

# Optimum Stand Selection for Juniper Control on Southwestern Woodland Ranges<sup>1</sup>

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## Highlight

The optimum time for a land improvement investment when both cost and benefits are changing is when the rate of change of benefits equals the rate of change of costs. This principle can be applied to selecting optimum weed-tree stands for control operations where stands are present in a variety of age classes. If the cost of the control method is fixed, older stands with zero rate of tree cover change represent optimal treatment areas, but if the cost of the control method increases with stand age, young stands represent optimal treatment situations.

A common land management decision involves (1) a situation which will continue to worsen (as evidenced by decreasing productivity or usefulness as time progresses), (2) a corresponding return to some higher level of productivity or usefulness following application of appropriate management practices, and (3) a cost schedule of management practices which often shows that costs will increase as application of the management practice is delayed. The decision to institute new management practices may be made for economic or non-economic reasons; the optimum time of application of the management practice is, in any case, that which results in the greatest benefit:cost ratio. If several stages of developing situations are present at the same time on different management units, the same concepts apply in selection of the optimal management units for treatment.

These principles are readily seen in certain rangelands of southwestern United States. Increases of juniper trees (*Juniperus* spp.) and pinyon (*Pinus edulis* Engelm. and *P. monophylla* Torr. and Frem.) have led to declining forage production and increased ranch operating costs (Arnold et al., 1964; Cotner and Kelso, 1963). Although tree increases are general on pinyon-juniper ranges, a given management unit usually has several stages of stand development represented. The decision for the land manager, therefore, is to select those

tree stands which can be optimally controlled with a given arsenal of control methods. This arsenal includes cabling (a long cable drawn between two large tractors), bulldozing, and individual tree burning. Methods for controlling these weed-tree species have been developed (Arnold et al., 1964; Cotner, 1963; Jameson, 1966; Johnsen, 1966), but no quantitative procedure is generally used to select optimal areas for treatment.

A general procedure using discount theory for calculating the optimum time to practice pinyon-juniper control was developed by Cotner (1963). This procedure requires knowledge of (1) the rate of forage decline due to increases of tree growth, (2) the rate of forage increases following control, and (3) the rate of change of treatment costs.

## Computational Methods

### Rate of Forage Decline

*Tree cover changes of stands.*

Direct evaluation of forage decline due to increases in growth of pinyon and juniper would require repeated sampling for forage production over many years. No such data were available, so existing tree growth data and tree-forage relationships were used in a computer simulation procedure which minimized the needed data. In 1940 a series of plots in the southwestern pinyon-juniper type was established. Two plots of about one-fourth acre each were established at each of 14 locations. Each plot was sampled with 20 randomly located 50-ft transects, using the line intercept method of Canfield (1941). With this technique the intercept of tree canopy along a line is the measure of tree cover. In 1953 these plots were remeasured and an additional 12 plots were measured at seven other locations. The plots ranged from Reserve, New Mexico, on the east, to Peach Spring, Arizona, on the west.

All the plots were remeasured in 1966. Some of the original plots were destroyed by juniper control operations and in these cases the 1953 and 1966 data were unusable. The plots that were first measured in 1953, of course, had data only for 1953 and 1966. Eighteen of the plots had data from only one time period; the other plots had data from both time periods. Stands with few trees had low growth rates as did overmature stands; cover increases were greatest for stands with 10 to 35% canopy intercept. There was no apparent relation between cover changes and any site characteristics. More detailed description of the plots were given in Arnold et al. (1964).

The relationship that is needed for planning juniper control operations is tree cover and time. Change in tree cover was divided by the number of

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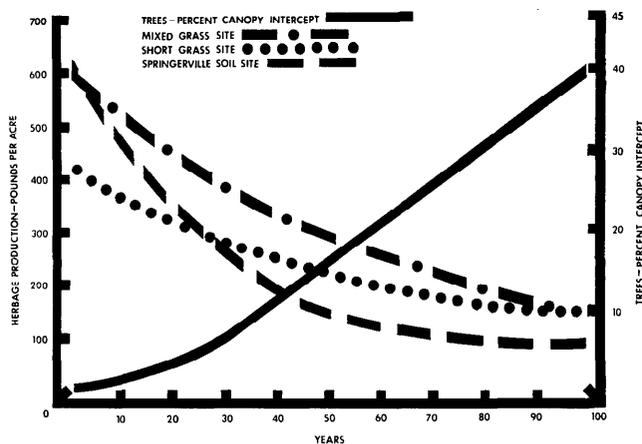


FIG. 1. Average canopy-time and herbage production-time relationships for three sites of the southwestern pinyon-juniper type.

years between measurements to calculate the change in tree cover per year:

$$\Delta C = \frac{C_{i+t} - C_i}{t} \quad (1)$$

where  $\Delta C$  is the annual cover change;  $C_i$  is cover at the first measurement time,  $C_{i+t}$  is the cover at the second measurement time, and  $t$  is the number of years between measurements.

The data on cover changes fell into three populations as follows:

Percent tree cover ( $C_i$ )	Annual cover change ( $\Delta C$ )	
	Mean	Standard deviation
<1	0.1227	0.0879
1-3	.2493	.1173
>3	.4197	.3767

Pseudo-random numbers were converted to normally distributed populations with means and standard deviations the same as the appropriate population of annual cover change. The annual cover change for each year was then added to existing cover to build up cover-time data for a 250-year period. For any year  $n$ , the tree cover was, therefore

$$C_n = \sum_{i=1}^n \Delta C_i \quad (2)$$

Many synthetic cover-time tables were developed to examine the effects of different random samples. An average of 10 of the synthetic stands is presented in Figure 1; many other runs were used to determine the effects of changing various input parameters such as mean annual tree cover change.

#### *Growth patterns of individual trees and individual tree treatments.*

Although costs of some broadcast methods of treatment can be adequately related to a whole-

sale expression of the stand growth such as percent cover, individual tree treatments such as bulldozing and individual tree burning require an accounting of individual trees. Such individual tree data were available for this study (Jameson, 1965). The data consisted of over 500 individual tree heights and crown diameters taken in 1938, 1948, and 1958 at a study plot located 25 miles north of Flagstaff, Arizona. The data represent only one location rather than being spread across the pinyon-juniper type as was the case of the tree cover data, but important aspects of stand changes could nonetheless be evaluated.

One-foot size classes of trees were considered to be states in a Markov chain problem, and transition probabilities from states of year "i" to states of year "i + 1" were computed. For any year i the distribution of tree size classes is

$$x_i = x_{i-1} P \quad (3)$$

where  $x$  is a vector of tree sizes and  $P$  is the transition probability matrix. Synthetic stands for 250-year periods were generated; stands of 20 to 180 trees per acre were included to examine the effect of tree density.

#### *Relationship of forage production and trees.*

As tree canopy increases forage production decreases (Arnold et al., 1964). If midgrasses are originally present they will be replaced by blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud), probably because of competition for moisture between the midgrasses and trees. If the original grass stand is primarily blue grama, the rate of loss of grass production is less because the effect of trees on blue grama is primarily due to the tree litter and much less to competition for moisture (Jameson, 1966, 1970). Some soils of the pinyon-juniper type, specifically the Springerville series, will not support a stand of blue grama when an appreciable tree stand is present. The loss rate for forage production is greater on these soils than for other soils (Jameson and Dodd, 1969).

Herbage production and tree cover data from 186 plots collected earlier (Arnold et al., 1964) were stratified into three groups according to the grass and soil combinations as follows: (1) Mixed midgrass and shortgrass (blue grama) on Springerville series soils, (2) mixed midgrass and shortgrass on other than Springerville series soils, and (3) areas of primarily shortgrass. Overstory-understory relationships were computed using the model:

$$Y = H + A(1 - e^{-bx})^M \quad (4)$$

where  $Y$  is herbage;  $x$  is tree cover,  $H$  is the upper asymptote of the curve and represents herbage production with no trees,  $H + A$  is the lower asymptote,  $b$  is a computed constant that deter-

mines curvature of the line, and M determines the location of the inflection point, if any (Jameson, 1967).

For the three groups of data the equations were:

$$\text{Mixed grasses, Springerville soils,} \\ Y = 614 - 532 (1 - e^{0.098x})^{\frac{1}{2}} \quad (4a)$$

$$\text{Mixed grasses, other soils,} \\ Y = 599 - 686 (1 - e^{0.014x})^{\frac{1}{2}} \quad (4b)$$

$$\text{Shortgrass, } Y = 433 - 322 (1 - e^{-0.036x})^{\frac{1}{2}} \quad (4c)$$

#### *Decline of forage production with time.*

The decline of herbage production with time was computed from the overstory-understory equations of the preceding section and synthetic tree-time relationships for both the tree cover method and the individual tree method (Fig. 1). Loss of forage for any year  $i$ , which will be prevented by treatment, is therefore

$$L_i = Y_{i-m} - Y_i \quad (5)$$

where  $L_i$  is the forage loss prevented,  $Y_i$  the forage at year  $i$ ,  $Y_{i-m}$  the forage at the time of treatment, and  $m$  the years since treatment.

#### **Recovery of Forage Increases Following Juniper Control**

Typical forage production with no trees is about 400 lb. per acre on shortgrass sites (equation 4c) and 600 lb. per acre on sites with mixed midgrasses and shortgrasses (equations 4a and 4b). Locations studied by Arnold et al. (1964) had an average recovery rate of 91.6 lb. per acre per year from time of tree control until the level of forage production without trees was reached. That is, for any year  $i$ , the gain in forage is

$$G_i = 91.6 m \quad (6)$$

subject to the constraint that for blue grama sites

$$Y_{i-m} + G_i \leq H \quad (7)$$

where  $G_i$  is the gain following juniper control,  $Y_{i-m}$  is the forage production at treatment time,  $m$  is the years since treatment, and  $H$  is the maximum production of equation (4). Additional studies have indicated that, although loss rates and total losses are different, similar recovery rates can exist on Springerville sites, other mixed grass sites, and shortgrass sites. In some cases, particularly on the Springerville sites, recovery of forage is retarded by weed growth; to study this condition some calculations were made assuming no recovery of forage.

#### **Rate of Change of Treatment Costs**

Times required for cabling stands developed by equation (2) were calculated from the stand data

for each of the 250 years according to formulas presented by Cotner (1963):

$$\log v = 1.955 + 0.01629c \quad (8)$$

where  $v$  is cabling time per acre in seconds and  $c$  is percent tree cover.

The difference in the time required to treat a stand in two successive years can thus be computed from equation (8) by inserting the appropriate tree cover. Percent of time changes for each year is identical to percent of treatment cost change and an expression of treatment costs in dollars is not required for this study.

Time required to treat these stands by individual tree burning and bulldozing was calculated for each of 250 years by formulas presented by Cotner and Jameson (1959). The time required for burning is:

$$v_x = 0.0303 + 0.015x + 0.001x^2 \quad (9)$$

where  $v$  is time in minutes and  $x$  is tree height in feet. The total time per acre for burning is determined by using the vector  $x$  (equation 3) in the time formula (equation 9). The travel time between trees is:

$$v_f = 0.4204f \quad (10)$$

where  $v$  is time in seconds and  $f$  is distance between trees in feet. Distance between trees was changed by changing the number of trees per acre.

Time required to bulldoze each tree is:

$$v_x = 0.041 - 0.00053x + 0.00058x^2 \quad (10a)$$

where  $v$  is time in minutes and  $x$  is tree height in feet; and travel time between trees is:

$$v_f = 0.5268f \quad (10b)$$

where  $v$  is time in seconds and  $f$  is distance between trees in feet.

Total treatment time  $v$  for both burning and bulldozing cases is  $v_x + v_f$ . As in the case of cabling, percentage treatment time changes of bulldozing are equivalent to percentage cost changes without modification (Table 2). In the case of individual tree burning, however, the cost during burning is greater than the cost of travel between trees because of the expenditure of torch fuel. In the study by Cotner and Jameson (1959) the cost of burning in an individual tree burning operation was 1.779 times the cost of travel in this type of treatment; therefore, burning times were multiplied by this figure to make the two time figures equivalent. Since the computations require only percent of change, rather than actual costs, all other figures in this report are computed without assigning dollar values.

**Computation of Optimum Timing  
for Juniper Control**

For computation of the best time to do a juniper control operation the reader is referred to Cotner (1963). His formula for discounting the future benefits of juniper control is as follows:

$$\begin{aligned}
 PV_{TC} = & \left( \sum_{i=C-1}^R \frac{I}{(1+r)^i} (a_1 i) \right) \\
 & + \left( \frac{I}{(1+r)^{R+1}} \frac{k_1}{r} \right) \\
 & + \left( \sum_{i=C-1}^D \frac{III}{(1+r)^i} (a_2 i) \right) \\
 & + \left( \frac{IV}{(1+r)^{D+1}} \frac{k_2}{r} \right)
 \end{aligned} \tag{11}$$

where:

- PV = present value of flow of "gross" benefits.
- T = time (years).
- C = initial year of control.
- D = years required for site to reach maximum depletion if not controlled.
- R = years required for site to recover full potential after treatment.
- $a_1$  = average rate of recovery from  $T_C$  to  $T_R$ .
- $a_2$  = average rate of depletion from  $T_C$  to  $T_D$ .
- $k_1$  = potential annual gain after full recovery (production at full recovery less production at  $T_C$ ).
- $k_2$  = potential annual loss after full depletion (production at  $T_C$  less production at full depletion).
- $i = 1, 2, 3, \dots, \infty$  (years).
- $r$  = interest rate.

Since the rate of depletion is nonlinear and "full depletion" takes many years, this formula can be made more usable by considering that change is always occurring and portions **II** and **IV** of equation (11), which deal with steady state conditions, can thus be omitted. Only portions **I** and **III** of equation (11) are used to accumulate values of discounted forage production for some given planning period. The average rate of recovery times the numbers of years of recovery ( $a_1 i$ ) is replaced by  $G_i$ , which is the difference between production at the time of control and production at  $i$  years following control. The average rate of depletion times the number of years of depletion ( $a_2 i$ ) is replaced by  $L_i$ , which is the difference between production at the time of control and production that would have occurred at year  $i$  had the control not been undertaken. Terms **I** and **III** can be

combined by adding  $G_i$  and  $L_i$ . The equation for a 50 year planning period then becomes:

$$PV_{TC} = \sum_{i=C-1}^{50} \frac{1}{(1+r)^i} (G_i + L_i) \tag{12}$$

Values of  $L_i$  can readily be computed by using the synthetic stand tables together with the equations for overstory-understory relationships (4a, 4b, 4c). The value of  $G_i$  can be taken to be 91.6 (with the restriction that total production does not exceed  $H$  of equation 4).

With the above information available, selection of the optimum time for a given control operation is that time when rate of change in benefits (discounted at an appropriate rate for an appropriate planning period) is equal to the rate of change of costs. The optimum cover condition is that cover which occurs at the optimum time.

Several parameters, including tree growth rate, the tree-forage relationship, rate of forage increase following recovery, discount rate, number of trees per acre (for individual tree treatments), and length of planning period, obviously could change the predicted optimum time of treatment. To investigate the magnitude of errors that might be introduced by misjudging these parameters, a range of values of each parameter was evaluated in the simulation runs.

### Results and Discussion

The simplest case for evaluation is a fixed cost treatment: the rate of cost change of such a treatment is zero and the optimum time for treatment is that when the rate of benefit change is also zero. This occurs when a stand is mature and the tree cover is no longer increasing. Because future results are also included as well as the present situation, the "no change" condition is approximated when the stands have greater than 25% cover. "No change" stands would be the optimum for treatment with an aerial chemical spray that has a fixed cost regardless of tree cover; but low cost aerial sprays do not presently exist for pinyon-juniper control. Some newer mechanical methods using very large machines appear to be "fixed cost" methods, but cabling, burning, and bulldozing methods reported here are "variable cost" methods.

Results for other methods are influenced by the fact that treatment costs increase, often at an increasing rate, as the tree cover increases with time.

Because of the rapid decrease of forage production with only a sparse stand of trees, the rate of change of discounted value of the forage starts declining with the sparsest stand of trees. The rapid rise of treatment costs and the rapid decline of forage combine to produce optimum timing of variable cost treatment at an early stage of stand

**Table 1. Optimum tree cover (%) for pinyon-juniper cabling for various synthetic stands.**

Synthetic stand number	Optimum cover for control		
	Shortgrass site	Mixed grass site	Springerville site
1	4	6	3
2	6	6	6
3	8	8	4
4	6	6	6
5	4	4	4
6	4	4	4
7	4	5	3
8	5	5	5
9	11	11	5
10	5	6	4

**Table 2. Optimum tree cover (%) for individual tree methods of pinyon-juniper control for various numbers of trees per acre.**

Trees/acre	Optimum cover for pinyon-juniper control	
	Individual tree burning	Bulldozing
20	2	2
40	1	5
60	1	6
80	2	7
100	3	7
120	3	7
140	3	9
160	4	11
180	5	11

development. The number of years required to reach optimum timing was quite variable for the different stand situations studied, and significant changes in optimum time of treatment is introduced when mean annual tree cover change is given different values. The canopy cover at the optimum time, however, was restricted to the range of 3–11% (Table 1). In addition to being more consistent than time, cover is more readily identifiable than stand age under field conditions and is more germane to the management question of selection of optimal stands to treat.

The average optimum stand for control by cabling was about a 6.5% cover for the shortgrass and mixed grass sites. The forage decline on Springerville soils is more rapid, however, and eventually more severe than on the other sites. This gives a faster decline in the rate of change of benefits and accelerated the optimum tree cover for treatment by cabling from an average of 6.5% back to 4.5%. If the “no recovery” situation due to weed growth is assumed, prevention of losses remained as an important factor, but potential increases above that predicted at treatment time were not realized. Protection against future losses thus becomes predominant and the optimum cover for cabling on all sites dropped to 3%. In any case, the optimum situation for cabling is reached only where there are scattered stands of rather large trees; a stand of 4 to 6% cover normally contains many trees that are too small and flexible for adequate cabling. In practice, these optimum stands for cabling have been recognized intuitively by land managers and many have already been cabled.

Optimum cover for individual tree burning was in the range of 1 to 3% for all tree stands of 20 to 180 trees per acre and for all sites (Table 2). Optimum cover for bulldozing, on the other hand, increased with increase in number of trees. For

example, on the shortgrass site optimum cover for bulldozing ranged from 2% with 20 trees per acre to 12% with 200 trees per acre. The other sites showed similar relationships.

Proper stand selection was the most critical for the burning treatment. Treatment of stands denser than the optimum increase benefits but increase costs even more. Treatment of stands with 8% cover rather than the optimum 3% reduced the benefit/cost ratio by 24%. A similar error in stand selection with mechanical methods caused less than a 10% reduction of the benefit/cost ratio.

Different discount rates from 1 to 10% resulted in differences in indicated profitability of treatment from fourfold to sixfold, but had little influence on selection of optimum time (or optimum stands) for treatment. For some synthetic stands, there was actually no difference in optimum cover regardless of discount rate; the average spread of optimum tree cover due to discount rate was about 1%.

Length of planning period was likewise unimportant in determining the optimum cover at the time of control provided that the planning period was 20 years or greater. Planning periods of 5, 10, 20, 30, 40, and 50 years were investigated; the 5- and 10-year periods resulted in about a 1% greater tree stand for the “optimum” condition, but there was no difference in any of the longer periods. The major effect of the shorter planning periods is to emphasize the uncertainty of future benefits; longer planning periods had more stable rates of benefit change.

The results obtained in this study apply to the variable cost treatments that are commonly used for juniper control. If a treatment were available at a fixed cost per acre the treatment would have a zero rate of change of cost for all tree cover. The optimum timing for such a treatment would be when the rate of change of benefits is also zero; in

other words, when the tree cover reaches a maximum and forage production is minimum. Because future benefits are considered as well as the present condition of the stand, a fully depleted state is approximated at about 25% tree cover. At present there is no control method available that can be optimally used for tree stand of 12 to 25% cover; all conceivable methods will optimize with cover either less than 12% or greater than 25%.

### Summary

A representative land management problem is the increase of weed-tree stands on western rangelands which result in losses of forage, and these losses increase with time. The expected benefits from control of these weed-tree species, and the cost of treatment, also increase with time. Tree stand, forage increase, and treatment cost tabulations were simulated by various techniques, and parameters used in these simulations were taken from the literature.

For evaluation of broadcast treatment methods such as cabling, pinyon-juniper cover measurements from 36 plots during the period 1940 to 1966 were used to construct a time-tree cover relationship. This was in turn combined with equations for overstory-understory relationships on these pinyon-juniper sites to give a forage production-time relationship. Similar computations were made for individual tree treatment methods such as individual tree burning and bulldozing from growth records of over 500 trees measured from 1938 to 1958. Annual treatment cost changes also were computed from the same tree data.

Rate of change of future forage production discounted at an appropriate rate can be used to indicate optimum timing and tree cover for juniper control operations. Optimum tree cover for cabling operations was about 4% on Springerville soils and 6% on other sites. In practice, many of the stands in the Southwest most suited for cabling have already been cabled. Many remaining stands in the 4-6% cover class contain many small trees which are not killed by cabling.

Sensitivity analyses pointed out that most of the decision variables to be considered could be

disregarded and general guidelines to optimal practices could thus be established. For individual tree burning the optimum cover for treatment was 1 to 3% and for bulldozing the optimum cover ranged from 2% with 20 trees per acre to 12% with 200 trees per acre. For methods which do not have increasing costs with increasing tree cover, the optimum cover for treatment would be 25% or more.

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