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RANDOM ENTRY FORESTRY: TIMBER MANAGEMENT IN A TIME OF SPECIES CONSERVATION

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ABSTRACT. In this paper we propose a timber management scheme which mimics the patchy stand structure of a fire climax forest and has the desirable characteristic of retaining stands of trees of very old ages. We go on to do a preliminary economic analysis and determine that if management is taking place under the restriction that a certain fraction of the forest must be of at least some given age then this approach may be far superior to standard single age rotation schemes.

KEY WORDS: Timber harvest, rotation, land management, biodiversity, economics.

Introduction. With the current concern for the conservation of many forest dwelling species, harvest restrictions are arising on both public and private timber lands. Frequently, this results in a desire (or mandate) to maintain some fraction of the forest in stands much older than would naturally arise from standard timber management scenarios and with a stand structure which more closely matches that of a natural forest.

Even-aged harvest techniques all involve the concept of a rotation age. The rotation age is picked to maximize either biological potential or monetary potential. Using simple area control as an example, and assuming equal productivity across the landscape, for a T year rotation, $1/T$ of the land will be harvested each year. This system is easy to optimize, and easy to implement (see Davis et al. [1984]). The problem, from a biodiversity standpoint, is that none of the area treated will exceed T years in age. Very simple stand structures will result and species that depend on older trees will vanish from these systems. The only way to develop older stands within this even-aged paradigm is to extend the rotation-and this has serious economic consequences.

Uneven-aged silviculture is often portrayed as a biologically attractive alternative to even-aged systems (Daniel et al. [1979, p. 47]), but forests managed using these systems have at least as many problems as do even-aged area-control systems. Not only does uneven-aged silviculture not protect older stands from entry, but it requires much more extensive roading, tends to favor shade-tolerant species, and provides abundant opportunities for pathogens such as root diseases to become established. One variant on uneven-aged systems is to retain particular trees as a remnant population (Verner et al. [1992]). This will effectively maintain an element of older trees within the stands and this may be sufficient to maintain dependent species-but it may not. Leave-tree systems will tend to leave scattered large trees when older groups or stands may be more biologically appropriate. Leave tree schemes also meet with considerable resistance from foresters because they tend to leave the most valuable trees. Leaving most of the high-value trees may make sales economically impractical, and if the leave trees are diseased (dwarf-mistletoe may be common in older trees, for instance) then this disease will be transferred to the regeneration-reducing future productivity.

Neither alternative does a satisfactory job of protecting older trees without inflicting severe economic burdens. The common response to this problem has been to separate the landscape into reserves in which no management occurs and areas of high-intensity even-aged forestry. This lowers total timber output, but allows sales in those areas open for harvest to be carried out with few constraints.

Reserves, however, only promise to be stable in the long-term if they are large enough that natural disturbances can be allowed to occur within the reserve and if the climate remains fairly static. If the reserves are too small and natural processes such as fires are suppressed, then they will become very unnatural and will fail in their original goal. If the climate changes, then the “island” nature of reserves will become a severe detriment to their function; species will need to flow freely and quickly to meet new climatic imperatives and reserve designs, by their very nature, impede the free-flow of organisms across the landscape.

What is required in those areas where large and frequent reserves are not practical is a system that maintains older stands at predictable levels throughout the landscape, allows timber harvest to occur at reasonable levels, and allows timber sales to be efficient, that is, allows even-aged block designs.

A model from nature: disturbance as a stochastic process. Natural fires, in many ecotypes, are often stand-replacing events (see Gruell [1983] for examples). For years, this understanding has been used by forest managers as a rationalization of clearcuts. In terms of the retention of older stands, however, natural fires are very different from standard even-aged area-control systems. Fires are stochastic events. If fires worked the way clearcuts do, then after a fire event, when the next fire occurred, the unburned blocks (from the first fire) would burn and none of the areas that previously burned would be touched. In areas where the average return time of a fire is > 40 years, this type of scenario is extremely unlikely. Remnant patches are likely to be no more flammable than the previously burned areas. Natural wildfires generally are driven by the vagaries of the wind coupled with the local topography. In extreme conditions, fuel loadings may become irrelevant. The most likely scenario for a repeat fire is that it will re-burn some of the original burn and also some of the previously unburned areas as well. Even after many fires there will probably be some areas that, by chance, haven't been burned. These chance events, when expanded to the landscape, will generate a proportion of the landscape in very old conditions, even though the fires are stand replacing and the yearly acreage burned is equivalent to the acres harvested using short rotation clearcuts.

Probabilistic rotation as an alternative. Consider an idealized landscape broken up into equal sized blocks. As with the area control system, we will, on average, harvest a fixed proportion of the landscape every year using even-aged harvest methods. But instead of harvesting the stands when they are at a particular age, we simply harvest them randomly, regardless of age. We will refer to this process as probabilistic rotation. Because every block will have an equal probability of being harvested each year regardless of its past history, harvest is a simple Markov process in which the probability of moving from state $t \rightarrow 0$ is the probability of being cut (p) and the probability of moving from state

$t \to t+1$ is $1-p$ for all t. This will result in a landscape dominated by younger age classes, but also with a significant old growth component. That is, the proportion of the landscape (once we have reached the steady-state condition) that is at least t years old will be:

(1) $$P_t = [1-p]^t.$$

At this point it is fair to ask, So what? From a practical viewpoint this system is silly; most of the stands “harvested” are too young to have any merchantable trees. This pathology can, however, be corrected by imposing a minimum age or age of “maturity,” M, below which stands will not be harvested. The new transition rules are:

$t < Mt \to t+1$ with probability 1.0
$t \to 0$ with probability 0.0
$t \geq M, \quad t \to t + I$ with probability $1-p$
$t \to 0$ with probability p.

Imposing a minimum age requirement will lead to a steady-state forest with constant proportions up to the minimum age and then declining exponentially (Figure 1).

Let F_i be the fraction of the land in which cutting will not be permitted (the immature stands) and F_m the fraction of the landscape in which cutting may be done; then $F_i + F_m = 1$. If R is the probabilistic rotation (the number of years required to cut through the stands that are currently mature), then $1/R$ is the fraction of the mature trees cut each year. Choosing $M = 60$ years and $R = 40$, 60% of the land will support trees less than 60 years old and 40% will hold trees greater than 60 years of age. The proportion of the total landscape cut every year

(2) $$\text{Annual Cut} = (1/R)F_m$$

which is also the fraction of the land in each age class up to maturity (since we assume that harvested acres are immediately replanted).

$$F_m = 1 - F_i = 1 - MF_m/R \quad \to \quad F_m = R/(R+M).$$

As a result, the fraction of the forest cut each year is $1/(R+M)$. In our case, 1/100 of the forest is harvested each year which, in terms of area entry, is equivalent to a 100 year rotation.

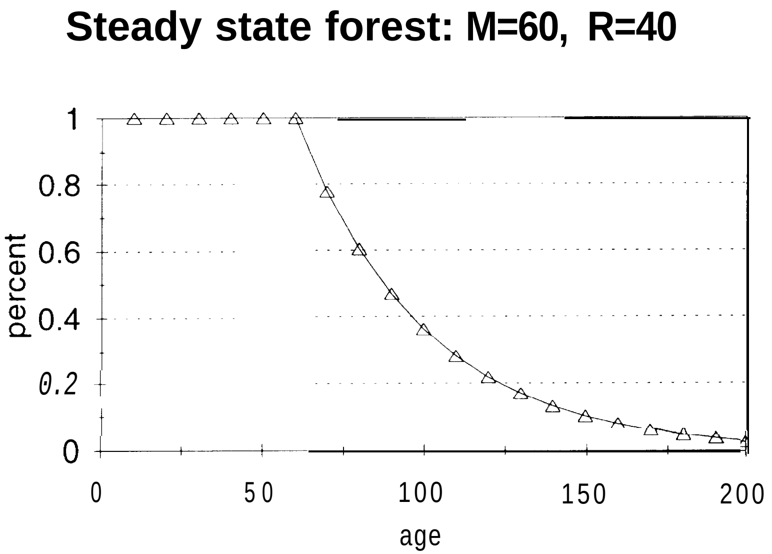


FIGURE 1. Steady age distribution for trees in forest under random entry harvesting.

The fraction $1/(R+M)$ of the trees mature each year and (assuming the deterministic case) $1/R$ of the newly mature trees are cut while $1 - 1/R$ of them escape. Thus, $(1 - 1/R)[1/(R+M)]$ reach age $M + 1$ in any given year, and $1/R$ of these are cut the next year. Following this pattern a fraction

$$P_{M+k} - P_{M+k-1} = \frac{(1-1/R)^k}{R+M} \tag{3}$$

are of age $M + k$ at any given time. While the fraction of trees of age at least T is

$$P_T = \sum_{k=T-M}^{\infty} \frac{(1 - 1/R)^k}{R+M} = \frac{R(1-1/R)^{T-M}}{R+M}. \tag{4}$$

With $M = 60$ and $R = 40$, 4.1% of the trees are at least 150 years old and 14.5% are at least 100.

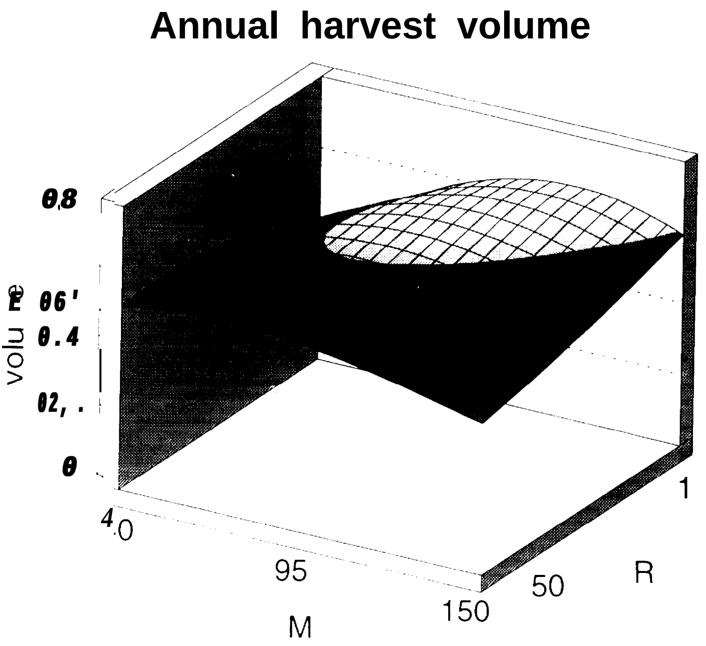


FIGURE 2. Expected harvest volume as a function of age of maturity and probabilistic rotation age. With $R = 1$ we get a standard single age rotation.

Volume production associated with probabilistic rotation. The annual cut in each age class ($t \geq M$), in the steady state, will be proportional to the area in that class. Annual harvest will therefore be

$$\begin{aligned} \text{Annual Harvest} &= \sum_{t=M}^{\infty} (P_{t-1} - P_t)\frac{1}{R}V(t) \\ &= \sum_{k=0}^{\infty} \frac{(1 - 1/R)^k(1/R)}{R+M} V(M+k) \end{aligned} \tag{5}$$

where $V(t)$ is the expected volume associated with unit area of trees with age t. These equations, in conjunction with a volume table allow us to compute the expected steady-state volume associated with any combination of M and R (Figure 2). We can also, using equation (3), determine the proportion of the total area that will be in any age class. Using equation (2) we can determine the proportion of the landscape to be treated each year and contrast the volume produced (equation (5)) with the expected volume derived from treating the same number of acres using an even-aged fixed rotation system. The expected harvest from an even-aged rotation schedule results when R is taken to be one in the figure above.

Economic analysis. Estimation of present value for land in an even-aged fixed rotation system is given by

$$PV = \frac{NI(t)}{(1+r)^t - 1} \tag{6}$$

where PV is the present value, $NI(t)$ is the net income derived from harvesting a stand at age t and r is the discount rate. At steady state, present value of our probabilistic rotation can, based on equation (6), be stated as:

$$PV = \sum_{k=0}^{\infty} \frac{(1-1/R)^k}{R} \frac{NI(M+k)}{(1+r)^{M+k} - 1} \tag{7}$$

where $(1 - 1/R)^k(1/R)$ is the expected fraction of the forest to be harvested at age $M + k$ and we must sum over all rotation periods. Figure 3 gives the present value as a function of M and R. The standard value for a single aged rotation is given when $R = 1$.

Using this method of evaluation, if the fixed length rotation for the land is longer than the rotation designed to maximize PV, then under many circumstances, the probabilistic rotation will exhibit better economic performance than a fixed rotation schedule that impacts the same proportion of the landscape. In particular, if M approximates the rotation maximizing PV, most of the cutting will be in age classes close to this maximum. There are, in fact, many circumstances in which rotation schedules are set far longer than would be suggested by maximization of PV, either to assure maximization of biological potential (culmination of MAI) or to mitigate environmental consequences associated with rapid rotation silviculture.

Formal optimizations: For biomass and PV. The annual harvest volume and PV for a forest managed using random entry harvesting may both be thought of as rather complicated functions of the two

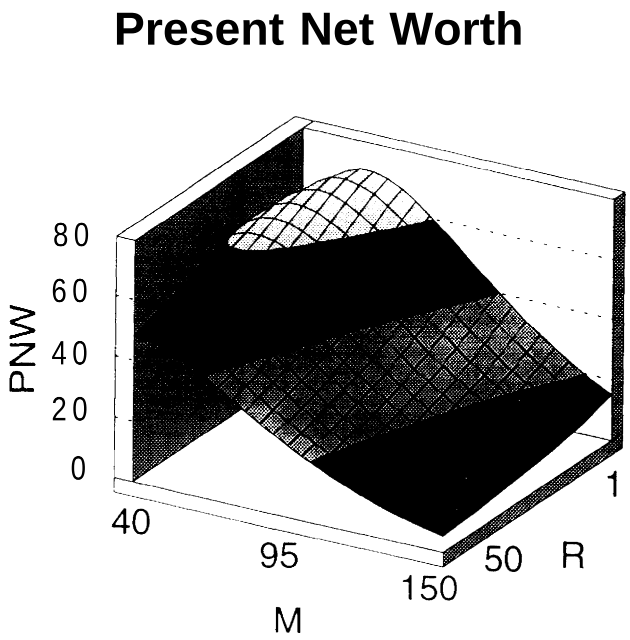
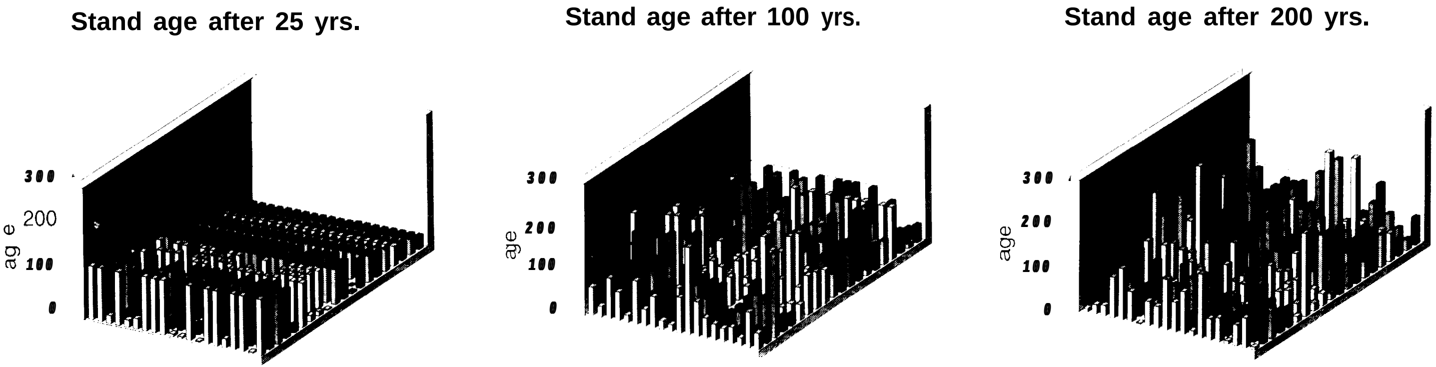


FIGURE 3. Expected present value as a function of age of maturity and probabilistic rotation age. With $R = 1$ we get a standard single age rotation.

variables M and R as is shown in Figures 2 and 3 or equations (5) and (7). Mandated environmental constraints may be of a form which prescribes that a certain fraction of the forest must be maintained in trees of greater than a certain age. Once the age and percentage (T and P_T) are specified, equation (4) provides an implicit relationship between R and M. Intersecting this relationship with either the surface in Figure 2 or 3 forms a curve of suitable values on the respective surfaces. Any point on or below this curve will provide a harvest system (M and R) which satisfies the constraint with the optimal choice in each case resulting from taking the high point on this curve. In theory, this is an elementary calculus problem while in practice the complicated nature of the functions requires us to obtain the solution numerically.

It is also possible to satisfy two simultaneous constraints of this type; for example, constraints that require 15% of the trees over 100 years of age and 5% over 150. This can be accomplished with $M = 43$



Stand age after 25 yrs.

Stand age after 100 yrs.

Stand age after 200 yrs.

FIGURE 4. The heights of the bars in the graphs represent the ages of trees in each block after 25, 100 and 200 years of harvesting using random entry forestry. The simulation was initialized with a normal forest having four blocks in each age class 1 to 100.

and $R = 46$. However, with the two constraints applying there is no flexibility for optimization-a single combination of age of maturity and probabilistic rotation period must be chosen.

Interim conditions: Closing on the steady state condition. Figures 4a, 4b and 4c show graphically the results of a simulated conversion of an idealized, regulated forest with 400 plots where four are in each age class 1 through 100. Random entry with $M = 60$ and $R = 40$ was used. In Figure 4 we have the graphs of the percent of the forest in each age class after 25, 100 and 200 years along with a three-dimensional bar graph where each plot is represented by a bar with height directly related to the age of the trees. Figure 5 is the fraction of the forest greater than 100 and greater than 150 years of age as a function of the time since conversion began.

Biological implications: What the forest will look like. The forest generated by random entry harvesting will be primarily young. It will, however, contain stands of larger timber, including a few very ancient stands. There is no maximum period between harvests. A forest managed with $M = 40$ and $R = 40$ will, in the steady state, have 1/80 of the land harvested every year and 50% of the land < 40 years in age. In this regard it resembles an 80 year fixed rotation system. It also has, however, 32% of the total land area in stands > 80 years in age. It has, therefore, 36% fewer lands in the 40-80 year range. It is reasonable to ask, is this a fair trade-off? If the question is asked in terms of biodiversity, the answer is almost certainly yes. Few animals or plants have specialized adaptations to these mid-aged stands. Studies of biodiversity have shown that mid-aged stands are relatively depauperate when compared both with younger and older stands (Halprin et al. [1992], Lowe and Franklin [1992], Franklin [1993]). Further, the species complex associated with young and old stands will be very different. Mid-aged stands lie at a transition stage in which the disturbance specialists are falling out of the community and the old forest specialists are beginning to colonize. From a biological standpoint it is probably disadvantageous to have, perhaps, 50% of the landscape in these mid-aged stands.

Flexibility. Random entry harvesting should lead to forests that

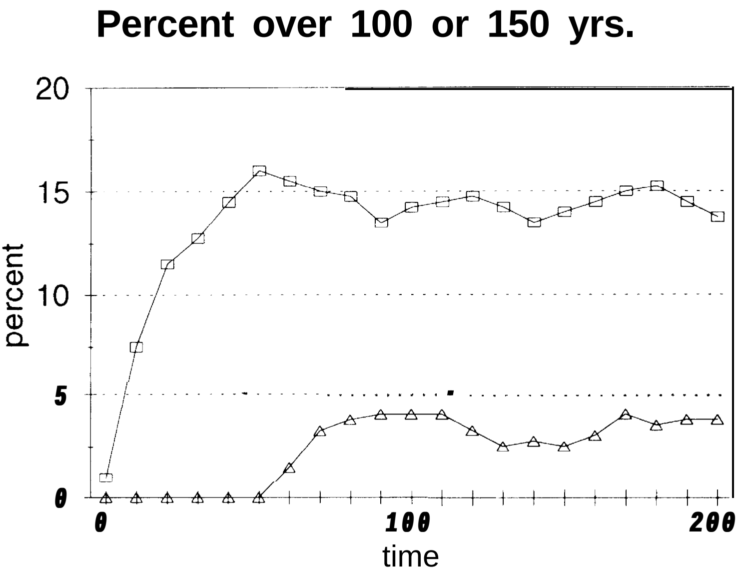


FIGURE 5. The upper curve shows the percent in trees over 100 years of age as a function of time since harvesting began on a normal forest. The lower curve shows the percent over 150 years of age.

are more flexible than standard regulated forests, both in product output and in the spatial arrangement of landscape. Even-aged systems provide relatively few products, primarily they produce trees having the size and characteristics associated with the rotation age. Market demands for products derived from trees older than the rotation age can only be met by extending the rotation and waiting for the trees to age. In random entry harvesting, all tree ages are present on the landscape and adjustments of *M* and *R* can incrementally adjust the product mix to better meet market demands.

Even-aged systems also tend to "freeze" a particular landscape pattern. Once an area comes into regulation the patterns of the original cutting are reinforced by the fixed rotation period. Random-entry systems, particularly if they are applied over large land areas so that proportional area in each age class can be substituted for probability of harvest, offer much more flexibility. For a specific sub-region, all stands greater than *M* are available for cutting at any time period. The only constraint is that the global level of removal not exceed *R**, the proportion of the landscape in each age class.

TABLE 1. Various harvest schedules, volume output and present values.

Min. Age	Rotation	Even-Age	% Over Age		Vol.		Pres. Val.	
M	*R*	*T*	100	150	Rndm	Even	Rndm	Even
40	20	60	1.5	0.1	.47	.47	61.3	70.7
40	40	80	10.9	3.1	.53	.58	55.2	64.3
40	60	100	21.9	9.4	.52	.64	47.9	48.8
60	20	80	3.2	0.2	.57	.58	62.6	64.3
60	40	100	14.5	4.1	.57	.64	51.0	48.8
60	60	120	25.5	11.0	.54	.66	42.3	32.9

Conclusions. Probabilistic rotation offers a reasonable alternative to reserves for the maintenance of very old stand structures throughout the forest. Systems can be developed that maintain a significant proportion of the forest in older age classes and have much more favorable economics than are associated with long rotations. In particular, the large proportion of young stands harvested will provide for a good return on invested capital. In terms of biomass output, an 80 year probabilistic rotation ($M = 40$, $R = 40$) in moderate productivity stands will produce nearly as much wood (93%) as a fully regulated forest operating on an 80 rotation. In higher productivity (Site Index = 100-200) it will produce 89% of the wood. In addition, it provides for a constant flow of high-value wood products associated with older stands-a product class that is generally lost under even-aged rotation schemes. The desired mixture of these products can be adjusted at any point by shifting M and R.

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