2000: 2nd Interface Between Ecology and Land Development in California
Edited by Melanie Baer Keeley

Age Mosaics and Fire Size in Chaparral: A Simulation Study

Paul H. Zedler[1,2], Leslie A. Seiger[1]

[1] *Biology Department, San Diego State University, San Diego, CA 92182*
Tel. (619) 594-6328; Fax (619) 594-5676

[2] *Present address: Arboretum and Institute for Environmental Studies, University of Wisconsin - Madison,*
1207 Seminole Hwy., Madison, WI 53711
Tel: (608) 265-8018; Fax (608) 265-2993

Abstract. Large fires are a serious problem along the urban-wildland interface of Mediterranean-type shrublands in California. Managers are being urged by some in the research community to base their management on a theory which emphasizes the controlling importance of fuels on the fire regime and the close correspondence between age and propensity to burn (the "fuel/age paradigm"). Arguing from these premises, the deduction is made that fire suppression, by allowing vegetation to form large blocks of burnable vegetation, is the principal cause of the large fires which are presently characteristic of California shrubland landscapes. It has been suggested that management should de-emphasize suppression and reestablish an age mosaic which would return the landscape to a more natural condition in which fire size is constrained by discontinuities in fuels. In this paper we question if the age mosaic postulated in the fuel/age paradigm would be sustained by a pattern of random uncontrolled fires. We use spatially explicit models that incorporate the essential elements of the fuel/age paradigm. We conclude that age-based mosaics following the strict rules of the fuel/age paradigm are a transient phenomenon, and therefore we question if fine-grained age mosaics are characteristic of natural systems and whether they should be the objective of long-term landscape planning.

Keywords: Fire, chaparral, coastal sage scrub, California, cellular automata, fire spread, fire management, fire suppression, landscape mosaic.

Introduction

Fire is the most important non-site factor influencing the chaparral of southern California. Though it has been much studied, there remains considerable disagreement about both historical fire regime and the use of fire as a management tool. One of the most important questions centers on the relation between fire size and fire frequency. This has both historic and current management importance. From a historical point of view, we wish to know if the regional conflagrations that occur today were always a feature of the vegetation dynamics of the chaparral, or if large fires were rare or non-existent before modern fire suppression technology was imposed. Practically and currently, we wish to know if management burning and fire suppression can be used to minimize the probability of large uncontrolled fires while maintaining other desirable attributes of the system such as biodiversity and watershed protection.

We identify two extremes on the continuum of ideas about what controls fire size. One view stresses the importance of weather factors, arguing that although there can be many small fires, most of the acreage of chaparral landscapes burns in large fires that occur under extreme meteorological conditions (e.g., protracted drought followed by high winds and low humidity) when differences in the amount and type of fuel exert minimum control on fire size. Though the age of the vegetation is a factor affecting ignition, the age-fuel loading correlation is weak (Paysen and Cohen 1990). It follows that management actions that burn small portions of the landscape to create a mosaic of age patches are unlikely to provide significant protection against catastrophic fire unless the fire rotation is shortened significantly so that a substantial portion of the landscape is maintained in an early fire recovery stage.

At the other extreme are the fuel based theories which stress the accumulation of biomass over time as the fundamental control on fire occurrence and fire size. For chaparral, the clearest statement of this view is contained in a series of articles by Minnich (e.g., Minnich 1983, 1989, 1995). Similar views, however, are widely held by those concerned with fire management in the western U. S. We believe that this view can be fairly represented by the following propositions and deductions from them:

1) The amount of fuel is the primary variable determining whether or not a fire occurs. 2) The accumulation of fuel is strongly age-related (e.g., Green 1981), so that increasing age inevitably means increasing fuel. 3) A minimum amount of fuel must accumulate before an area will burn, therefore there is a minimum age below which fire is highly improbable. 4) As a consequence of #3, where a diverse age mosaic is present, fires will cease to spread when they encounter areas less than this minimum age. 5) Under primeval (i.e., without humans), pre-European conditions, and today in areas where fire protection is not practiced or is ineffective, ignitions are not limiting, and therefore areas will burn soon after reaching the minimum age of flammability. 6) Because of #4 and #5, if a diverse age mosaic is present, the mosaic will be perpetuated. 7) In contrast, in situations where fire suppression is practiced without compensatory management burning, areas will age beyond the minimum age. More and more of the landscape will move into a burnable condition until eventually fires larger than those possible without suppression will occur. This obliterates the age mosaic and sets up the region for a cycle of recurrent large burns. Thus comparison of landscapes with and without fire suppression show that in a non-suppression landscape fires are more numerous but on average much smaller than those that occur in a suppression landscape (Minnich, 1983, 1989, 1995).

As a consequence of this reasoning, proponents of the fuel/age paradigm urge land managers to reestablish the age mosaic either by abandoning suppression or supplementing it with a burning program that substitutes management burning for natural or unregulated human burning.

Is it possible for an age mosaic operating under the rules of the fuels model to be stable?

This is an important question for managers, because the appeal of the fuels model is that it offers the hope of building a landscape that is immune from very large fires. Because management would be presumed to be working with, rather than against nature. it would seem possible to maintain this immunity with relative ease and low costs. But if the age mosaic is not stable, then something beyond age-based management will be necessary to prevent large fires, such as the establishment of firebreaks, or burning with a frequency significantly higher than that of the recent past, or control on the number of ignitions at times of the highest fire danger.

The implication of the fuel/age paradigm is that a fine-grained age mosaic is the natural condition of a shrubland landscape. There are some empirical reasons to doubt that this necessarily is the case, but this study was motivated by a suspicion that fine-grained mosaics are inherently unstable even under the rules of the fuel/age paradigm, and therefore not likely to be more than a transient condition of shrubland landscapes. This has implications for management because, if a fine-grained mosaic is not a natural tendency, more time and effort will be needed for management to maintain this condition. There is the additional concern that the management necessary to maintain what might be an artificially complex mosaic might bring about changes in the system that would have other unintended negative consequences, such as increasing soil erosion, or a reduction in the abundance of rare species.

The model

We explored the question of stability and persistence of age mosaics with the simplest possible spatially explicit model, a landscape of cellular automata (Green 1997). The model simulated a shrub-dominated landscape composed of a mosaic of shrub patches of different ages and was designed to conform qualitatively to the elements of the fuel-based theory noted above. For heuristic purposes, we examine age boundaries in a two-cell landscape. Questions about age mosaics were explored with a simulated landscape composed of 400 grid cells (20 x 20 cells), the attributes of which were location and age. The model ran in annual time steps with vegetation repeatedly exposed to the possibility of fire within each annual time step. We assumed that there is a minimum age that vegetation must reach before it is capable of burning (MINAGE) and that prior to this age vegetation will not burn, even if exposed to an ignition. Input variables were the number of years to be simulated, the number of ignition events per annual time step (IGNITS), and the minimum age at which a patch has sufficient fuel to carry fire (MINAGE).

At the start of each run, each cell was randomly assigned an age between 0 and 60 years so that every simulation began with an even age distribution. In each year, an ignition event was randomly assigned to an individual cell. If the age of the cell were less than the minimum age at which burning was possible (MINAGE), the ignition event failed. If the age of the cell were greater than MINAGE, it was considered burned and the age reset to zero. There is much anecdotal but relatively few rigorous quantitative data on what actual values of MINAGE might be. Managers seem to think of MINAGE as being in the range of 15 to 30 years, but it is known that chaparral less han 20 years old will commonly burn (Barro and Conard 1991).

Fire spread contagiously from burned cells to all contiguous cells and ceased to spread when all contiguous cells had ages less than MINAGE. This was repeated until the preassigned number of ignition events had occurred, after which the ages of all cells were incremented by one year and the next annual time step began.

We ran the model using different values of MINAGE (10, 20, 30, 40 and 50 years of age) and IGNITS (1, 4, 10, 42, or 100 strikes/year). These latter represented ignition event probabilities of .0025, .01, .025, .1 and .22, respectively. Each simulation was carried out for 500 annual time steps. The simulation was repeated 10 times for each set of conditions using a unique random seed and the results were averaged. A subset of these simulations was carried out for 1000 annual time steps, with five replicate runs.

It is widely recognized that weather affects fire, and we therefore wished to explore the effect of extreme weather on the age mosaic by a set of simulations in which the probability of occurrence of a Santa Ana-type extreme fire danger day (SA) was set at the beginning of the run. Within each one year run each ignition event was assigned either to a “Santa Ana” day with a probability SA or to a “normal” day with probability 1-SA. The effect of extreme weather was simulated by lowering the MINAGE by 5 years, which meant that a greater proportion of the cells could be burned. The probability of these extreme events (SA) was set to 0.02 for all runs.

Results

Persistence of age boundaries – the two-cell landscape.

For purposes of clarifying the behavior of age boundaries, we begin with the simplest possible landscape mosaic, one consisting of two cells A and B of equal size and of age a_A and a_B, in general for the initial condition $a_A \neq a_B$. Thus the boundary between the two cells is an age boundary. MINAGE, following the definition above, is the minimum age at which a fire can be carried. We also assume that each cell has a probability p of being burned in each year. If a fire occurs, and the age is equal to or greater than MINAGE, the cell burns. If the age of the other cell is less than MINAGE, it cannot burn. If it is greater than MINAGE fire will spread into it and both cells will burn.

The state of the age boundary can be followed over time in a graph in which the two axes are the age of the two cells (Fig 1A). With increasing time, and no fires, the system moves along the bold lines in the direction of the arrows (upward and to the right), necessarily parallel to the line of no difference because the cells age at the same rate. MINAGE can be plotted on each axis of this graph to define four sectors. When the system is in the lower left sector, both cells are younger than MINAGE, and neither can burn. When it enters the upper left or the lower right, one but not the other can burn, and if it enters the upper right, both cells would burn because both have ages that equal or exceed MINAGE. When a cell does burn, its age instantly drops to zero, and the system is moved to one of the two axes, or to the origin with the age of the burned cell (or cells) set to zero. This is indicated by the dashed lines, which represent the instantaneous change in age. When both cells burn, both are moved to origin. We use the term coalescence to describe the situation that occurs when two cells of different age burn at the same time, that is, the system moves from $0 < a_A \neq a_B$ to $a_A = a_B = 0$ and the age boundary disappears.

In Fig. 1A, p = 1, meaning that as soon as a cell reaches MINAGE, it is burned and its age set to zero.

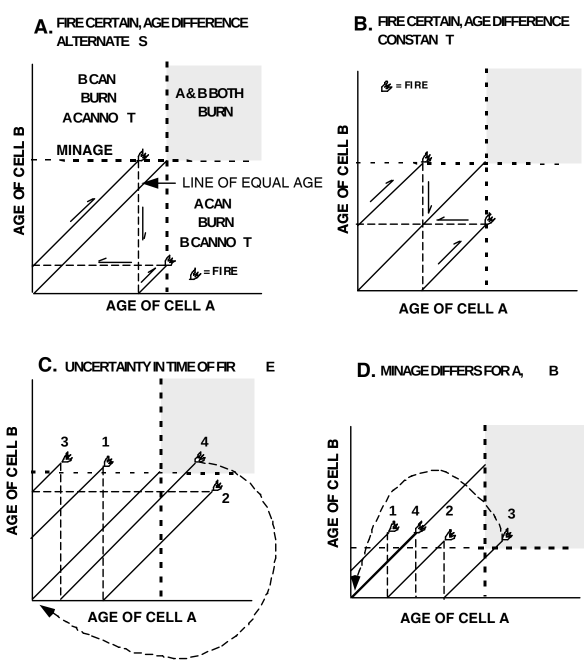

Fig. 1. Behavior of an age boundary in a two-cell landscape. Between fires, the two cells age, moving parallel to the line of no difference or on the line of no difference. When a fire occurs, the age of the burned cell falls to zero -- indicated by the lighter dashed lines. MINAGE, the minimum age at which fire can occur, defines four sectors in the graph space. In the lower left quadrant, when both cells are less than MINAGE, neither can burn. The other three sectors are labeled in A) and described in the text. A) Case where the age difference is asymmetrical and fire is certain. B) Fire certain, but the age difference constant. C) Example of behavior when fire is not certain so that one or both cells can age beyond MINAGE. D.) Example of behavior when MINAGE differs for the two cells. Further explanation in the text.

If the system is launched with either age difference d1 or d2, the landscape will follow the graphed pattern, cycling between the two age differences. It cannot enter the upper right sector. It is possible for the age difference to be unchanged by fire, a situation represented in Fig 1B. It is apparent from the geometry of the graph that this will be the case when d1 = d2 = MINAGE/2 .

If $p < 1$, it is possible for the landscape to enter the other three sectors because when years pass without fire, the cells can age beyond MINAGE. In Fig. 1C, the landscape is burned four times, starting with fire #1. In the first three fires, one of the cells has aged beyond MINAGE, with the result that through time the landscape does not follow a fixed path.

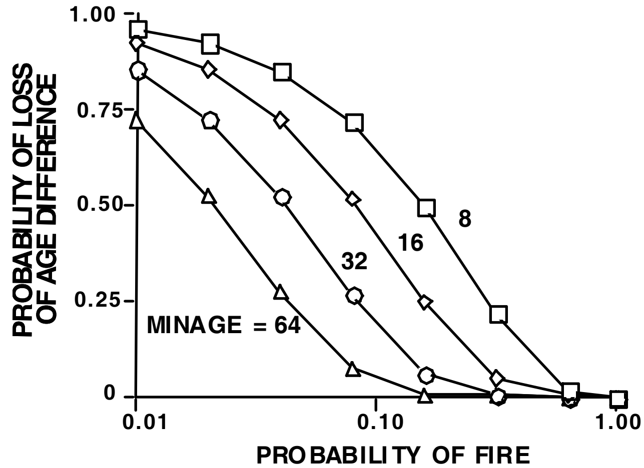

Fig. 2. Probability of the loss of the age difference (coalescence) in the two-cell landscape for the special case of one fire only in a situation like that of Fig. 1. B. Essentially this is the probability, for different values of probability of fire (p) and MINAGE, of the system crossing into the upper right quadrant before being burned. If this occurs, both will burn and their ages simultaneously be reset to zero. This probability decreases with increasing p and MINAGE.

Finally, prior to fire #4, the two cells both age beyond MINAGE, so that when the fire occurs both burn and the landscape is returned to the origin (0,0). In the next period and forever after, the landscape will move up the diagonal line of no difference and return to origin, that is, $a_A = a_B$ is an absorbing condition (Feller 1950). Thus unless $p = 1$, the system must eventually coalesce.

When $p < 1$ and for a given MINAGE the time it takes, on average, for the age boundary to disappear will be a function of the initial age difference along the boundary, and p. From the graphs, it is evident that, on average, starting with an age difference of MINAGE/2 (corresponding to Fig 1B) will lead to the longest persistence. This is because the greatest period of time is necessary to traverse the upper left and lower right sectors. When the initial situation places the system on the lower line of Fig. 1C, the persistence time should be shorter.

Varying MINAGE also changes the time before loss of the age boundary because the average period of time from crossing the MINAGE line to entering the upper right sector will be less when MINAGE is smaller. This can be illustrated for a special case where the age difference is set to MINAGE/2 and the probability of reaching the upper right before the first fire occurs is calculated. This will simply be $(1-p)^n$ where 1-p is the probability in any one year of a fire not occurring, and n = MINAGE/2. Plotting this probability as a function of p for different values of MINAGE (Fig. 2) shows that as the probability of fire approaches 1, the probability of coalescence approaches 0 (as pointed out above); and also that for any given intermediate probability of fire, the probability of coalescence increases with decreasing values of MINAGE.

If MINAGE is different for the two cells the behavior of the system will be different, most interestingly when $p < 1$ (Fig. 1D). This could occur if, for example, dead wood accumulated at different rates on the two sites. Because of the asymmetry, when by chance the system enters the upper right sector and is returned to the origin by a fire, the system is not trapped on the line of no difference, as for the case where MINAGE is equal for both cells. In the example (Fig. 1D) there is a sequence of four fires. The first two occur in the upper left sector, which returns the system to the x axis. The third fire places the system at the origin, that is, the ages of A and B are the same as the cells age along the line of no difference. But the fourth fire takes the system off of the line of no difference, recreating an age boundary.

What this simple example shows is that an age boundary governed by rules that correspond to those of the age paradigm cannot be stable unless it is certain that fires will occur in the year that MINAGE is attained, or equivalently, that ignition events occur in each cell in every year. This suggests that age mosaics in a more realistic probabilistic system are likely to be transient phenomena. They are likely to persist longest when MINAGE is high, and when the age difference in the initial condition is half of MINAGE.

The example also shows that age boundaries can regenerate if MINAGE differs between the cells. This is equivalent to allowing fuel characteristics to be a function of site as well as age. Thus if MINAGE is different on two adjacent sites, age boundaries can reestablish after coalescence.

Age mosaics can persist in a deterministic system. .

From the results of the 2-cell case and simple logic, it is apparent without resorting to simulation that persistence of an age mosaic of any degree of complexity is possible within the rules set out above. This will be the case if a) the maximum age of the vegetation at the onset of the first fire season is equal to MINAGE, and b) each patch, or at least each patch that is at MINAGE receives an ignition event. When these conditions hold, by definition, each year all blocks at MINAGE will burn and only blocks at this age will burn. The vegetation then ages a year, a new cohort of patches reaches MINAGE, these and only these burn, and the original age mosaic can persist forever. The details of the spatial configuration are irrelevant.

The case where the initial mosaic includes patches greater than MINAGE is only slightly more complicated in that there will be a one-year transient condition in which all patches greater than or equal to MINAGE burn in the first year, after which all these patches form a new cohort which will burn in MINAGE years, and the resulting mosaic will then persist forever. If there is a sufficient number of cells greater than MINAGE, then there can be a large fire in the first year and, consequently, at regular intervals every time this large group of cells reaches MINAGE. Thus the persistence of an age mosaic in itself does not preclude large fires.

Persistence of the age mosaic with randomness.

Simulation using the 400 element landscape allows us to follow the changes in the age mosaic for stochastic situations. The single variable of greatest interest is the maximum fire size per year, expressed as the percent of the total landscape. The variation in this statistic over simulated time bears out conclusions reached for the 2-cell case (Fig. 3). Three examples of the transient behavior of the landscape for different values of MINAGE and IGNITS show that in all there is a tendency toward coalescence as evidenced by the fact that the maximum fire size increases over time, starting with the highly diverse mosaic. Further, as expected, increasing MINAGE tends to slow the process (Fig. 3A vs. Fig. 3C). The effect of the probability of fire is shown by comparison of a high rate of ignition versus a low rate of ignition (Fig. 3B

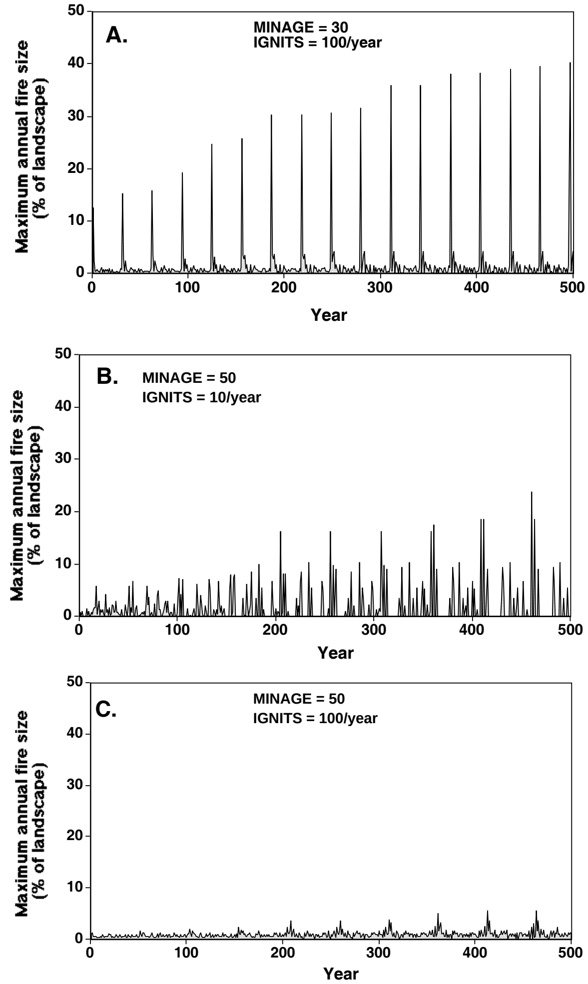

Fig. 3. Transient behavior of the 400 cell model with respect to the maximum size fire occurring in each year. Simulations were run for 500 years. A. MINAGE at 30 with high ignition of 100/year. B. MINAGE at 50 with ignitions at 10/year. MINAGE at 50 with 100 ignitions/year. All three graphs show an increase in the maximum fire size with time as coalescence occurs, but the rate of increase is very slow with a very high MINAGE and a very high rates of ignition.

versus Fig 3C). With a higher rate, there is a lower probability that adjacent blocks of different age will both exceed MINAGE with the subsequent loss of the age boundary when either receives an ignition event.

The time sequences also show a marked periodic behavior, most apparent in Fig 3A. This would be expected according to the rules of the fuel-based model, because as coalescence proceeds, it becomes almost certain that the largest blocks will burn at or soon after MINAGE because the probability of a hit somewhere increases in proportion to the area occupied by burnable cells. To the best of our knowledge, it has never been suggested that this kind of fuel-driven periodic behavior exists in chaparral landscapes, yet it would be expected in a strictly fuel-based system. The exception would be the special case in which the age-size distribution was uniform, and coalescence precluded by a certainty of ignition, as explained above.

The outcome of the 500 year simulations can be summarized to show the effects of MINAGE and IGNITS by displaying the maximum fire size as function of both (Fig. 4). At very low MINAGE, the complex mosaic is substantially lost for all ignition

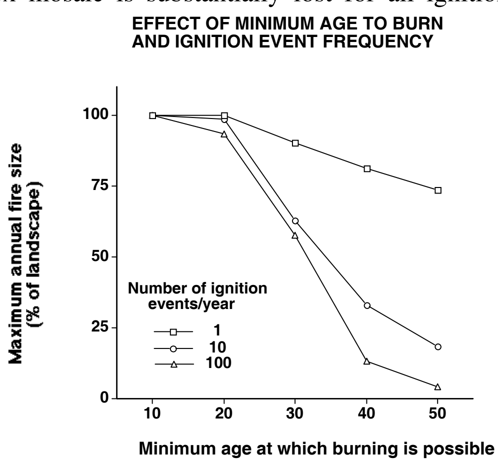

Fig. 4. Maximum fire size in the 400 cell landscape as a function of the minimum age at which burning is possible (MINAGE) and the number of ignitions per year. High rates of ignition and high MINAGE slow the loss of the mosaic.

rates, and maximum fire size becomes very large. With increasing MINAGE, the maximum fire size declines, slowly for low rates of ignition, and more rapidly for high. Thus increasing ignition frequency can sharply decrease the maximum fire size, but only where MINAGE is above 30 years. Recalling that our initial condition is to set maximum vegetation age at 60 years, this result is expected from percolation theory, which predicts that contagion (in our case fire) sharply increases when more than about 60% of the elements of a landscape are susceptible (Stauffer, 1985).

It is apparent from Fig. 3 that there is a tendency toward coalescence for all values of IGNITS and MINAGE, suggesting that the main difference between landscapes with different sets of values is the length of time before coalescence occurs. To confirm this, we ran a subset of the simulations for 1000 years, replicating the runs five times, varying IGNITS and MINAGE. We observed that for all combinations of the parameters, for MINAGE 20 years or less, complete coalescence was observed within the 1000 year simulations (Fig. 5). Where this was the case, maximum fire size is that of the entire landscape. High rates of ignition significantly slowed the minimum time required for coalescence, and more than the 1000 years of the simulation was required for coalescence when MINAGE was greater than 20 for 100 ignitions/yr and greater than 30 for 10 ignitions/yr. This shows that mosaics may disappear slowly, but they do disappear.

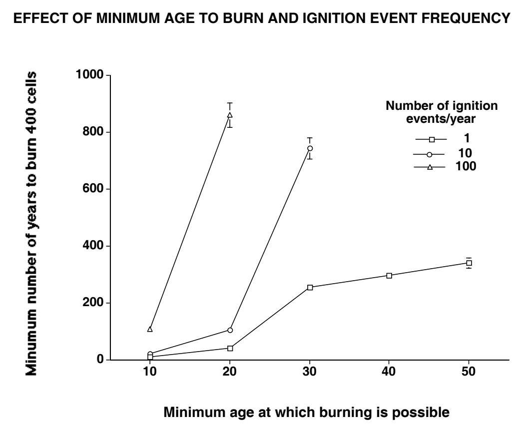

Fig. 5. Minimum time out of 5 runs of the 1000 year simulation for the entire landscape to burn, that is, for complete coalescence to occur. The missing points indicated that complete coalescence was not achieved in any of the 5 replicate 1000 year runs.

Because we believe in the overriding importance of weather, we considered how the occasional imposition of simulated extreme conditions might affect the coalescence process. We imposed "Santa Ana" years in which MINAGE was dropped to simulate extreme weather in which vegetation is burnable at a younger age than usual because of the extremely dry conditions. As expected, moving more cells into the burnable classes increased the maximum annual fire size in the 500 year simulations (Fig. 6).

For completeness, we might have also run a simulation in which weather unusually unfavorable for fire reduced the number of susceptible cells by raising MINAGE. This would, of course have the opposite effect, but could not regenerate elements of the mosaic lost to coalescence.

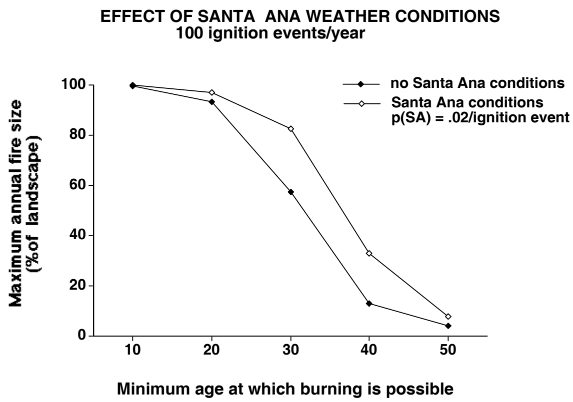

Fig. 6. Effect of introducing severe weather into the simulation model. The method used increases the population of susceptible elements in the mosaic, thereby increasing maximum fire size attained in each 500 year simulation. except where values converge at the entire landscape at MINAGE of 10.

Discussion

The simulation results at face value

We must first acknowledge that our simulation clearly supports one of the major tenets of the fuel/age paradigm, namely that suppression of fires (in our model: reducing ignition events) has the effect of hastening coalescence and therefore leads to an increase in maximum fire size. But our simulation also shows that within the strict confines of a fuel/age paradigm coalescence is inevitable regardless of degree of suppression so long as there is some fire and the probability of a block burning in the year it achieves MINAGE is less than 1. As explained in the 2-cell landscape, this is because failure to burn results in aging which inexorably leads to coalescence, though at variable rates depending on the parameters chosen. Thus within a strict fuel/age model, a fine-grained age mosaic is only a transient phenomenon. We also show that during this transient phase, the landscape will probably have a periodic behavior in acres burned.

We believe that the fuel/age paradigm does not describe the inevitable tendency of a natural system. An age mosaic inevitably fades away and cannot be regenerated without invoking other processes or controlling factors.

Models and reality

Of course our simulated landscape of cellular automata is at best a sketch of the behavior of real fires in real landscapes. Our purpose was to test the validity of the basic elements of the fuel/age paradigm. Our model is simple, but relative to the complexity of nature, we believe that it is commensurate with the fuel/age paradigm. A theory is fairly tested by the simplest system to which it applies.

We also recognize that the conclusions of our simulation can be dismissed on the basis of many *ad hoc* arguments. One avenue of attack was suggested in our 2-cell results which show that age boundaries can persist if the age boundaries are also fuel discontinuities that cause MINAGE to differ significantly across the boundary. The asymmetry of MINAGE offers the possibility of the rebirth of age boundaries to offset their loss through coalescence. But to invoke this goes against the basic assumptions of the fuel based theory. Heterogeneity in fuels is required so that age boundaries will correspond to discontinuities in the rate at which fuels accumulate, or the rate at which flammability develops. This amounts to saying that site as well as age determines the propensity to burn. If the distribution of these site-determined fuel characteristic boundaries is appropriate, it might be possible for a fine-grained mosaic to be stable. If site is important, then differences in fire behavior in different regions cannot be wholly ascribed to differences in management practices.

Specifying such a paradigm-saving modification is easy, but presenting hard data to show that it corresponds to reality would be more difficult. Someone must demonstrate the reality of such boundaries and show that their effect on fire size is as postulated in general, and not just in a few specific instances. If this proves to be the case, it would then be the job of managers to locate the discontinuities and to use them as the boundaries of management burns.

Another simple modification of the fuel model would be to allow fires to stop before reaching the limits of a particular burnable patch rather than inexorably propagating to limits of the contiguous burnable age classes, as in our model. As in the previous case, this would allow a mechanism by which new age boundaries could be created to offset the loss of boundaries by coalescence. But what mechanistic explanation can be given for fires behaving in this way? There could be site-determined variation in fuel characteristics, which makes this essentially the same point as that of the previous paragraph. Or a purely random limit to propagation could be postulated: “Fires will spread in burnable vegetation until they cease to spread.” If weather is invoked to explain such random behavior, the purity of the fuel-based model is lost (appropriately, we believe) and then attention must focus on introducing weather explicitly into the fuel/age model. At a minimum it would be necessary to state: “At any given time, the spread of fire is determined by the meteorological conditions." Then it is the task of the fire managers to demonstrate that although weather is an important control, its capacity in a non-suppression landscape to create new age boundaries within existing mosaic elements offsets the tendency of weather to lead to coalescence in extreme weather conditions.

Comparisons with a more detailed model.

Davis and Burrows (1994) published a far more complex simulation based on the Rothermel fire spread model (Rothermel 1972) that described spatial patterns of fire in chaparral. They parameterized their model with data from a 1865 ha area in Santa Barbara County dominated by *Adenostoma fasciculatum*. Their conclusions that "[the results] conform to the behavior of fire mosaics predicted by ...... Minnich (1983)" and that "... over long time periods (e.g. 500 years) ..... chaparral fire mosaics may behave as quasi-equilibrium systems" appear to contradict our conclusions. We believe, however, that Davis and Burrows were speaking only generally. Their model results do not agree with the expectations of the fuel/age paradigm. Further, it seems to suggest that factors other than age are very important in determining fire behavior.

For example, they note that the average age of vegetation is sensitive to numbers of ignitions, as is the average fire size. With many ignitions, the mean age of the landscape is lower than it is with fewer ignitions. This observation, which seems reasonable to us, violates the tenet of the fuel/age paradigm that regions with and without suppression have about the same recurrence interval (Minnich 1983, 1989).

In Davis and Burrows model, unlike our "pure age" model, factors other than age can stop fires. These include a change in vegetation type, topography, a change in weather conditions, or the presence of an inflammable cover type. As noted above, introducing these complexities would be expected to promote greater age diversity, but owe nothing to a belief in the fuel/age theory. Another contradiction appears in the comparison of fire interval in a modern landscape in which the chaparral is fragmented to that in the more continuous vegetation of the prehistoric landscape. This revealed that the average recurrence intervals were dramatically longer in the modern landscape because isolated patches are protected from fire and can reach great ages. Again, this shows that in a stochastic system average vegetation age is a variable and can be very sensitive to factors other than age.

The quasi-stability they observed is difficult to evaluate. Because we believe that the age-dependent component cannot be stabilizing, we presume that the quasi-stability they report arises from the interactions of the other factors with each other or with age, and not from the age factor itself.

Finally, the model results of Davis and Burrows can be compared to the empirical study of Moritz (1997) of fire size and recurrence in a region not far from the modeled landscape of Davis and Burrow. Moritz could find no evidence that fire suppression in his two study areas had an effect on the size of the largest fires, though it did appear to reduce the frequency of smaller fires. He attributed this to the fact that the largest fires are controlled by extreme climatic events. If such a system can be said to have quasi-stability, it seems very unlikely that the kind of age mosaic expected under the fuel/age paradigm could be an important means by which the variability of the landscape mosaic is constrained. Further, it shows that whether the scattering of small fires expected under a non-suppression situation are present or not, large fires will still occur. This raises questions about how effective artificially produced age mosaics can be in limiting fire size unless they shift average age of the vegetation to unprecedented low levels.

Empirical tests

We believe that our simple model does point the way toward appropriate empirical tests of the fuel based theory. The age-dependent fuel model promises to deliver a landscape which is immune to very large fires. In thinking what this means, a useful simplification is to visualize the landscape at each moment being divided into burnable and not burnable. The age-dependent theory holds that this division corresponds closely to age, with young vegetation being not burnable and old vegetation burnable. It also seems to presume that "old" and "young" is in this context similar for all landscapes, whether subject to stringent societal pressures against ignitions and vigorous suppression, or to a regime of frequent and widely distributed ignitions and less certainty of effective suppression. Moreover, it also holds that the proportion of old-burnable will almost always be a relatively small proportion of the whole. In our terms, the assumption is that MINAGE is great enough to insure that only a small portion (certainly less than about 60 percent, according to percolation theory) will be in the burnable category. This assertion could be tested by a combination of measurements to assess flammability and observations of actual fires to determine the age of the vegetation in which they propagated, the number of age boundaries that they burned over, whether or not they stopped along an age boundary, and the ages on either side of the boundary.

Note that simply observing that fires often extinguish along age boundaries is not a sufficient proof of the validity of the age/fuel paradigm. In our model, in which fire size grows with time and coalescence is inevitable, fires *always* stop along age boundaries. In the transient condition, however, this typically occurs only after one or more age boundaries have been obliterated. Thus for the fuel/age paradigm to hold, what must be shown is that the pattern of burning acts against the coalescence pattern, with each fire on average creating the same perimeter of age boundary as it destroys.

There are also questions about age and fuel discontinuities. Paysen and Cohen (1990) showed that fuel/age correlations are weak. A similar question could be asked about the magnitude of fuel differences along age boundaries as a function of age difference and the youngest age. Obviously there will usually be very large differences where 75 year old chaparral abuts 2 year old chaparral But can one statistically separate 30/50 year boundaries from 40/70 boundaries?--very possibly not.

Another question concerns the change in fuel type. If it were true that the features of our simulation model applied to the real world, then there would be a MINAGE below which fires could not be sustained. Whether or not this were attainable in a natural setting, it would be possible to insure by artificial means that a substantial fraction of the landscape were maintained below MINAGE. This could be done, for example, by a management-imposed rotation in which all stands that exceeded MINAGE were burned each year.

This system would not preclude vegetation from burning, but merely delay burning until young vegetation matures, at which time it would again be capable of burning. In order to maintain a majority of vegetation below MINAGE, MINAGE has to be high so that there is a significant range of ages possible in the unburnable condition, and the probability of ignition would have to be 1 so as to prevent coalescence. That is, control burning would have to be carried out annually wherever vegetation exceeding MINAGE did not burn from natural causes.

Further, the success of such vigorous management is based on the assumption that MINAGE in more natural landscapes and in human influenced landscapes is the same and is not subject to changes that might be brought about by the use of fire. In terms of our model, the assumption is that MINAGE remains constant over the full range of IGNITS. But in the real world there is a significant complication because changing fire regime can also cause changes in fuel type. Specifically, frequent burning can increase the herbaceous component in vegetation which can have the effect of lowering MINAGE to 1 in cases where herbaceous production is sufficient in a single year to carry fire. Thus an attempt to alter the landscape by insuring that a large proportion is below MINAGE for the existing shrub vegetation may shift the system to one in which fire at short intervals is possible (Haidinger and Keeley 1993). How likely this is to occur is probably impossible to predict in theory, but relatively straightforward to observe empirically. For shrublands the question is: how short can a fire rotation be before there is a significant increase in the herbaceous and suffrutescent component? To prevent an increase in herbaceous fuels, at the least, it would seem necessary to allow the vegetation to age until the shrub canopies had eliminated most of the gaps receiving direct sunlight and rainfall.

We doubt that such empirical observations will support the age/fuel theory. Rather, we predict that detailed study will show that even quite young vegetation will burn under the right conditions, and that fire boundaries will be related much more to topography and to changes in weather conditions during the burn than to age boundaries. That is, we expect that study will show that the age mosaic is continually shifting over time with new fires being overlaid on old without much respect to the age of patches.

Forests and shrublands

The age/fuel paradigm is seen by many as relevant beyond Pacific Coast shrublands. There is a clear consensus that fire is sorely lacking in many of the woody plant communities of the western U. S. The arguments in favor of more controlled burns in western forests parallel those made for shrublands. Fires were frequent in the past, they are rare now. Fuels have built up, and therefore there are uncontrollable regional conflagrations (e.g., Dickmann and Rollinger 1998). It seems possible to us that in forests, as in shrublands, there may be the application of a too-simple model to a complex situation, but we set this concern aside and accept that the case for the fuel/age paradigm is more compelling for forests. But does granting this strengthen the case for the applicability of the paradigm in shrublands?

In forests the issues of the vertical distribution of fuels and fuel types looms large. In the past in ponderosa pine forests, it is said, ground fires that were carried in herbaceous and light woody fuels were the rule and stand-replacing crown fires only local. In the present, it is said to be almost the reverse. Shrubs and saplings form dense sub-canopy populations that both suppress herbaceous fuels and provide a bridge by which fires can be carried upward into the canopy (Agee 1993). But in shrublands, no one can claim such a dramatic change in fuel structure and type. In northern Baja California, Mexico, fires in scrub and chaparral typically remove almost all of the living above ground biomass, just as they do in California. Indeed, since vegetation is said to burn at about the same age in the two systems (Minnich 1983), even the intensity factor cannot be markedly different since roughly the same amount of fuel must be consumed. Thus, according to the fuel/age paradigm the choices in shrublands are alleged to be between intense crown fires that burn small areas or intense (or if one prefers, very intense) crown fires that burn large areas.

Of course, as noted above, significant change in fuel type is observed in shrublands, but this is not because of fire exclusion, but a consequence of the introduction of exotic species, or high fire frequency, or both (Zedler et al. 1983; D'Antonio and Vitousek, 1992). Because this kind of conversion is known to occur, it could be a management objective. There would be certain advantages to a grass-dominated landscape. Although fires could still be large, they would not be nearly as intense because there would be less fuel. Despite these advantages, few would advocate such conversion as a regional policy. We emphatically do not.

Living with the land

The conference at which is this paper was presented was concerned with the interaction of development and ecology. Discussion of fire in such a forum is very fitting, because fire is one of the most serious problems along the urban-wildland boundary. Like many others, we propose that the solution to the wildfire problem is to learn to live with it instead of clinging to the idea that we can always manage the forces of nature to suit ourselves. This means keeping our human habitations out of harm's way. In principle, there is no reason that this could not be done. In practice, our society seems very reluctant to accept natural limits and the inconvenience of natural processes.

Literature Cited

Agee, J. K. 1993. Fire ecology of Pacific Northwest Forests. Island Press. Washington, D. C.

Barro, S.C. and S.G. Conard. 1991. Fire effects on california chaparral systems: an overview. Environemental International 17:135-149.

D'Antonio, C. M. and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63-87.

Dickmann, D. I. and J. L. Rollinger. 1998. Fire for restoration of communities and ecosystems. Bulletin of the Ecological Society of America 79: 157-160

Feller, W. 1968. An introduction to probability theory and its applications. Volume I. Third Edition. John Wiley and Sons, New York.

Green, D. G. 1997. Modelling plants in landscapes. Pages 85-96 In M. T. Michalewicz, Editor. Plants to ecosystems. CSIRO Publishing, Collingwood, VIC, Australia.

Green, L.R. 1981. Burning by prescription in chaparral. Pacific Southwest Forest and Range Experimental Station. USDA Forest Service. General Technical Report PSW-51, 36 p.

Haidinger, T.L. and J.E. Keeley. 1993. Role of high fire frequency in destruction of mixed chaparral. Madroño 40:141-147.

Minnich, R.A. 1983. Fire mosaics in southern California and northern Baja California. Science 219: 1287-1294.

Minnich, R.A. 1989. Chaparral fire history in San Diego County and adjacent northern Baja California: an evaluation of natural fire regimes and the effects of suppression management, pp. 37-47. In S.C. Keeley (ed), The California chaparral: paradigms reexamined. Natural History Museum of Los Angeles County, Los Angeles, Science Series No. 34.

Minnich, R.A. 1995. Fuel-driven fire regimes of the California chaparral, In J.E. Keeley and T. Scott (eds), Brushfires in California wildlands: ecology and resource management. International Association of Wildland Fire, Fairfield, Washington.

Moritz, M.A. 1997. Analyzing extreme disturbance events: fire in Los Padres National Forests. Ecol. Appl..7: 1252-1262.

Paysen, T. E., and J. D. Cohen. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. Western Journal of Applied Forestry 5:127-131.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper INT-115. Inter-Mountain Forest and Range Experiment Station, Ogden, UT.

Stauffer, D. 1985. Introduction to percolation theory. Taylor & Francis Ltd., London.

Zedler, P. H., C. R. Gautier, and G. S. McMaster. 1983. Vegetation change in response to extreme events: The effect of short interval between fires in California chaparral and coastal scrub. Ecology 64: 809-818.