Redwoods: A Population Model

Matrix methods may be used to model the growth, survival, and harvesting of California redwoods.

C. A. Bosch

"If you've seen one redwood tree, you've seen them all," said the governor of California. Will the day come when there will be only one redwood? Are we logging the magnificent redwoods of northern California into extinction? These questions concern conservationists the world over, for the redwood exists only in central and northern California. This article will examine some of the factors associated with survival of the redwood, present a mathematical model of their population dynamics, and provide a discussion of the salient data, assumptions, and conclusions. But let us first consider a brief historical and descriptive sketch of these fascinating trees.

Background

"Redwood" commonly refers to two entirely different trees, the Sierra redwood and the coast redwood (*1, 2*). Until 1939, they were thought to be two species of a single genus, *Sequoia.* But in 1939, Buchholz (*1, 2*) concluded that the differences between *Sequoia sempervirens* (coast redwood) and the *Sequoia gigantea* (Sierra redwood) were too great for them to belong to the same genus. So the Sierra redwood was renamed *Sequoiadendron giganteum* (*1*).

The Sierra redwood was discovered in 1833 by the Walker expedition (*2*). These trees grow along the west slope of the Sierra Nevada, between altitudes of 4500 and 8000 feet, the southern limit of their growth belt being in Tulare County. They grow as far north as Placer County, with several of the finest groves in Calaveras County. The Sierra redwood grows to an average height of 250 to 275 feet. The oldest authenticated age for the Sierras is about 3200 years.

Almost all (90 percent) of the Sierra redwoods are in national parks and forests, principally Kings Canyon, Sequoia, and Yosemite (*1*). The only groves on state property are in Calaveras Big Trees State Park. Interestingly enough, the Sierra redwood is commercially undesirable since the wood is too soft and pulpy. Whether there is a correlation between their inferiority commercially and their preservation in parks since 1890 is worth speculation.

The Sierra redwoods are very hardy. Since they are in no immediate danger of either natural or man-made extinction, and are already in parklands, I will not treat them further in this article.

The coast redwood was discovered near San Francisco in 1769 by Gaspar de Portola's expedition (*1*). The trees were named Palo Colorado ("red tree") (*2*). Several years later, Fray Pedro Font of de Anza's expedition wrote a lengthy description of these obviously different trees. On 26 March 1776, Fray Font noted that he had seen "a tree that is certainly beautiful; and I believe that it is useful for its timber, for it is very straight and tall. . . ." Indeed it is! And the placement of coast redwoods in public park lands has been a tough battle during this century.

The coast redwoods grow in the central and northern California fog belt, from the Big Sur area in Monterey County to extreme southern Oregon. The finest stands are in Humboldt and Del Norte counties in California. To emphasize, the species *Sequoia sempervirens* grows in a belt 450 miles long and about 35 to 40 miles wide in northern California, and no other place in the world.

The tallest trees in the world are the coast redwoods in Humboldt County. Their average height is more than 200 feet. The oldest known coast redwood is only 2200 years old, compared to the additional 1000 years of the Sierra redwood. Coast redwoods are extremely hardy. They grow not only from seeds deposited in their cones, but also sprout from stumps and felled trees. Sprouting is often very vigorous. In one location, there were 72 sprouts per stump on the average, and some stumps had more than 100 sprouts (*3*).

Sequoia sempervirens is very valuable commercially. Even the sawdust is profitable, for example, in the form of compressed logs. Some of the old growth timberlands are held by the Arcata Redwood Company (ARCO) (*4*). At the current rate of logging, we will run out of old growth, virgin redwoods in the early 1980's (*4*). ARCO claims they will have old growth timber left until 2010. But at the 1965 rate of logging, no old growth timber (in ARCO lands) will be left by 1984. Bronson (*4*) claims that the real date will probably be 1981 because of the increased rate of logging since 1964. ARCO feels that a balance between harvesting and new growth can be maintained by the end of the century, thus assuring a continuing supply of redwood. But the old growth will be gone.

There is some interest in determining whether redwoods are headed for extinction. It is clear that cutting down the 1000-year-old trees loses them to us forever. Less clear is whether redwoods can be harvested or whether we are in danger of exhausting our supply. The question posed for this article is "Can the survival of redwood populations be modeled, and can meaningful conclusions be drawn from this model?"

The mathematical modeling of biological phenomena is not new. Volterra (1931) and Lotka (1936) both formulated equations to study the stability of populations, the former stressing predator-prey relations. Leslie (*5*) and Lewis (*6*) explored the field during World War II. Leslie's original paper provides an extensive treatise

---

The author, a mathematician, is manager of the Software Analysis and Operations Department at TRW Systems Group, Sunnyvale, California. This article was written in conjunction with graduate studies at the University of Santa Clara, Santa Clara, California.

on the use of matrices to model the growth and stability of homogeneous populations. The theory was extended by Lefkovitch (*7*) to include unequal age groupings. The current state-of-the-art is summarized in such textbooks as that by Pielou (*8*).

The Model

The basic model chosen for this article is a matrix that relates the reproductive and survival characteristics of different age classes of redwoods. In general, if we form k age-classes of redwoods, then

$$M = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1k} \\ s_{21} & s_{22} & \dots & s_{2k} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ s_{k1} & s_{k2} & \dots & s_{kk} \end{bmatrix}$$

is the matrix of coefficients that relates the population at one time point to the population some time later. Thus the k-dimensional vector $N(t)$ is related to $N(t + \Delta t)$ by

$$N(t + \Delta t) = MN(t)$$

In order to make the problem manageable, restrictions have to be placed on k and M. Without a computer, k must be small enough to allow hand calculation. It is generally an excellent idea for M to have constant elements. Thus, the model becomes linear. This is an idealization, since the survival of an age-class generally depends on its size and density.

The behavior of the population can be effectively studied by analyzing the properties of M, in lieu of simply propagating N forward in time. The size of the population at $t + p\Delta t$ can be related directly to the size at t, the reference time. Thus

$$N(t + p\Delta t) = M^p N(t)$$

It is well known (*9*, *10*) that the characteristic values of M, which are unique, establish a set of characteristic or modal vectors. These modal vectors form a basis for a vector field which includes $N(t)$. Thus $N(t)$ can be expressed as a linear combination of the modal vectors $R(i)$,

$$N(t) = \sum_{i=1}^{k} C(i)R(i)$$

Note that there are k vectors R, one for each characteristic value of M (assuming all characteristic values are distinct). Thus, the summation is over the k characteristic vectors. The characteristic values, called λ_j, are the roots of the determinantal equation

$$|M - \lambda I| = 0$$

Now we can write

$$N(t + p\Delta t) = M^p \sum_{i=1}^{k} C(i)R(i) =$$

$$\sum_{i=1}^{k} C(i)M^pR(i) = \sum_{i=1}^{k} \lambda_i{}^pC(i)R(i)$$

since $MR(i) = \lambda R(i)$ (*9*, *10*).

Table 1. Age distribution of redwoods.

Age (years)	Number	Percentage
20 or less	1000	43
20 to 200	696	31
200 to 400	197	9
400 to 600	183	8
600 to 800	105	5
800 to 1000	65	3
1000 or more	17	1

Table 2. Age-class structure.

Age-class	Number	Percentage
1	1696	74
2	485	22
3	82	4

It can be seen that the future size of the population classes is determined by λ and $R(i)$, both properties of M. As a matter of fact, the stability of the population may be found from the set of λ_j alone. If $|\lambda_j| > 1$, then the population grows without bound. If $|\lambda_j| < 1$, then the population component associated with λ_j tends to extinction. If $|\lambda_j| = 1$, we have a stable population.

For the problem at hand, the model chosen is a 3×3 matrix:

$$M = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix}$$

The age-classes chosen are: class 1, 0- to 200-year-old trees (young); class 2, 200- to 800-year-old trees (mature); and class 3, > 800-year-old trees (old). The time increment $\Delta t = 50$ years. Letting N_1, N_2, and N_3 correspond to the number of trees in classes 1, 2, and 3, we have

$$\begin{bmatrix} N_1(t+50) \\ N_2(t+50) \\ N_3(t+50) \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ s_{21} & s_{22} & 0 \\ 0 & s_{32} & s_{33} \end{bmatrix} \begin{bmatrix} N_1(t) \\ N_2(t) \\ N_3(t) \end{bmatrix}$$

The zeros in the matrix arise from the fact that class 3 trees cannot graduate to class 2, and class 1 trees cannot graduate to class 3 directly. The significance of the b_{1j} is that they represent "birth" rates. The s_{ij} represent survival rates. We can now obtain the characteristic values λ:

$$0 = |M - \lambda I| = \begin{vmatrix} b_{11} - \lambda & b_{12} & b_{13} \\ s_{21} & s_{22} - \lambda & 0 \\ 0 & s_{32} & s_{33} - \lambda \end{vmatrix}$$

Expanding the determinant, we obtain

$$0 = (b_{11} - \lambda)(s_{22} - \lambda)(s_{33} - \lambda) - s_{21}[b_{12}(s_{33} - \lambda) - s_{32}b_{13}]$$

which, upon rearrangement, becomes

$$0 = \lambda^3 - \lambda^2(b_{11} + s_{22} + s_{33}) + \lambda(b_{11}s_{22} + b_{11}s_{33} + s_{22}s_{33} - s_{21}b_{12}) + (s_{21}b_{12}s_{33} - s_{21}s_{32}b_{13} - b_{11}s_{22}s_{33})$$

This cubic is solved for specific values in a later section. The next task is to determine the values of the coefficients. Before going on, one should note that the model gives the correct results for at least one degenerate case, namely when there is no reproduction. This means $b_{11} = b_{12} = b_{13} = 0$. Thus, the equation becomes

$$\lambda^3 - \lambda^2(s_{22} + s_{33}) + \lambda s_{22}s_{33} = 0$$

The characteristic values are 0, s_{22}, and s_{33}. Clearly, the population dies out at a rate associated with the survival rate.

The underlying assumptions should also be noted. The model is linear, that is, the coefficients are assumed to be constant. Further, the three age classes are assumed to represent internally homogeneous groups. Better realization might be obtained by making more age-classes and, if necessary, allowing the coefficients to vary with the size of the age-class. There is a trade off between a model so complex as to defy analysis and one so simple that no real conclusions can be drawn from it.

The model could be refined considerably. For one thing, more and smaller age-classes could be used. For example, trees less than 20 years in age produce practically no seeds. That should be a separate class. Sprouting should be included. The possibility of using variable elements in the matrix should be considered. A computer could be used to find the characteristic values of the large matrix. The modal vectors could be determined and analyzed. This, in conjunction with a smaller time interval, would allow more extensive studies of the stability of the individual age-classes. In addition, it would be interesting to attempt an optimization of the harvesting policy.

The Data

Before proceeding, we must obtain reasonable values for b_{11}, b_{12}, b_{13}, s_{21}, s_{22}, s_{32}, and s_{33}. We start by explicitly defining each coefficient: b_{11} is the fraction of class 1 trees produced by current class 1 trees; b_{12} is the fraction of class 1 trees produced by current class 2 trees; b_{13} is the fraction of class 1 trees produced by current class 3 trees; s_{21} is the fraction of class 1 trees that graduate to class 2; s_{22} is the fraction of class 2 trees that remain in class 2; s_{32} is the fraction of class 2 trees that graduate to class 3; and s_{33} is the fraction of class 3 trees that survive. In each of the above, the time interval is Δt.

The finest redwoods are in Humboldt County. A typical virgin stand there had the age distribution of trees shown in Table 1 (*3*).

This should be a good source of data for determining the s_{ij}, since all ages are represented and unnatural interference has been minimal. Table 2 shows the regrouping of data to conform with the three age-classes.

Using a simple approach, one can infer that 22 out of 74 of class 1 trees graduate to class 2. Similarly, 4 out of 22 of class 2 trees reach class 3. Thus $s_{21} = .30$; $s_{32} = .18$.

Based on the age-class sizes and the 50-year interval (Δt), one can deduce the diagonal elements. Since class 1 is a 200-year period, in 50 years three-fourths of the class 1 trees are still in class 1. For class 2, 600 years in duration, the fraction is 550/600. Therefore $s_{22} = .92$ and $b_{11} = .75$, in the absence of new trees (this will be dealt with below).

For class 3, a slightly more involved technique is used. Class 3 is about 1400 years long (assuming that the oldest possible redwood age is 2200 years, the current record). According to the above data, 65 of the 82 trees in this age-class survive the first 200 years, and hence only 17 trees are greater than 1000 years old. We can then assume an exponential decay in the number of trees in this group. Letting n be the number of trees at any time,

$$n = \alpha e^{-k(t-800)}$$

Fitting the data to this model readily yields $\alpha = 82$ and $k = .00787$. So n is given by

$$n = 82e^{-.00787(t-800)}$$

The number of trees left in 50 years is then

$$n(50) = 82(.675) = 55.3$$

Thus $s_{33} = .675$, because that is the fraction of class 3 trees that survive.

The reproductive factors b_{11}, b_{12}, and b_{13} remain to be determined. A special note about b_{11} is necessary. It is the product of the factor determined above (.75) and whatever the reproductive capacity of class 1 trees is. In other words, b_{11} is a combined reproductive and survival factor.

Sequoia sempervirens reproduces in two ways—by seed and by sprouting (*1*). Sprouting seems to be significant primarily in cutover areas. Typically, 8 percent of new trees are sprouts. Sprouts grow out of the root crowns of stumps or felled trees. Their growth and number is sometimes dramatic (*3*). Because of the large variability in the sprouting phenomenon, and because it is not as significant as seed growth in mature stands, I have chosen to ignore sprouting.

Coast redwood seeds are carried in cones, which mature in 1 year. The average cone yields 60 seeds. The capacity of seeds to germinate varies from 1 to 36 percent, depending on many factors, including the age of the parent tree. Temperature and humidity at the time of flowering as well as germination are extremely important. The minimum seed-bearing age for redwoods is about 20 years. The maximum is attained at about 250 years age. Trees are considered mature at 400 to 500 years (*1, 3*).

The number of seeds produced by a tree varies greatly, as might be expected. However, we have to find some average to fit into our model. In one stand, 12 trees produced 2 million seeds; in another, 20 trees produced 3 million seeds. We can calculate an average of 170,000 per tree in the first case and 150,000 in the second (*3*). Thus, 160,000 seeds per tree is not an unreasonable average. About 8 percent of the seeds are sound. An average 10 percent of these are viable (*3*). However, the viability factor varies with age so that we should determine a factor for each age-class.

We know that at 20 years of age, seed viability is about 1 percent. At 1200 years, it is about 3 percent. The maximum 36 percent occurs at 250 years (*3*). Plotting this as in Fig. 1 allows us to select an average for each age-class. The age-classes are indicated and a reasonable average is shown. For class 1, seed viability is about 17 percent, for class 2 it is 20 percent, and it drops to 5 percent for class 3.

We can assume that 160,000 seeds per tree is a good average for all ages except in class 1. Although 74 percent of the trees are contained in this class, only 55 percent are more than 12 inches (1 inch = 2.54 cm) in diameter and bear seeds. Translating this to age means that the only *significant* reproduction in class 1 comes from trees in

Table 3. The reproductive characteristics of *Sequoia sempervirens*.

Class	Seeds per tree	Soundness	Viability	Seedlings per tree	New trees per tree
1	120,000	.08	.17	1632	16
2	160,000	.08	.20	2560	26
3	160,000	.08	.05	640	6

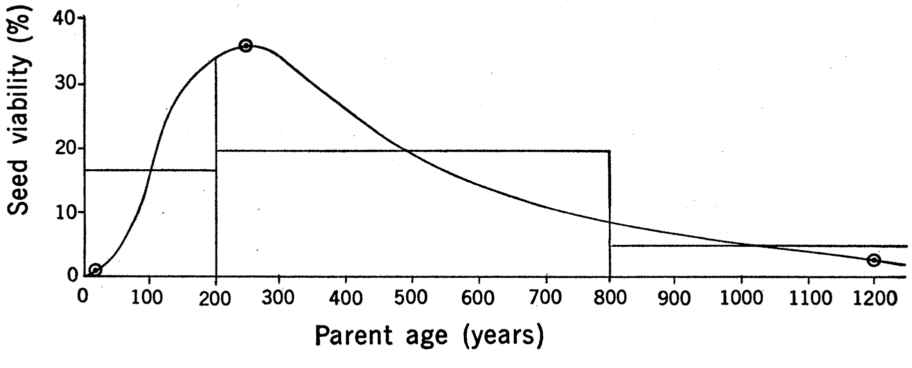

Fig. 1. Seed viability varies with the ages of parent trees.

the 60- to 200-year age subclass. Thus, for class 1, about 120,000 seeds per tree are chosen, representing three-fourths of the total trees.

The survival percentage of seedlings is another variable which is difficult to obtain. Hartesveldt told me that the survival factor for Sierra redwood is about 3.5 percent (*11*). He feels that the factor would be lower for coast redwoods since they sprout (the Sierra redwood does not sprout) as well as seed. He agreed that 1 percent would be a representative number.

These reproductive characteristics are summarized in Table 3. The last column represents the b_{ij}. Only the first number needs to be corrected to account for class 1 survival. Thus $b_{11} = (.75)(16) = 12$. The matrix now looks as follows:

$$M = \begin{bmatrix} 12 & 26 & 6 \\ .30 & .92 & 0 \\ 0 & .18 & .67 \end{bmatrix}$$

There is no question that a great deal of averaging was done to arrive at this matrix. The reproduction of redwoods varies enormously with the mineral content and looseness of soil, with variations in rainfall and temperature, and many other factors. It is the essence of modeling to idealize and simplify, to extract unity, and to reject excessive variability.

Results

The characteristic equation of the foregoing matrix is

$$f(\lambda) = \lambda^3 - 13.59\lambda^2 + 11.90\lambda - 2.49 = 0$$

The form of this was derived earlier. We can make some observations about the roots of this equation. Since $f(0) = -2.49$, and negative λ yields negative $f(\lambda)$, there are no negative roots.

By means of the Newton-Raphson iterative method, we can find any one of the roots. This root is then used to find the corresponding quadratic which can be solved with ease. Suppose the first root to be found is λ_1. Then

$$f(\lambda) = (\lambda - \lambda_1)\,Q(\lambda) = 0$$

where $Q(\lambda)$ is a quadratic in (λ). $Q(\lambda)$ can be determined by straightforward long division.

One of the real roots of $f(\lambda)$ above is $\lambda = 12.67$. The corresponding quadratic is

$$Q(\lambda) = \lambda^2 - .923\lambda + .198 = 0$$

The two roots of this equation are $\lambda = .58$ and $\lambda = .34$. The three characteristic values of M thus are .34, .58, and 12.67. Since one of the λ's is greater than 1, the redwood population will grow indefinitely.

This represents one of the shortcomings of the model. We are clearly not going to be overgrown by redwoods. But the model does not account for the damping factor caused by increased competition among the redwoods. What the result does mean, however, is that, in the absence of harvesting, redwoods will grow in healthy numbers. This is borne out by the qualitative descriptions (*1–3*).

It seems interesting now to construct a new matrix M'. This matrix differs from M in that the survival of seedlings is reduced to 0.1 percent. Thus M' is

$$M' = \begin{bmatrix} 1.2 & 2.6 & .6 \\ .3 & .92 & 0 \\ 0 & .18 & .67 \end{bmatrix}$$

Its characteristic equation is

$$f(\lambda) = \lambda^3 - 2.79\lambda^2 + 1.742\lambda - .251 = 0$$

Again we note that there are no negative roots. Using the same technique as before, one root is $\lambda = 1.973$. The quadratic is

$$Q(\lambda) = \lambda^2 - .818\lambda + .1271 = 0$$

Its roots are $\lambda = .611$ and $\lambda = .206$. Thus, the characteristic values of M' are .206, .611, and 1.973.

This looks more stable but there is still healthy growth projected, as evidenced by $\lambda = 1.973$. This reinforces the qualitative statements made by many authors that you just cannot keep redwoods down. Redwoods are amazingly hardy and adaptive trees. One of the principal functions of a follow-up study should be the verification of the survival and reproductive data used in this article.

The propagation of a typical population distribution is indicated next. Using the Humboldt stand cited earlier, we have

$$N(t) = \begin{bmatrix} 1696 \\ 485 \\ 82 \end{bmatrix}$$

Thus

$$N(t+50) =$$

$$\begin{bmatrix} 12 & 26 & 6 \\ .30 & .92 & 0 \\ 0 & .18 & .67 \end{bmatrix} \begin{bmatrix} 1{,}696 \\ 485 \\ 82 \end{bmatrix} = \begin{bmatrix} 33{,}491 \\ 956 \\ 142 \end{bmatrix}$$

using M. To compare, using M' gives

$$N(t+50) =$$

$$\begin{bmatrix} 1.2 & 2.6 & .6 \\ .30 & .92 & 0 \\ 0 & .18 & .67 \end{bmatrix} \begin{bmatrix} 1696 \\ 485 \\ 82 \end{bmatrix} = \begin{bmatrix} 3349 \\ 956 \\ 142 \end{bmatrix}$$

We next consider harvesting. Suppose that half of all the trees are harvested except for trees more than 800 years old. Then M takes the form M_h:

$$M_h = \begin{bmatrix} 6 & 26 & 6 \\ .15 & .46 & 0 \\ 0 & .09 & .67 \end{bmatrix}$$

The characteristic equation is

$$f(\lambda) = \lambda^3 - 7.13\lambda^2 + 3.18\lambda + .68 = 0$$

This has one negative root, $\lambda = -.1574$, The corresponding quadratic is

$$Q(\lambda) = \lambda^2 - 7.29\lambda + 4.33 = 0$$

Its roots are $\lambda = .655$ and $\lambda = 6.63$. Thus the characteristic values of M_h are $-.1574$, .655, 6.63.

Even if survival rates were cut in half, redwoods would still survive and flourish. However, once the majestic old trees are cut down, hundreds of years must elapse before we can marvel at them again. If the lumber companies will content themselves with younger trees, however, there would seem to be hope that everyone may benefit.

Summary

The chief conclusion to be drawn from the results of this study is that redwoods are amazingly vigorous. The results support both the lumber companies and the conservationists. There is no question that old growth giant redwoods must be preserved. Only commercial greed could be a basis for refuting that stand. On the other hand, the lumber companies seem to be supported in their contention that redwoods can be farmed without driving them to extinction. The central issue revolves around the old trees. And here profit is the big factor.

Lumbering is an important industry in California, and redwood lumbering represents about 20 percent of the industry (*1*). Most of the big names in timber, such as Weyerhaeuser and Georgia-Pacific, are involved in logging the California redwood. At the current rate of logging, particularly of old growth stands, the Bank of America estimates that employment in Humboldt County will be down significantly by 1975 (*4*). It has been argued that tourism would more than compensate for the lower employment in logging. But not if the trees that the tourists come to see are gone. Why can't young and mature trees be harvested at a reasonable rate, the old trees saved, and both tourism and logging flourish?

The question posed earlier has been answered. Redwood growth and survival can be modeled, using matrix methods in a new context. Meaningful conclusions may be drawn. And the results are sufficiently tantalizing to inspire further research.

References and Notes

1. "The Redwoods of California" (Resources Agency, Sacramento, Calif., 1964).
2. N. B. Drury, *Amer. Forests* **75**, 24 (1969).
3. D. F. Roy, "Silvical Characteristics of Redwood (*Sequoia Sempervirens*)," *U.S. Forest Serv. Res. Pap. PSW-28* (1966).
4. W. Bronson, *How to Kill a Golden State* (Doubleday, Garden City, N.Y., 1968).
5. P. H. Leslie, *Biometrika* **33**, 183 (194[illegible] *ibid.* **35**, 213 (1948).
6. N. A. Lewis, *Sankhyā* **6**, 93 (1942).
7. L. P. Lefkovitch, *Biometrics* **21**, 1 (1965).
8. E. C. Pielou, *An Introduction to Mathematical Ecology* (Wiley-Interscience, New York, 1969).
9. R. A. Frazer, W. T. Duncan, A. R. Collar, *Elementary Matrices and Some Applications to Dynamics and Differential Equations* (Cambridge Univ. Press, London, 1960).
10. I. S. Sokolnikoff and R. M. Redheffer, *Mathematics of Physics and Modern Engineering* (McGraw-Hill, New York, 1958).
11. R. Hartesveldt, Department of Biology, San Jose State College, private communication.
12. I thank Mrs. Madeline Bosch, the Save-the-Redwoods League and Mr. DeWitt, the Sierra Club and Mr. Robinson, Mr. Cramer Adams of the California Redwood Association, and Dr. Glenn Moffat of Foothill College, Los Altos Hills, California.

The General Scientific Association: A Bridge to Society at Large

William Bevan

A major concern of this meeting, as with many gatherings of scientists these days, is the apparent disaffection of society in its several segments from the scientific enterprise. Federal expenditures for scientific education and research have leveled off. The scientific community's influence in Washington has declined. Science graduates are experiencing difficulties in finding jobs for which they have been trained. Student interest has swung toward the humanities and toward the traditions of intuition and mysticism. The general public is apprehensive that science is responsible for many of our current environmental problems and fears that even greater untoward effects will follow in the wake of future scientific advances. Newspapers and magazines are replete with observations that some food additives appear to be toxic, that plastics have become hard-to-eliminate mountains of refuse, and that psychological principles are potential means of thought control.

Why the Problem?

There is a complex of reasons for this current state of affairs. First of all, it has resulted, in part, from certain long-ingrained attitudes in the practice of science. Our emphasis on excellence in individual performance has fostered a psychology of elitism that has made both our enterprise and our body of knowledge esoteric and increasingly inaccessible to the layman at all levels of society. Where the artist has chosen to illuminate commonly shared truths, the scientist has chosen to become the master of the highly specialized fact and to proclaim its overriding importance. But the line between high priest and villain is often a fine one, and the public's deference has been tempered by distrust. The comic-strip stereotype of the mad (that is, evil) scientist still emerges from time to time in the layman's thinking about us.

Furthermore, we have persisted in the view that science is value-free, and we have displayed only minimal interest in the several uses of scientific knowledge and their consequences. But one need only observe the keen competition that exists among one's colleagues in the pursuit of discovery, or hear their anguished cries as the shifting of research funding follows the waxing and waning of particular fields, to hold suspect the widely proclaimed neutrality of science. Indeed, one need only compare the distribution of funds within the scientific community at any particular time to recognize that values influence the behavior of scientists.

Finally, the preoccupation with the primacy of creativity in individual investigations has prompted a circumscribed perception of the implications of one's scientific work and a tendency to ignore opportunities for research that bridges the free-ranging interests of basic science, on the one hand, and the practical requirements of technology, on the other. Just as we are inclined to denigrate the task of applying science, so we tend not to seek out fundamental problems in applied settings.

In addition, we scientists have failed to comprehend the significance of certain basic characteristics of individual and collective human behavior. People are apprehensive about things they don't understand, for they rightly perceive that they cannot control what they do not understand. Examples abound. One from a less emotionally charged era of several years back is the controversy over fluoridation. Just as the layman will fear things he does not understand, so will he be impatient with things he considers to be irrelevant. We may conjecture about the current diminution of public interest in space science. There is, of course, the tedium of essentially perfect precision. I suspect, however, that the real reason is reflected in the remark of a television personality who recently wondered aloud whether or not those moon rocks were all that important. But if the man in the street has been faced with an increasingly esoteric science, the lay leadership, particularly that at the federal level, has become

---

The author is publisher of *Science* and Executive Officer of the AAAS. This article is adapted from a speech given on 22 March 1971 at the annual meeting of the National Research Council.