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Introduction

The National Forest Management Act (NFMA) of 1976 (16 U.S.C. 1600) requires that each National Forest, by 1985, prepare one integrated management plan that provides for multiple use and sustained yield for goods and services (36 CFR 219). Such plans must, by inference, emphasize single resources only to the extent that thresholds or minimum legal conditions for all other resources are always provided (Clawson 1975). The goal for wildlife to be met by each forest plan is: manage wildlife habitats to maintain viable populations of all existing native vertebrate species in the planning area (the forest) and maintain and improve habitat of management indicator species (MIS) [36 CFR 219.12(g)]. To meet this goal, wildlife habitat objectives representing threshold or minimum legal habitat conditions must be stated in forest plans to assure adequate consideration of the wildlife resource in all integrated management alternatives. Objectives representing the most desirable (optimum) habitat conditions must also be stated to provide direction for management emphasizing wildlife.

In specific portions of forested ecosystems to be determined in individual plans, planners are encouraged to establish wildlife habitat objectives stating threshold and most desirable levels of: (1) forest vegetation age class distributions and (2) habitat dispersion (USDA Forest Service, in prep.). In this paper, age class distribution refers to specific proportions of forest vegetation age classes or successional stages needed by wildlife. Habitat dispersion refers to spatial distribution or scattering of age classes needed by wildlife within a geographic area.

Recent planning efforts have been relatively successful integrating into forest plans habitat objectives stating age class distributions needed by wildlife. Such habitat objectives provide the quantity of habitats required by dependent vertebrates, but they do not necessarily assure needed habitat dispersion that provides cover and edges. Efforts to develop and quantitatively express habitat dispersion objectives in resource integration models have not been very successful. This problem, to be described later as the "dispersion problem," results from uncertainty among planners about what habitat dispersion objectives can or should be, and also reflects some limitations of current resource integration models to accommodate dispersion objectives.

This paper: (1) presents a synopsis of some past work on procedures to ensure

on a forest the continual presence of different age classes needed by wildlife and explains why such procedures are insufficient to ensure that habitat dispersion objectives will also be met; (2) discusses the legal requirements for habitat dispersion in integrated planning; (3) describes the dispersion problem; (4) sets out a theoretical basis for developing wildlife habitat dispersion objectives for forested ecosystems; and (5) presents a process for incorporating such objectives into Forest Service planning models.

The questions of when, where, and how much of a national forest to subject to habitat dispersion objectives are not addressed in this paper. Neither is the question of other resource considerations (e.g., visual, watershed, and timber) in developing multiple use dispersion objectives. Such questions are to be resolved through an interdisciplinary team process that draws on applicable local, regional and national public issues and multiple use management concerns. The theory presented in this paper for developing wildlife habitat dispersion objectives is intended to serve as one of the considerations in developing dispersion objectives for national forests.

Ensuring Age Class Distribution Without Ensuring Habitat Dispersion

Mealey and Horn (1981) documented the integration into a forest plan of wildlife habitat objectives, stating acreages of vegetation age classes needed by wildlife through time. For the forest and some subdivisions of it, the linear programming timber harvest scheduling model was constrained to ensure that minimum acreages existed in each key age class in each period.

The general case of this example is represented as follows: assume the harvest of an area composed of two types of stands (young growth and old growth) is being planned. The net value from cutting the timber over two periods is to be maximized, subject to an even-flow constraint and a requirement that some minimum acreage of mature timber be left in each period after harvest. Old growth acres harvested in period 2 meet the requirement for period 1. Old growth acres left uncut can meet the requirement in both periods, and young growth acres left uncut after the second period also will be old enough to meet the requirement in the second period. The following linear program represents this decision problem.

Maximize:

$$P_{o1}o_1 + P_{o2}\,o_2 + P_{y1}\,y_1 + P_{y2}\,y_2$$

Subject to:

Acreage control constraints

$$o_1 + o_2 + r_o \leqslant A_o$$
$$y_1 + y_2 + r_y \leqslant A_y$$

Inventory acreage constraints

$$o_2 + r_o \geqslant T_1$$
$$r_o + r_y \geqslant T_2$$

Even-flow constraint

$$-V_{o1}o_1 + V_{o2}\,o_2 - V_{y1}\,y_1 + V_{y2}\,y_2 = 0$$

where: i = any period

o_i = acres of old growth cut in period i

y_i = acres of young growth cut in period i

r_o = acres of old growth left uncut after period 2

r_y = acres of young growth left uncut after period 2

P_{oi} = net return from cutting an acre of old growth in period i

P_{yi} = net return from cutting an acre of young growth in period i

V_{oi} = volume/acre of old growth cut in period i

V_{yi} = volume/acre of young growth cut in period i

A_o = acres of old growth

A_y = acres of young growth

T_i = minimum number of acres of mature timber that must be left uncut in period i

The expression being maximized (often called the objective function) is composed of four terms. Each term provides the net value/acre cut times the acres cut for one of the four decision variables (acres of old growth cut in period 1, acres of old growth cut in period 2, acres of young growth cut in period 1, and acres of young growth cut in period 2). Summing these four terms gives the total net value from cutting the two stand types over the two periods. This expression is maximized subject to the constraints specified on the solution.

Three types of constraints appear in the problem. Acreage control constraints ensure that the total number of acres in period 1 and period 2 plus the acres left uncut do not exceed the total number of acres in each stand type. Inventory acreage constraints ensure that the acres of mature timber left uncut in each period is equal to or exceeds some amount. Even-flow constraints ensure that the timber harvest in period 1 ($V_{o1}o_1 + V_{y1}y_1$) equals the timber harvested in period 2 ($V_{o2}o_2 + V_{y2}y_2$).

In problems formulated this way, each stand type is usually composed of stands from across very large areas and sometimes from the entire forest. Old growth from the north end of a large area is combined with old growth from the south end and so on. Location of individual stands, their size and their spatial location in relation to other stand types (here young growth) are lost in the aggregation process. Constraints on minimum acreages in key age classes assure the presence of needed habitat within the planning area, but do not assure that the habitat can be spatially arranged throughout the area in a manner needed by wildlife.

Legal Requirement for Habitat Dispersion

As indicated, the term *habitat dispersion* refers to the distribution or scattering of cutting units and associated wildlife habitats within a geographic area. The NFMA implicitly establishes the legal requirement for habitat dispersion by setting maximum size limits for areas to be regeneration harvested in one operation (Sec. 6(g)(3)(F)(iv)) and by requiring that such cuts be carried out in a manner consistent with the protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the timber resource (Sec. 6(g)(3)(F)(vi)). Maximum size limits on cuts require that some portions of some harvestable stands remain uncut. This imposes some degree of scattering of harvest blocks among uncut areas. Compatibility of such cuts with the protection of wildlife resources demands a certain amount of edge and retention of cover which are necessary for wildlife.

Effective edge and cover in timber harvest areas result from adequately scattering cuts through uncut areas.

The Problem

The "dispersion problem" can be stated as follows: *Habitat dispersion objectives reflecting timber stand harvest rates compatible with requirements for maximum cut size and wildlife cover and edge have been lacking. As a result, forest planning models (such as the linear program given above) used to schedule timber harvests produce harvest schedules that may be impossible to achieve without violating explicit cut size limits and implicit wildlife cover and edge requirements of the NFMA Regulations (36 CFR 219).*

Solution requires: (1) a theory supporting dispersion objectives leading to specification of proportions of cut to uncut timber to be maintained in stands over time to meet cut size limits and wildlife cover and edge requirements; and (2) a process for incorporating such objectives in multiple use timber harvest scheduling models.

Timber harvest scheduling models lacking incorporation of dispersion requirements may schedule "too much" of a stand or adjacent stands for harvest during a decade (Baglien 1981, Mitchell 1981). For example, assume that a single stand of 100-year-old lodgepole pine (*Pinus contorta*) occurs on 1,200 acres (480 ha) of highly productive land. One harvest prescription applicable only to this stand requires clearcutting with a rotation age for future stands of 100 years. During the first decade, all 1,200 acres are available to the prescription. If the prescription contributes the most to the objective being maximized and there are no constraints on the stand's rate of harvest, all 1,200 acres might be assigned to the prescription. If that happened, the entire 1,200-acre stand would be scheduled for clearcut in one decade. Harvest according to this schedule would not be consistent with any reasonable maximum cut size or wildlife cover and edge requirements. As pointed out previously, even-flow or acreage inventory constraints specifying age class distributions cannot be relied upon to solve such a problem because constraints would apply only to total acres of large areas or entire forests. They would not constrain the harvest rates of individual stands.

This example characterizes the way many national forest timber harvest scheduling models have functioned. In fact, Johnson (1981) indicates that, in the past, Forest Service timber harvest scheduling was concerned primarily with forest-wide assessments of the biological sustainability of timber harvest over multiple rotations rather than with the spatial implications of timber harvesting, including considerations of habitat dispersion needs of wildlife on sub-units of the forest. Such an approach tends to overstate timber harvest capability when additional multiple use objectives for watershed and soil, recreation and visual, and wildlife and fish resources must be met.

Solution

Theory For Developing Dispersion Objectives

As indicated earlier, alternative sets of dispersion objectives must be developed that allow different land use emphasis. Two emphases are considered: the first

favors rapid timber production while meeting minimum legal habitat conditions for wildlife (e.g., conditions for minimum populations of wildlife in a specified area). The second favors wildlife habitat (most desirable habitat conditions) with timber production a consequence.

Timber Production Emphasis—Minimum Legal Wildlife Conditions. In this case, dispersion objectives must be developed which specify the minimum time in which stands or groups of stands can be regeneration harvested and still retain edge and cover required by minimum populations of wildlife during the regeneration period. The principal theoretical assumption is: *the length of time required for regenerated vegetation to grow to become cover for large animals (e.g., elk [Cervus elaphus]) is the primary factor in development of threshold habitat dispersion objectives. Size and shape of cuts are other major factors. Rotation ages of stands are not factors.*

An example (Figure 1A) will help illustrate the way in which vegetation growth rate influences development of objectives. This example is based on clearcuts with a two-decade opening life. Two-decades of vegetation growth provide marginally effective cover in this case.

Figure 1A represents 18 cutting units in one mature stand. The number of decades necessary for stand regeneration, assuming the stand must be harvested each decade, is determined by scheduling individual units for harvest so there is at least a 20-year vegetation age difference between all adjacent units. In this case, the required vegetation age class differences cannot be achieved if more than 20 percent of the stand is cut in any decade and the stand is regenerated in less than 50 years. The timber harvest schedule for the stand, conveying the harvest rate compatible with requirements for maximum cut size and wildlife cover and edge, must meet the dispersion objectives that no more than 20 percent be harvested per decade and that the stand be totally regenerated in no less than five decades.

If the stand need not be harvested each decade, it could be divided into a checkerboard pattern with alternate blocks scheduled for harvest in decades 1 and 3. An even flow of timber could be achieved in the area by pairing the stand to another stand with cuts scheduled in decades 2 and 4. This pattern is shown in Figure 1B. The harvest schedules for the stands would permit 50 percent of each stand and 25 percent of the total area to be harvested each entry with 20 years between entries. The area could be totally regenerated in four decades. It would not be possible to provide the desired 20-year age difference between all adjacent cutting units along any common boundary of the two stands. Dispersion is minimal in this case since only two age classes occur in each stand. This condition may not be acceptable for large stands where greater diversity is necessary.

If rows 1, 2, and 3 in Figure 1A each represented different stands (e.g., different species) with similar ages and growth rates for regenerated vegetation, the indicated harvest schedule would be valid for the entire area since minimum age of cover and cut size are the primary determinants of dispersion objectives. If rows 1, 2, and 3 each represented stands differing in age but with similar growth rates, then a coordinated timber harvest schedule for the area would be necessary. The coordinated schedule would specify the harvest dates of individual cutting units such that the vegetation age of adjacent units would always differ by 20 years. A coordinated schedule for Figure 1A is shown in Table 1. The harvest date for each unit in stand 1 (row 1) follows the schedule established in Figure 1A which assures

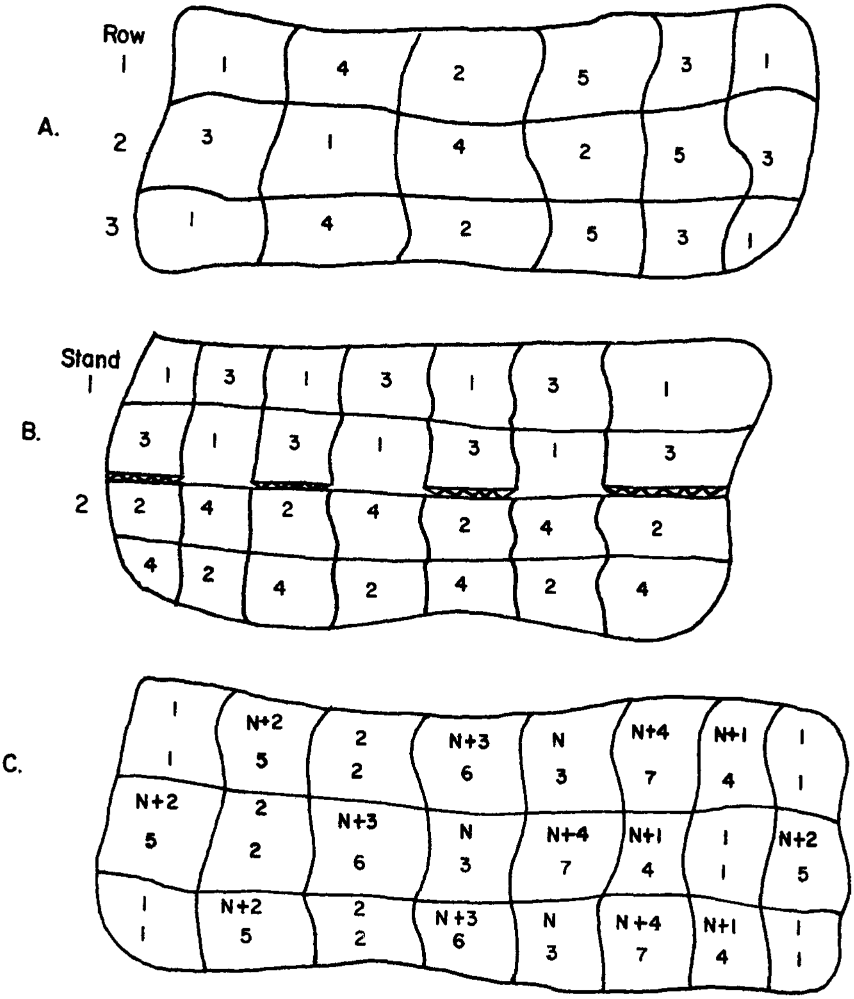

Figure 1. Patterns for laying out regeneration cuts to maintain adequate age differences along edges while regenerating stands rapidly. Numbers in each cutting unit indicate the decade of regeneration for the unit. *A* illustrates the pattern where stands are harvested each decade and age differences along edges must be at least two decades, *B* illustrates another pattern where stands need not be harvested each decade and two decade vegetation age differences are maintained along most edges, *C* applies a general rule to an example where the number of decades (*N*) required to establish wildlife cover following regeneration is 3.

at least two decades of vegetation age difference between adjacent cutting units. Stand 2 will not be ready for regeneration until the fourth decade (e.g., three decades after regeneration of stand 1 has begun). In order to maintain the habitat dispersion pattern begun in stand 1, regeneration of stand 2 begins with unit 4. Regeneration of stand 3 begins with unit 3 since it is ready for regeneration in the third decade.

Table 1. Example of a coordinated timber harvest schedule based on Figure 1A where row 1 represents a 100-year old stand, row 2 is a 70-year old stand, row 3 is an 80-year stand and rotation age for all stands is 100 years.

Stand		Decade of regeneration by cutting unit number				
Current age	Row number	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
100	1	1985	1995	2005	2015	2025
70	2	2035	2045	2055	2015	2025
80	3	2035	2045	2005	2015	2025

A general rule for establishing dispersion objectives that assures opportunity for the desired age difference between all adjacent cut units and some variety of age classes within an area follows: *The fraction of a stand to be regeneration harvested in any decade may not exceed* $1/(2N+1)$*; where N is the number of decades required to establish wildlife cover following regeneration.*

Figure 1C demonstrates how the general rule may be applied. The area is first divided into strings of cutting units $2N+1$ long. The end units of each string are scheduled for harvest in decades 1 and $N+1$. Units scheduled in decades 2 through N are spaced evenly in the string between units scheduled in decades 1 and $N+1$. The unit to the right of unit 1 is scheduled for decade $N+2$, the unit to the right of unit 2 is scheduled for decade $N+3$, etc. A new string begins to the right of unit $N+1$. Adjacent strings (e.g., the rows in Figure 1A) must be offset by at least one unit to assure edge contrast. The total number of units in the string $(2N+1)$ equals the regeneration period in decades. The reciprocal of that number $(1/(2N+1))$ represents the proportion of the stand area to be regeneration harvested per decade. Figure 1C shows that if $N=3$ decades, the minimum time to regenerate the stand is seven decades and, therefore, the maximum cut is 14 percent per decade. Similarly, if $N=4$, the minimum time to regenerate the area would be nine decades and the maximum cut per decade is 11 percent.

A general rule for establishing dispersion objectives that provides opportunity for age class differences between some adjacent cut units, and at least two age classes within an area, as shown in Figure 1B, follows: *The fraction of a stand to be regeneration harvested in any decade may not exceed ½ and the remainder may not be regenerated for N decades.*

If the above rule is used, cutting units will be laid out in a checkerboard pattern (Figure 1B) for each stand. If a relatively constant amount of area is to be harvested each year, there must be N stands of approximately equal size. Figure 1B shows that if N is 2, one stand will be regenerated in decades 1 and 3 and another in decades 2 and 4. Similarly if N is 3, one stand will be regenerated in decades 1 and 4, the second in decades 2 and 5, and the third in decades 3 and 6. Under these conditions, the fraction of the total area (including all N stands) that will be regenerated is $1/2N$.

Wildlife Habitat Emphasis—Most Desirable Habitat Conditions. In this case, dispersion objectives must be developed that assure the desired age difference between all adjacent cut units providing for optimum wildlife populations. Objec-

tives also provide for the maximum variety and scattering of age classes within an area. The principal theoretical assumption is: *Desired stand rotation age is the primary factor in development of most desirable habitat dispersion objectives. Size and shape of cuts are other major factors.*

A general rule for establishing dispersion objectives under this emphasis follows: *The fraction of a stand to be regenerated in any decade equals 1/R where R equals the desired stand rotation age in decades.*

Harvest schedules can be determined as before, except the number of units in strings equals the number of decades in stand rotation ages (Figure 2). The end units of each string are scheduled for harvest in decades 1 and $N+1$. Units scheduled for harvest in decades 2 through N are spaced evenly between units 1 and $N+1$. Individual units are scheduled as before (Figure 2A); however, if the rotation length is more than $2N+1$ decades, additional cutting units must be fit into the scheduling pattern. This is accomplished by continuing the pattern pre-

A.

B.

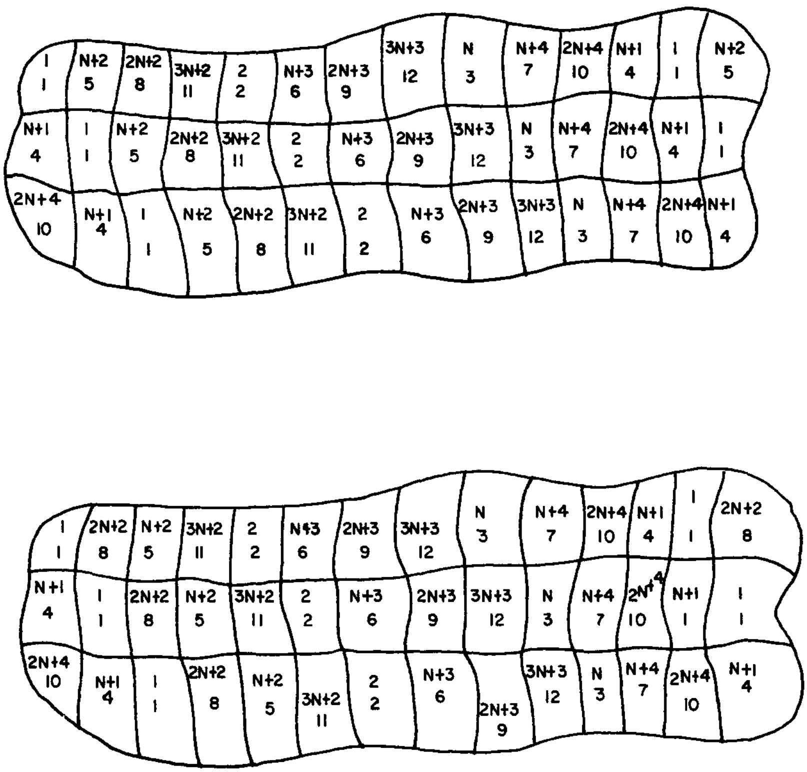

Figure 2. Application of the general rule for laying out clearcuts to the case where the number of decades required to establish wildlife cover following regeneration (N) is 3 decades, rotation length is 12 decades and openings are to be scattered as widely as possible at all times. *A* illustrates the general rule while *B* illustrates the modified rule which improves scattering when rotation length exceeds $3N+1$.

viously established (e.g., the unit to the right of unit $N+2$ is scheduled for $2N+2$, the unit to the right of $N+3$ is scheduled for $2N+3$, etc.). If the number of decades in the rotation exceeds $3N+1$, it is possible to improve the pattern by switching the scheduling of units scheduled for decades $N+2$ and $2N+2$ (Figure 2B). This will provide for better scattering of openings, particularly when units scheduled in decades $N+1$ and $N+2$ are both in openings.

Cut units are more widely scattered under the wildlife habitat emphasis (Figure 2) as compared with the timber production emphasis, and age class distribution as well as high quality habitat dispersion are assured. Also, under the wildlife emphasis, age class variety would continue throughout the rotation, whereas under the timber emphasis, age class variety would be minimal between decade $2N+2$ and rotation age. As a consequence, habitat diversity under the wildlife emphasis would be much greater.

Size and Shape Considerations. Dispersion objectives applicable to both emphases must also address size and shape of cutting units because size and shape impacts the effectiveness of the patterns discussed above. In most cases if size and shape of cutting units are governed by the needs of elk and deer, the opportunity for meeting the needs of other species within these units will be provided. The objectives recommended here are therefore based on elk and deer needs. If indicator species in a specific area include a species whose needs cannot be met under these conditions, more restrictive standards should be applied.

In cases where regeneration is to be completed rapidly (less than $3N+2$ decades), some or all cutting units must serve as cover areas surrounded by openings at some point in the regeneration period. If we assume that, on the average, a cover patch must be at least 600 feet (180 m) wide to be effective for big game (Thomas et al. 1979), the minimum size cutting unit should be about 10 acres (4 ha) and any unit this small should be approximately square. Because big game animals use recently regenerated areas to obtain forage, but generally do not use such areas if they are more than 600 feet from cover, cutting units should be no more than 1,200 feet (360 m) wide. This means that any unit over 30 acres (12 ha) in size should be longer than it is wide, and units approaching 60 acres (24 ha) should be two to five times as long as they are wide.

Optimum cutting units, especially for big game species, would probably fall in the range of 20 to 30 acres (8 to 12 ha) and would be one-and-one-half to two times as long as they are wide. In any case, cutting unit widths should fall between 600 and 1,200 feet (180–360 m). This standard will be met if average length to average width ratios fall within the range indicated by the shaded area in Figure 3. Higher length to width ratios are acceptable if regeneration is to take place over $3N+2$ or more decades, since in these cases cover areas will always be two units wide.

The minimum cutting unit size of 10 acres (4 ha) implies a minimum stand size for application of dispersion objectives. For the timber production emphasis case where stand harvest is required each decade, the minimum stand size equals $10 \times (2N+1)$. For example, if the number of cutting units in a string $(2N+1)$ is 5, then minimum stand size equals 50 acres (20 ha). For the case where stand harvest is not required every decade, the minimum stand size equals 20 acres (8 ha). For the wildlife habitat emphasis case, the minimum stand size equals $10 \times$ Rotation Age. Scheduling of stands smaller than the minimums should be coordinated with adjacent stands.

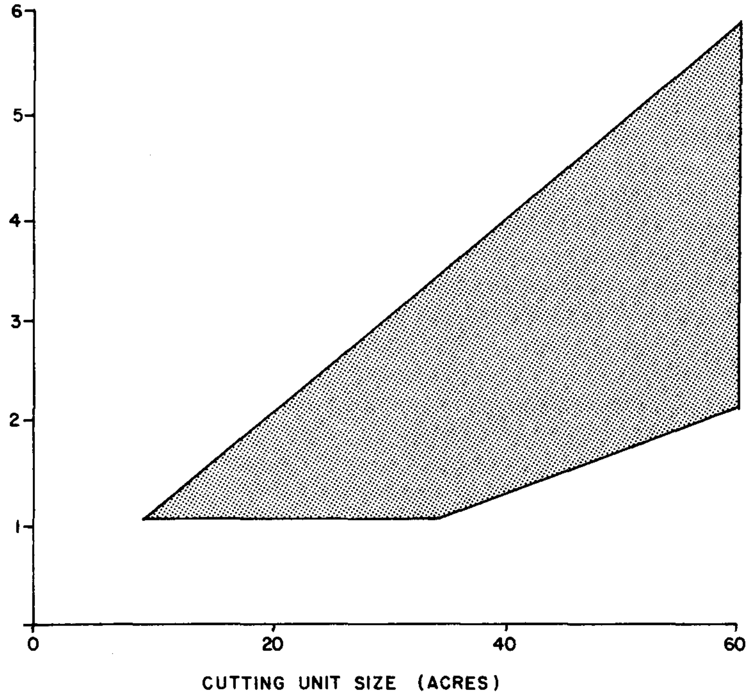

Figure 3. Relationships between size of cutting units and the corresponding shape factors (ratio of average length to average width) that are desirable for big game habitat. Shape factors within the shaded area are desirable where a large stand is to be regenerated in less than $3N+2$ decades (where N is the number of decades required to establish wildlife cover following regeneration).

Required Changes In Multiple Use Timber Harvest Scheduling Models

Inclusion of habitat dispersion objectives in multiple use timber harvest scheduling models used on most large forests requires either a substantial increase in model constraints or a restructuring of model components (i.e., decision variables).

Times of harvest (decision variables) could be developed for each stand, as opposed to grouping similar stands for harvest as was done in the linear program given above, and explicit constraints could link the harvest timing of adjacent stands. Thompson et al. (1973) demonstrated such an approach on the Pocomoke State Forest in Maryland. They recognized "66 separate and essentially homogeneous stands" and augmented a linear program of the type given above with constraints on maximum size of harvests in each stand in each period and the maximum size of harvests in adjacent stands in each period.

This approach has the advantage of making all habitat dispersion requirements explicit, thus enabling measurement of their cost. It has the disadvantage of possibly creating a problem too large to solve. The model created by Thompson et al. had 630 constraints to coordinate the harvest of 60 stands—a fairly large linear program. Most national forests contain 5,000–15,000 separate and distinct

stands. Use of the Thompson et al. formulation could easily result in a problem containing 50,000–150,000 constraints. This would result in a linear program too large to solve on currently available computers.

A second approach fundamentally redefines the model's decision variables. In the timber harvest scheduling model given at the beginning of this paper, basic decision variables were defined as the number of acres of a particular stand grouping (old growth or young growth) to be cut in each period. Except as constrained by even-flow or inventory acreage constraints, the decision of how much old growth to cut in a period was independent of how much young growth was cut and could not assure consideration of habitat dispersion. The second approach defines decision variables as complete harvest schedules (as in Table 1) that contain habitat dispersion objectives for all stands in specific areas or locations. Each decision variable reflects a management emphasis-harvest timing combination over the entire planning horizon. Choices among decision variables become choices among alternative harvest schedules.

Mathematically, this decision problem can be represented (for two watersheds each with two harvest scheduling choices) as:

Maximize: $P_{w1} w_1 + P_{w2} w_2 + P_{x1} x_1 + P_{x2} x_2$

Subject to:

Inventory acreage constraints

$$Z_{w11} w_1 + Z_{w21} w_2 + Z_{x11} x_1 + Z_{x21} x_2 \geqslant T_1$$

$$Z_{w12} w_1 + Z_{w22} w_2 + Z_{x12} x_1 + Z_{x22} x_2 \geqslant T_2$$

Even-flow constraint

$$V_{w1} w_1 + V_{w2} w_2 + V_{x1} x_1 + V_{x2} x_2 = 0$$

where:
- j = any schedule
- i = any period
- w_j = proportion of watershed w assigned to harvest schedule j
- x_j = proportion of watershed x assigned to harvest schedule j
- P_{wj} = net return from assigning watershed w to harvest schedule j
- P_{xj} = net return from assigning watershed x to harvest schedule j
- Z_{wji} = acres of harvest schedule j for watershed w that are mature timber in period i
- Z_{xji} = acres of harvest schedule j for watershed x that are mature timber in period i
- V_{wj} = (maximum volume which could be harvested in period 2 in watershed w under harvest schedule j) − (maximum volume which could be harvested in period 1 in watershed w under harvest schedule j)
- T_i = minimum number of acres of mature timber that must be left uncut in period i

Two types of constraints appear in the problem. An even-flow constraint assures that the timber harvested in period 1 equals the timber harvested in period 2. Inventory acreage constraints ensure that the acres of mature timber left uncut in each period across the forest exceeds some amount. The harvest schedules com-

pete to determine which can most efficiently meet area or forest-wide inventory requirements.

This approach has the advantage of permitting the consideration of spatially feasible harvest choices in mathematical programs that are solvable. It has the disadvantage that the spatial considerations are embedded in the decision variables and, therefore, their costs are difficult to measure.

Overall, the approach can ensure that habitat dispersion requirements are met across time and space. Each decision variable contains a scheduling package that represents a spatially feasible harvest schedule, e.g., a harvest schedule that meets habitat dispersion objectives. These feasible harvest schedules compete to determine which best meets the objective being maximized within the constraints on harvest flow, acreage inventory requirements, and related concerns.

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