced trees on the site over the entire rotation, and such historical bioassay (HB) predictions are not limited by either our still incomplete understanding of the determinants of forest growth, or our limited ability to quantify those determinants.

Unfortunately, the relationship between stand age and biomass accumulation which is the basis for HB yield predictions is changed if one or more of the major determinants of tree growth are significantly altered in the

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future. Changes in edaphic, climatic and biotic determinants of growth can alter the temporal pattern of production and biomass accumulation on a site, thereby reducing the accuracy of HB-based yield predictions. New HB yield predictors can be prepared for the new growth conditions, but this usually requires measurement of biomass accumulation over another crop rotation. The long time requirement of HB preparation can result in many decades of inaccurate yield predictions, and there is a significant risk that management and environmental conditions may have changed yet again by the time the new HB has been prepared. This problem has been referred to as "future shock" in yield forecasting (Kimmins 1985).

The inability of HB yield predictors to predict forest growth accurately under changed future growth conditions was recognized by German mensurationists as early as the mid-nineteenth century (Assman 1970). They concluded that forest yield should be predicted on the basis of an understanding of the determinants of forest growth, and estimates of how these determinants will change in the future, rather than on the record of past tree growth. This conclusion became the basis for the subsequent century of process-oriented research on forest production and yield, and the process simulation models that have been developed therefrom. Conceptually sound, and extremely valuable in education and research, such process-simulation models have yet to be accepted by forest managers as a practical means of predicting yield. Process models of forest growth have tended to be either too simple to account for all the significant determinants of growth (and are therefore inflexible), or they have become extremely complex where attempts have been made to include all (or a large number of) significant determinants. Lack of adequate calibration data, lack of access to sufficiently powerful computational facilities, and/or lack of understanding of the internal workings of very complex process models has acted to limit acceptance of this type of model by forest resource managers.

This paper describes an alternative to the HB and process simulation approaches to forest yield predictions: the hybrid simulation approach. An example of a hybrid yield simulator, the FORCYTE series of ecosystem models, is briefly introduced. More details of this model can be obtained in Kimmins (1986a, b), or in the User's Manual (Kimmins and Scoullar 1987).

THE HYBRID SIMULATION APPROACH

In spite of their shortcomings, both HB and process simulation approaches to yield prediction have significant advantages. HB yield predictors are the most believable for futures that are the same as, or very similar to, the past, but cannot predict growth accurately for significantly altered futures. Process simulation predictors theoretically have the flexibility to predict yield under a wide variety of future conditions, but in actuality they generally share with HB predictors the problems of inflexibility because they usually do not account for all major growth determinants that may change in the future.

The hybrid simulation approach involves combining these two approaches, using the major strength of each approach to compensate for the major shortcoming of the other. The HB approach provides the best estimate of the future net biomass accumulation by a particular crop on a particular site under the conditions that pertained over the past rotation. By combining this estimate with a simulation of those major growth-determining processes that will be altered under the set of future conditions for which you want a yield prediction, the hybrid simulation approach is able to evaluate whether or not the HB yield predictions will be achieved. Under improved growing conditions, growth may exceed HB predictions. Under less favourable circumstances, the HB predictions may be overly optimistic.

There is no single "best" design for a hybrid simulation model. The processes that are to be simulated will depend entirely on the intended application of the model. For example, if the major expected change in growth-determining conditions between the past and the future is the availability of nutrients (caused, for example, by a change from conventional to whole-tree harvesting), nutrient cycling processes should be simulated and used to assess whether or not the HB predictions can still be achieved. Yield prediction under such changed utilization standards does not require a simulation of temperature and moisture effects on growth since these are already represented in the HB, and they are not altered by changing utilization levels. In contrast, prediction of yield under altered future climatic regimes would require a simulation of direct temperature and moisture efects on plants as well as of the effect of these climatic changes on nutrient cycling and other processes.

Inclusion of a process in a hybrid simulator is therefore determined by whether or not the user believes that the factors determining that process will be changed in the particular future the user wishes to predict. In many applications of the model, it will not be necessary to include a simulation of a large number of determinants of growth. Other applications may require a much more complex set of simulations. It is not possible at the present time to include a simulation of all determinants of growth, and even if it were, it would probably result in a model of such size and complexity that the model would have little value for forest managers as a yield predictor.

FORCYTE* AS AN EXAMPLE OF A HYBRID SIMULATION MODEL

There are several examples of the hybrid simulation genre of yield prediction model. Most of these (e.g. FORTNITE (Aber and Melillo 1982); FORET (Shugart 1984); a nutrient version of FORET (Weinstein et al. 1982); LINKAGES (Pastor and Post 1985)) can be traced back in their development to the JABOWA model of forest succession (Botkin et al. 1972). The FORCYTE series of models has a broad similarity to the JABOWA-derived series of models, but was developed from the outset as a series of forest management simulators rather than as an ecological research tool. There has been some convergence between the two lineages of model, the JABOWA-derived series becoming increasingly useful as forest management models, and the FORCYTE series becoming increasingly useful for research on ecological processes such as succession. The convergence is not yet

*FORCYTE: FORest nutrient Cycling and Yield Trend Evaluator complete, and the two different lines of development still have their own unique features and advantages.

FORCYTE is an ecosystem-level, hybrid simulation, stand production and yield model. It can represent any desired combination of a variety of plant life-forms (trees, shrubs, herbs, mosses, and, for tropical agro-forestry applications, bamboo), and, according to which version of the model is used, a variety of soil, management, and other growth-determining processes or events. All FORCYTE versions explicitly simulate nutrient cycling in geochemical, biogeochemical and internal cycling pathways, and nutritional limitations on growth. This nutritional basis for yield prediction does not imply that nutrients are necessarily the most important determinant of growth, but that the nutritional status of a site is one of the growth-determining site parameters that is most susceptible to change as forest management practices change.

FORCYTE-10 can only simulate one limiting nutrient. FORCYTE-11 can simulate up to 5 nutrients. The eleventh version of FORCYTE adds a simulation of canopy light conditions in order to permit the simulation of species mixtures, and an improved simulation of management-induced changes in stand structure and stand density (Kimmins et al. 1986). This addition permits the model to be used to examine light competition, early secondary succession, and various strategies of "vegetation management" (weed control), as well as the improved simulation of the response of tree and understory growth to thinnings. The planned twelfth version will include explicit representations of temperature and moisture effects to facilitate the use of the model in the prediction of yield under changed future climatic conditions and the effects of vegetation management and stocking control in moisture-limited environments.

All versions of FORCYTE are stand-level models which are driven by inventory-type, stand-level, historical bioassay input data, together with data that define the growth-limiting processes that are to be simulated. FORCYTE-11 and subsequent versions also represent the growth of individual trees. This is achieved by allocating predicted annual stand production between the surviving plants using a distance-independent algorithm derived from input stand table data on stem biomass (derived from dbh) distributions. This approach appears to work well but requires further testing before its quantitative performance can be reported. It is anticipated that the approach will require further refinement to achieve the desired performance in predicting the response of diameter distribution to thinning.

A feature of all the versions of FORCYTE is the ability of the user to control both the action and the rates of all simulated processes via a series of input data files. This permits the model to be used in a variety of configurations. The user may choose to switch off many of the process simulations, thereby reducing FORCYTE to essentially an historical bioassay-type of yield predictor (not its intended use). Alternatively, the user may opt to include the simulation of any combination of a variety of soil and plant processes. Where a particular process is well understood, where reliable calibration data are available, and where it is believed that future changes in the process will significantly affect production and yield, the user may wish to include the process in the yield prediction. Where this is not the case, the user may omit the simulation of that particular process or may use the model to examine the possible yield consequences of various assumptions about the process. Users are reminded that omission of a process from a yield model can result in a prediction error that is as large as, or larger than, that which may result from the inclusion of a best estimate of that process. The ability to examine the possible consequences of adding additional processes to a simulation of yield is considered to be a useful feature of a yield predictor.

STRUCTURE OF FORCYTE-11

A major problem associated with providing a simulation model with a wide variety of capabilities is that this may result in the model becoming very large, with all the attendant problems thereof. One solution to this problem is to break up the modelling activity into a series of smaller sub-models, and FORCYTE-11 is in fact more of a modelling framework than a single model. This framework consists of three major activities :

1, A "setup" activity, in which a series of plant growth modules and a soil process module are calibrated and their performance evaluated by means of a series of graphical output files. Each of the plant growth modules is an HB production simulator in which the effects of light competition is simulated. The tree module has capabilities that include those of most traditional HB yield simulators and of many canopy/light process models.

2, Once the performance of these models is deemed acceptable for the intended application of FORCYTE, binary output files from these setup programs are used, in conjunction with a file describing the management scenarios to be simulated, as input to the second actitity: an ecosystem management simulatiom model, MANAFOR (MANAgement of the FORest). MANAFOR simulates the effects of both light and nutrient availability on biomass production.

3, Output from MANAFOR is a series of files, collectively known as FORECAST, which are used as the input for the third, data analysis, activity. This third activity involves the choice of a variety of output formats and data analyses. If FORCYTE is implemented on a microcomputer, these analyses may involve the use of a variety of commercially-available software packages (e.g. spreadsheet or graphical packages).

This model structure assumes that a forest scientist will be involved in the setup activity, gathering calibration data and evaluating the performance of the setup modules before the MANAFOR program is used by a forest manager. The second activity level will initially involve a forest scientist in an evaluation of the veracity of the ecosystem simulations, but once the performance of MANAFOR has been deemed to be acceptable for a particular application, the model will be made available to informed forest managers. MANAFOR is intended both as a management gaming tool and as an ecosystem simulation model for a variety of research applications.

ECOLOGICAL PROCESSES AND MANAGEMENT ACTIVITIES REPRESENTED IN FORCYTE-11

Tables 1 and 2 describe the main processes and management activities represented in FORCYTE-11. Details of the representation of these processes, and of the manner in which management activities are simulated, cannot be presented here, but are described in the FORCYTE-11 User's Manual (Kimmins and Scoullar, 1987). The reader is reminded that the user of the model controls the structural complexity and the processes to be represented in any particular application of FORCYTE. The model can be used with a single tree species, a single nutrient, and very few soil processes other than organic matter decomposition. Alternatively, it can be used with up to three species each of trees, shrubs, herbs and/or mosses, up to five nutrients (most users will probably only use two or three), and a variety of processes and management activities/natural events (Tables 1 and 2).

Table 1. Management Options in FORCYTE-11.*

Site preparation	- mechanical or fire (ploughing, broadcast burn, windrow, pile-and-burn)
Regeneration	- planting (any size/age of seedling/sapling/tree), coppice/root suckering, or natural seeding; monocultures or mixtures
Weed competition	- for light or nutrients by herbs, shrubs, or non-crop trees. Control of competition (manual or chemical)
Stand density control	- spacing or pre-commercial thinning; random or other defined spacing strategy
Thinning (commercial)	- high, low, random, or other defined thinning regime
Final harvest	- clearcut harvesting
Utilization level	- any defined proportion of any plant (or soil) component may be harvested at any time
Rotation length	- annual cropping, or short, medium or long (e.g. centuries) rotations
Fertilization	- broadcast or spot; single or multi-nutrients; inorganic or organic
Pruning	- removal of any defined proportion of live and/or dead branches
Herbivory	- e.g. insect defoliation of trees; wildlife browsing on herbs or shrubs
Fire	- prescribed stand or slash burning, or wildfire
Litter raking/slash harvest	- harvest of ectorganic layer, or of logging/thinning slash at any time. Upper soil layer(s) can also be removed

* The user decides which of these options are to be simulated, and how. Very simple or very complex scenarios can be simulated.

Table 2. Soil Processes or Management Impacts on Soil that can be Represented in FORCYTE-11.*

Organic matter decomposition, mineralization, immobilization
Humus decomposition and mineralization
Soil CEC and AEC, separately for organic matter and mineral soil
Soil sorption/desorption (e.g. of phosphorus)
Soil leaching
Soil mixing (soil animals, or mechanical mixing)
Root distribution by soil layers, according to nutrient availability
Allelopathic effects on decomposition
Organic matter substrate effects and plant effects on the ionic forms of nitrogen
Soil compaction and recovery therefrom
Soil erosion (sheet erosion, rather than mass wasting)
Denitrification (not presently operational)
Litterfall (and root mortality) inputs of organic matter and nutrients to the soil
Nutrient uptake from the soil and competition for soil nutrients by plants

* Because some of these processes may be either poorly understood or poorly documented for a particular site, the user may wish to omit any or all of them from the simulation, and can do so. However, the user is reminded that omitting the simulation of a process that is known to be important is as large an assumption as including it, and may lead to as great or even greater error than including a conservative simulation of the process.

APPLICATION AND IMPLEMENTATION OF FORCYTE-11

FORCYTE-11 was developed for use primarily in forest management and research, but because it is an ecosystem model, it can have a variety of other applications. A tropical version has been developed for agro-forestry research in Indonesia, and it is planned to develop the model for use in temperate agriculture. With further modification, it could be used in mined-land reclamation research, and the planned development of FORCYTE-12 will permit future use of the model in air pollution, acid rain, and "greenhouse effect" research.

Within forestry, the model is being modified to improve its temporal resolution of the processes in the early stages of stand establishment, especially competition for nutrients, light and moisture, but also antagonistic effects such as allelopathy. Research is under way to provide calibration and validation data to prepare and test the model for use in early succession and vegetation management research.

Because FORCYTE was developed as a management tool, it conducts economic, energy efficiency and manpower requirement analyses as well as biomass production and yield analyses. The optimum use of the model is in ranking the performance of a wide variety of alternative, stand-level, crop management strategies, and this ranking can be done on the basis of production, yield, economics, energy and/or manpower requirements, or on the sustainability of soil fertility and ecosystem productivity. Because such applications of the model involve repeated runs and very large quantities of optional output, a supervisory software package PROBE (Apps et al., this volume) has been developed. PROBE facilitates management gaming and sensitivity analyses of the model, as well as management of the output of multiple runs in conjunction with spreadsheet software packages such as SYMPHONY (TM Lotus Corp.).

With the improvement in computer hardware, FORCYTE (which was until recently a "mainframe" model) can now be implemented on microcomputers. FORCYTE-10 can be run on a standard 640k IBM PC, XT, AT (or compatible) equipped with a math coprocessor. FORCYTE-11 currently runs on any of these microcomputers if they are equipped with a 32-bit coprocessor (e.g. a Definicon DSI-32 board).

TROPICAL AGROFORESTRY APPLICATION OF FORCYTE-11 AS AN EXAMPLE OF THE MODEL'S CAPABILITIES

Although FORCYTE-10 has been, or currently is being, tested in plantation forestry in New Zealand, Brazil, South Africa, U.S., Canada, and Scandinavia, FORCYTE-11 has not yet been field-tested. Work is currently underway to calibrate and test it in these and other locations, but its first operational test will be in the simulation of an agroforestry system in Indonesia. This tropical agroforestry application of FORCYTE-11 provides a good example of the planned capabilities of this version of the model for when it is used in plantation forestry applications.

Large numbers of rural people in western Java depend upon a subsistence agroforestry cropping system on upland areas which have relatively poor soils. The "talun-kebun" system that they use has apparently provided a sustained supply of food and wood products for many generations (and probably many centuries) with very little external inputs of nutrients to maintain soil fertility (Christanty and Kimmins, mss in preparation[1]). However, a growing desire for cash crops is resulting in changes in this traditional method of land use, and there is growing concern about soil impoverishment and soil erosion.

The talun-kebun system consists of a six-to-seven-year management cycle in which stands of perennial clump bamboo are periodically clearcut and the area ("field") used for growing food crops for two years before being allowed to return to a four-to-five-year fallow period of bamboo. Clearcutting, raking the forest floor and slash into piles for burning, and hoeing the soil to a depth of 25 cm (thereby killing about 20t ha^{-1} of fine bamboo roots) reduces the vigour of the bamboo to the point at which it poses no competitive threat to the planted food crops in the first year. These crops are (typically) cucumber, bitter solanum and hyacinth (pole) beans. Ash from the burned slash piles, plus some animal manure and an application of NPK fertilizer, are used to increase the

[1] Based on L. Christanty's Ph.D. thesis at the Univ. of B.C. (in preparation).

production of these vegetables. In spite of these nutrient additions, the fertility of the upper soil layers declines during the first year, and the field is planted to cassava (a less nutrient-demanding root-crop) for the second year after clearcutting. During this second year, the bamboo has recovered some of its vigour and has progressed from the "grass" stage to the production of small (1-2m tall) culms (aerial shoots). Because these culms pose increasing competition for light, and because of below-ground competition from the increasing biomass of bamboo fine roots, the field is abandoned after two years and permitted to revert to an unmanaged stand of bamboo. The bamboo clumps produce successively taller culms and, because of the high silica content of the above-ground litterfall, a relatively slowly decomposing ectorganic layer (forest floor). Once this layer has accumulated to a certain depth, and the upper soil has become darkened with the accumulating humus, the bamboo is again clearcut and the cycle repeated.

The sustainability of the system appears to be based largely on the "nutrient pumping" action of the bamboo, the slow decomposition of its silica-rich litter, and the extremely high biomass of bamboo fine roots. The bamboo recovers much of the nutrients leached deeper into the soil profile during the two years of cropping and deposits them at or near the soil surface as above-ground litter and dead fine roots. This action is reflected in the rural farmer's saying: "without bamboo, the land dies".

FORCYTE-11 has been designed so that it can be used to perform simulation experiments on the possible consequences of changes in this traditional land use system. This requires the simulation of the growth of several different herbaceous food crop species and of bamboo, the harvesting of economic components of the biomass, the addition of ash, manure and fertilizers, the leaching and erosion of nutrients, the loss of nutrients in smoke, the addition of symbiotically-fixed nitrogen by the hyacinth beans and scattered Albizzia trees, the composting of food crop wastes and spreading of compost, the mixing of soil by soil animals and hoeing, the leaching of nutrients down through the soil, and various cultural activities associated with the management cycle. Nutrient and light competition must be simulated. Ideally, the spatial relationships of the clump bamboo and the interplanted food crops should be represented, but this must await the addition of a horizontal spatial representation of plants in FORYTE-12.

Simulation of the Javanese talun-kebun system demonstrates the potential of this modelling approach for research on and/or management gaming with conventional or innovative forestry, agroforestry, or agricultural cropping systems. The capability to simulate this tropical land use system confers on the model the ability to represent a wide variety of non-tropical silvicultural/agricultural systems.

FUTURE DEVELOPMENT AND AVAILABILITY OF THE MODEL

As already noted, several further developments of FORCYTE are planned. An explicit simulation of temperature and moisture determinants of growth and a spatial representation of individual trees and other plants will be provided in FORCYTE-12. The stand-level FORCYTE-11 and -12 will be linked up with a GIS and/or whole-forest management model to provide an improved basis for timber supply and regional economic modelling. It is also hoped to make the necessary modifications to render the model suitable for acid rain, greenhouse effect, and disturbed land reclamation research.

FORCYTE-10 is, and FORCYTE-11 soon will be, available through the Canadian Forestry Service's National Forestry Institute at Petawawa, Ontario. Any readers interested in the model may refer to the list of references appended or may contact the senior author.

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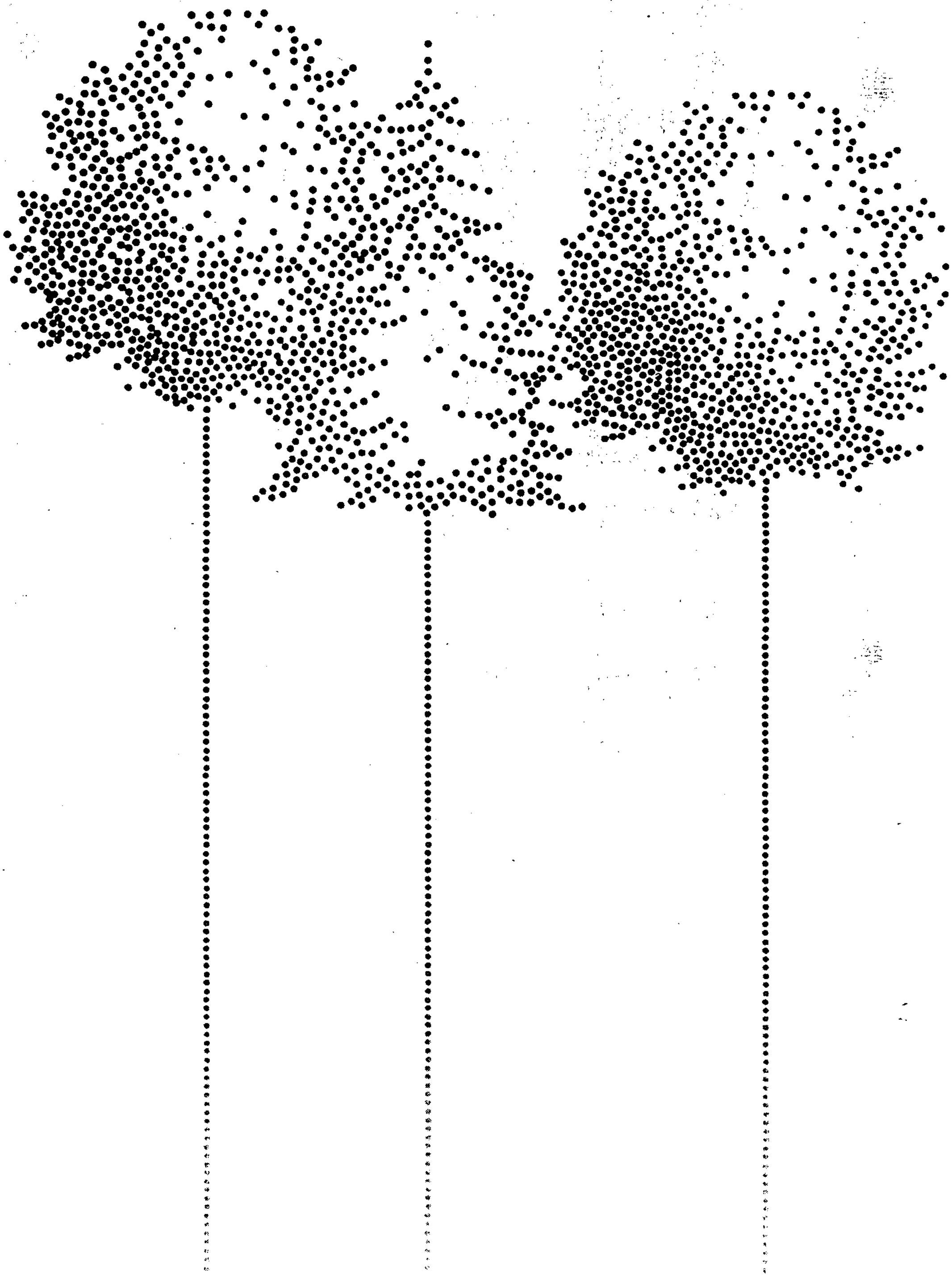

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