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THE APPLICATION OF A FOREST-SIMULATION MODEL TO ASSESS THE ENERGY YIELD AND ECOLOGICAL IMPACT OF FOREST UTILIZATION FOR ENERGY[1]

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ABSTRACT

This study examines the utilization and management of natural forest lands to meet growing wood-energy demands. An application of a forest simulation model is described for assessing energy returns and long-term ecological impacts of wood-energy harvesting under four general silvicultural practices. Results indicate that moderate energy yields could be expected from mild cutting operations which would significantly effect neither the commercial timber market nor the composition, structure, or diversity of these forests. Forest models can provide an effective tool for determining optimal management strategies that maximize energy returns, minimize environmental detriment, and complement existing land-use plans.

INTRODUCTION

Over the past few years the demand for fuel-wood has increased substantially, along with the rising economic incentives to utilize woody biomass for energy. In many areas (e.g., east Tennessee), natural forest resources are once again being exploited to provide stovewood and, in some instances, to supplement or replace conventional fuels used in small industrial operations. Regional studies of woody biomass production indicate a tremndous wood-energy potential from naturally occurring forests as well as from conversion to biomass plantations (Ranney and Cushman 1980). The advent of wood-energy plantations, however, has not yet occurred due to many questionable factors (e.g., capital outlay, crop procurement and merchandising, species selection, and site preparation and design among others) that tend to be quite variable depending on the specific land site and end use.

Recent studies reveal that much of the commercial forest lands are either underutilized or that forest residues (e.g., cull trees, tops, and limbs) generated from timber improvement practices are not being harvested (Curtis 1978, Howlett and Gamache 1977). In addition, there is significant acreage of marginal lands, wood lots, and tree farms which currently lack any management alternatives other than a primary source of firewood. These lands, particularly those in the Southeast, could potentially provide a significant wood-energy resource under more intensive and efficient forest management.

Intensifying the use of our forests for energy purposes is of major concern, and warrants a comprehensive evaluation of the associated environmental impacts, especially of indirect and long-term effects. Equally important to the wood-energy consumer is the reliability of the field source to sustain a relatively stable market supply over a period of years. These and related queries need to be addressed to fully assess the contribution and consequences of additionally managing our natural forest lands for energy production and use.

Forest simulation models can supplement field and laboratory studies, particularly where multi-use system effects and multi-year time scales are considered (Shugart and West 1980). This paper describes an application of FORET, a southern Appalachian forest simulator, to assess the energy yield and long-term ecological impact of harvesting wood-energy under four general silvicultural practices. A comparison of the resultant change in composition, structure, and diversity between model simulations including wood-energy harvests and the projected pattern of natural forest succession provides the basis for this assessment.

METHODS

Model Description

FORET, forest succession model for east Tennessee, was developed by Shugart and West (1977) to simulate the forest dynamics of a southern Appalachian forest type on lower slopes in Anderson County, Tennessee. It mathematically mimics the successional pattern and competitive interrelations of individual trees for a typical 1/12-ha plot of this forest. This stochastic model is one of a unique class of forest simulators, whose design consists of empirical formulas describing key ecological relationships of the forest community and its species and environment (Shugart and West 1980).

The major model routines, mainly tree seeding, growth, and death, are executed at yearly intervals. The growth of each tree is incremented as a function of climate, light availability, total stand biomass, and the inherent growth characteristics of the individual species. Tree death is modeled as a stochastic process with the probability of dying inversely related to growth and longevity. For detailed documentation of the FORET model construction and validation, refer to Shugart and West (1977).

Model Application

The present version of the model considers 32 tree species. Each is assigned an average energy value of oven-dry wood expressed in kilocalories per kilogram as shown in Table 1. Heating values for some species were not found in the literature, and thus shared equal value with their congenerics species. Energy harvests were then calculated by multiplying the heating value of each species times its total biomass (kg) harvested.

The simulated harvests were incorporated into the model in an additional subroutine called CUT. These cutting schemes were designed from four general silvicultural practices, namely, clear-cutting, selective-cutting, thinning, and high-grade cutting. All harvests were implemented on a discrete 60-year rotation schedule. This allowed the comparison of results among cutting selections without regard to the influence of varying harvest schedules.

The clear-cut routine involved the removal of all trees regardless of species or size. Selective-cutting allowed the harvesting of all species, but only individuals with stem diameters exceeding 30 cm were removed. In the intense thinning simulation, all species were considered eligible for cutting, but only trees below 30 cm dbh were included in the harvest. Lastly, high-grade cutting represented a specialized thinning where only noncommercial species (i.e., nonhickory, -oak, and -poplar group) were harvested. The latter cutting schemes are considered compatible alternatives for commercial forest lands where the management plan includes timber improvement practices. Results of these simulations, however, do not include the felling of commercially harvestable trees which in practice would actually be cut.

Following each cut, the model sums the total biomass and energy harvested. Model results for each simulation as a whole constitute the average of 120 plots projected over a 500-year period. These were then compared with the output from a control simulation which represented the pattern of natural forest growth and succession in the absence of timber management.

RESULTS AND DISCUSSION

Energy returns (i.e., the average expected kcals ha^{-1} $year^{-1}$) from each of the simulated harvest selections are given in Table 2. As expected, considering identical harvest schedules, clear-cutting reaped the highest yield, followed in order by the selective-cutting, intense thinning, and high-grade cutting. More important than the total energy output is the required harvestable forest land necessary to maintain a wood-energy supply on a sustained-yield basis for specific conversion to electricity or space heat. Three evaluations are presented: a 10-MW electric plant, a 50-MW power facility, and a 1000-cord fuelwood supply (Table 2).

It becomes evident from these findings that woodburning power facilities, even as small as 10-MW would require considerable land area to maintain continuous operation without directly competing for commercial timber and forest lands. This also emphasizes the importance of biomass plantations, short-rotation forestry, and species selection among other alternatives if woody biomass is to provide an energy resource for producing electricity.

In contrast, relatively little land area would be needed to generate 1000 cords (3.6×10^3 m^3) of fuelwood on a yearly basis. In this case, any of the harvesting schemes become viable alternatives regardless of the use or distribution of available lands. The primary end use, however, would be restricted to residential space-heating or industrial woodburning boilers. The cumulative contribution of these decentralized end uses cannot be overlooked for their significance on the local energy network, particularly in regions where fragmented noncommercial forest parcels are common and commercial timber production is of prime importance.

To account for the long-term ecological constraints of each of the simulated harvesting measures, we compared the resultant change in the composition, structure, and diversity of the managed forest with the projected pattern of natural forest succession. Compositional differences were distinguished by evaluating species rank values of the stand composition the year prior to each cutting, using the Spearman rank statistical test. The analysis required an ordering (i.e., numerical ranking from maximum to minimum) of the relative biomass by species for both the control and harvest simulations. Table 3 lists the results of this analysis in terms of an r_s coefficient representing the degree of compositional agreement between each simulated harvest and the control. Because these values signify the sum of species composition for all plots prior to harvest, they also provide some indication of the forest's ability to recover or its resiliency to disturbance.

This test indicated no significant differences in the overall compositions resulting from any of the harvest simulations with what might otherwise be expected over 500 years of forest succession. It can be seen, however, that the more severe cutting routines impose a greater shift in the overall species array as well as a greater stress on system recovery. The model does not account for differential seeding effects that might occur with overselecting certain species or eliminating parent trees. Without this input, the true shift of forest dominance towards early successional species is probably underestimated. Although the harvest selections did not appear to significantly effect the forest composition over the long-term, this does not take into account the changes in the actual distribution of species biomass and numbers (e.g., species diversity).

Changes in forest structure due to each simulated harvest were analyzed by comparing the mean stem density characteristics for an average 1-ha stand. This test involved the statistical comparison of cumulative diameter distribution of tree size-ranges from all plots on years prior to cutting. In effect, only the most mature stands were included in the test sample.

Diameter distributions represent the number of trees apportioned in defined diameter size classes over the diameter size range of the stand. The size class range used for testing the model results herein was 4 cm. The smaller the size range, the more powerful this test becomes for determining significant differences in forest structure. From one year to the next, individual trees may grow into larger size classes or remain in the same one, provided tree death, disturbance, or cutting does not occur. The shape and position of these diameter distribution curves relative to one another can give some indication of the successional maturity and dynamics of a forest stand. Figure 1 shows the relation of each simulated harvest with that of the control simulation.

These stem density figures were then converted into cumulative percentages of the total sample density for successive diameter classes from smallest to largest. This results in cumulative frequency distributions which can be statistically compared by using the Kolmogorov-Smirnov two-sample test. Derived D_k values (Table 3), representing the maximum differences between distributions, indicated that only the clear-cut and selective-cut samples were significantly different from the control sample. The differences in D_k values between the thinning and high-grade samples are perhaps attributable to the unrestricted size cut of the high-grade cutting routine.

Lastly, the simulated harvesting practices were evaluated for their effect on forest diversity. Diversity has been defined in many terms, but for the purposes of this text, it signifies an evenness or equitability with which the forest biomass is distributed among the model species. The index values herein were derived by using the Shannon-Weiner formula for evenness. This function generates S_w values ranging from 0 to 1, where 0 represents complete dominance by one species as in a monoculture plantation and 1 indicates equal dominance by all species.

Figure 2 illustrates the contrast of diversity through time between the simulated harvests and the control run. The most radical silvicultural practice, clear-cutting, generates the highest degree of variability in the diversity pattern, while the remaining harvest measures appear distributed slightly above or below the pattern for natural succession. Table 3 lists the average diversity values for all simulations and all years over a 500-year period. Repetitive clear-cutting and selective-cutting tend to increase the overall diversity index above the expected normal. On the other hand, high-grade cutting, selecting only cull species for harvest, had the sole distinction of decreasing the overall forest diversity. In general, one equates increased species diversity with a positive impact and decreased diversity with a negative impact. However, in this case we must consider the maximum absolute differences in diversity values as some indication of the ecological consequence of any harvesting practice or management plan. As already pointed out, the clear-cutting and selective-cutting seem to impose the most concern for environmental detriment in this regard.

CONCLUSION

Results from the four simulated harvest selections indicated that the extreme silvicultural practices, clear-cutting and selective-cutting, yielded higher energy returns over the less severe thinning operations. But even at the highest yield values, considerable land area would be necessary to fuel a woodburning power facility from natural forest resources. Such natural forest expanses are not without existing management plans or commercially valuable tree stock to allow the cutting of timber solely for energy purposes. The alternatives then seem to narrow to less extreme practices that could be incorporated into existing land-use plans and/or more direct uses of the wood-energy in small industrial boilers or residential woodstoves. The latter proposition appears more practical and ecologically sound when one also considers the potential environmental impacts not previously mentioned.

Although resultant changes in the forest composition from each of the harvest selections tested with no significant difference, it was apparent that clear-cutting and selective-cutting posed the greatest threat of changes in species composition away from the natural progression of forest succession. The structural impact of clear-cutting and selective-cutting showed a significant shift in stem density characteristics to fewer large trees and more abundant smaller trees. The thinning and high-grade-cutting harvests demonstrated no statistical difference in forest structure from that of the control simulation. Results of the effects on forest diversity indicated similar findings to those brought out in the structure and composition tests; namely-extreme harvest selections alter the species diversity much more greatly than do milder cutting operations. In addition, the reduced diversity generated in the case of the high-grade, cull-removal thinning lends some consideration to the effects of overselecting preferred species.

Clearly, the ecological impacts of intensively harvesting forests for energy go beyond the implications given herein of the projected long-term effects. A more thorough treatment would also consider short-term effects, both direct and indirect, including nutrient loss, soil disturbance and compaction, stand regeneration, and even changes in wildlife habitat (Van Hook et al. 1980). Though not included here, such additional considerations could be incorporated into this modeling scheme.

Forest simulation models can be effectively applied to examine potential energy yields and long-term ecological impacts of utilizing natural forests for energy needs. Where singular effects of specific forest uses (i.e., timber, wildlife) are fairly well documented, at least on the short term, the cumulative impacts of a multi-use forest plan become extremely difficult to determine without the aid of ecological forest models. By employing a modeling approach such as presented here, one can determine optimal or recommended harvesting strategies which maximize the energy return while minimizing any ecological detriment to acceptable standards. Also, models of this sort can be used to complement existing management plans by simulating the expected harvest selections and schedules, and thereby compute the potential wood-energy return in forest residue.

In the years ahead, the demands for energy from woody biomass will almost certainly intensify. These needs will likely be met through more intensive harvesting of existing forests and/or the advent of biomass energy farms. New energy-use alternatives for woodlots, tree farms, and marginal lands will undoubtedly develop with the rising energy demands. The increased attention drawn to woody biomass for energy will obviously lead to more careful consideration of how we manage our forest resources. In conclusion, forest models can provide an effective tool for testing and determining forest-energy management alternatives which maximize energy return, minimize environmental detriment, and compliment existing land-use plans.

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Table 1. Heating values for each of the species included in the FORET model parameter list. These values represent the energy content for dry wood as compiled from many sources by Conde and Huffman (1978) and Howlett and Gamache (1977)

Species	Heat value (kcal/kg)
Acer rubrum	4604
Acer Saccharum	4604
Aesculus octandra	4444
Carya cordiformis	4693
Carya glabra	4693
Carya ovata	4693
Carya tomentosa	4693
Cercis Canadensis	4444
Cornus florida	4444
Diospyros virginiana	4444
Fagus grandifolia	4697
Fraxinus americana	4768
Juglans nigra	4444
Juniperus virginiana	5389
Liquidambar styraciflua	4563
Liriodendron tulipifera	4786
Nyssa sylvatica	4650
Oxydendron arboreum	4444
Pinus echinata	5195
Pinus strobus	5195
Pinus virginiana	5195
Prunus serotina	4790
Quercus alba	4717
Quercus coccinea	4644
Quercus falcata	4644
Quercus prinus	4644
Quercus rubra	4644
Quercus stellata	4644
Quercus velutina	4644
Robinia pseudoacacia	4444
Sassafras albidum	4444
Tilia heterophylla	4586

Table 2. Expected energy yield and required harvestable forest land (ha) as determined for each harvest selection

Harvest selection	Energy yield (kcal/ha/yr)	Required harvestable forest land (ha)		
		10-MW	50-MW	10^3 cord[a]
Clear cutting	1.19×10^7	1414	7777	120
Selective-cutting	1.02×10^7	1649	9096	140
Thinning	2.23×10^6	7517	41343	450
High-grade cutting	1.46×10^6	11533	63316	700

[a]1 cord = 3.62 m^3.

Table 3. Ecological index values indicating alteration of forest composition, structure and diversity.

Harvest selection	Composition (r_s value)	Structure (D_k value)	Diversity (S_w value)
Clear-cutting	0.81	0.20	0.66706
Selective-cutting	0.88	0.19	0.67742
Thinning	0.89	0.02	0.58406
High-grade cutting	0.94	0.05	0.52896
Control	1.00	0.00	0.59691