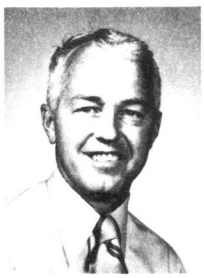
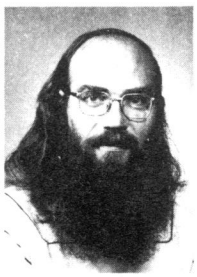


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Pesticide residue dynamics in a forest ecosystem: a compartment model

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ABSTRACT
This paper presents a computer model of the movement of pesticide residues in a forest ecosystem. As such, the paper deals primarily with the potential direct effects on target and nontarget organisms, but does not address the very long-term consequences of restructuring the vegetation in an ecosystem. Simulations using the model trace the movement of two herbicides (2,4,5-T and picloram) through two different environments, one typical of an Oregon forest and the other typical of southern California chaparral. The model is written in DYNAMO.

INTRODUCTION

Man is committed to the management of quasi-wildland systems such as forests. Management practices, to be successful, must be carried on economically and must operate within the bounds imposed by the biological constraints of the managed system. Biological systems at the ecosystem level are complex and heterogeneous. All the subtleties are not known; yet we need a basis for predicting the impact of proposed management practices, if only in terms of characteristic responses. The information needed for understanding ecosystem responses is best obtained through systems analysis. We have used this approach in an iterative process. The model is first structured on the basis of known information, and then is successively modified in the light of information obtained from experimentation. Data from simulation runs at each stage of development suggest particular real-world experiments to perform to obtain data for improving the model. In this paper, we present a model of pesticide movement in a forest ecosystem. So far, the model has been improved by one round of experimentation, but, like all models of large-scale biological systems, it does not represent a complete data set.

Pesticides are commonly used in wildland management and have proven to be both an effective and an economical means of controlling pests. Most are applied aerially at low rates. However, only a small percentage of the material is taken up by the target organism.[1] The remainder, or residue, then moves through the system as directed by the interactions of the physical-chemical properties of the pesticide and by the biota and physical environment of the ecosystem. Pesticides may reside in the environment for widely different periods of time after application. For example, DDT (dichlorodiphenyltrichloroethane) is known to persist for 10 years in some forest environments,[2] but an herbicide such as diquat (6,7dihydrodipyrido[1,2-*d*:2',1'-*c*]-pyrazinediium ion) is totally inactivated three days after application.[3] There is a growing need to understand the indirect and more subtle effects of pesticide residues on nontarget organisms as wildlife management intensifies and new pesticides and strategies for their use are developed. The need for this understanding extends far beyond knowing the relative persistence of pesticides in particular environments.

The simulation model presented in this paper describes the movement and persistence of two well-known herbicides commonly used in brush control on forested lands: 2,4,5-T (2,4,5-trichlorophenoxyacetic acid) and picloram (4-amino-3,5,6-trichloropicolinic acid) Herbicides are a major class of pesticides and are used for selectively killing weed species, thereby promoting growth of a crop plant. Generally, herbicides are much more innocuous than insecticides, and the probability that the proper use of registered chemicals will result in undesirable side effects is minimal. However, insecticides do not usually interact with the vegetation; therefore, a model of effects of insecticides alone would not be useful for studying the general problem of pesticides in the environment. By using herbicide behavior to structure the model, the substitution of an insecticide can be easily accomplished, although the reverse would not be possible.

Picloram and 2,4,5-T are quite different in their physical-chemical properties, their reactions with plants, and their persistence in the environment.[3] Generally, 2,4,5-T is less toxic to plants and less persistent in the environment than picloram. For example, Norris found 85% degradation of 2,4,5-T, but only 14% degradation of picloram, in forest litter in 120 days.[4] For a more complete review of the behavior of these herbicides, see appendices C and D in Reference 5.

Our objective was to use systems analysis and its "work horse," computer simulation, as the most efficient way to study and understand our problem – a problem with, seemingly, an infinite number of variables that would be prohibitively expensive to study with field investigations alone. Our working objective, the one from which we generated criteria for rejection or inclusion of information into the model, was to simulate the dosage of chemical that nontarget organisms would experience from an aerial application. The dosage, or combination of degree and duration of exposure, is well correlated with the response of organisms to foreign substances, as toxicological studies have shown.[6] Our aim was to generate a model output that would be a useful guide for judging the impact of pesticides on nontarget organisms and that would provide realistic estimates of the dosages nontarget organisms would receive in field applications of various pesticides. This information would provide valuable input data for appropriate toxicological studies.

We have structured the model to be as general as possible so as to encompass many kinds of ecosystems and types of chemicals. We also have structured the model so that parameters can be measured with commonly used techniques. Therefore, interested scientists can program the model to simulate specific instances of pesticide movement with a minimum amount of restructuring of the model.

STRUCTURE OF THE MODEL

Movement of a pesticide through an ecosystem after a deposit from an aerial application is characteristically a "cascading" process. The material passes from the forest canopy to the forest floor and then into the soil. Feedbacks are essentially nonexistent. Biomass (organic materials) moves through the ecosystem in much the same way. If an herbicide is applied, the transfers of biomass are often dependent on the effects of an herbicide on the vegetation.

To determine pesticide concentrations in the biomass in selected compartments into which the model of the ecosystem is divided, biomass and herbicide dynamics have been separated into two major submodels (see Figure 1). Movement of both pesticide and biomass is controlled externally by two environmental variables, precipitation and temperature. Some transfers are implicit in the inherent interaction of the species with the climate. Other transfers are the result of the killing action of herbicide on target vegetation. Compartments in both submodels represent a spatial average for a particular ecosystem.

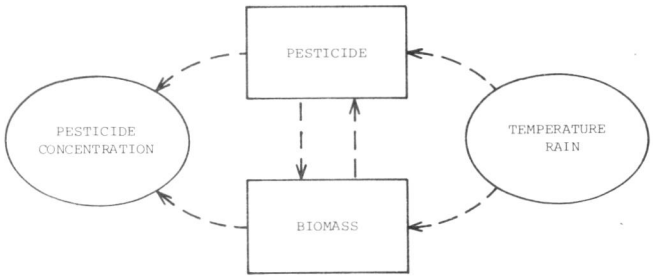

Figure 1 - Generalized compartmentation of pesticide and biomass submodels. Dotted lines represent information transfers that control internal movement of pesticide and biomass.

The herbicide submodel for the simulation study discussed here has fourteen compartments, which are listed in Table 1. These compartments represent two species in the vegetation complex, named the primary and secondary species, which can occupy space in the same horizontal plane or in two different planes. Four compartments represent the important litter layer and the soil. The unit of the state variable for herbicide concentration is milligrams of chemical per square meter of soil surface.

The biomass section has six compartments, which also are listed in Table 1. Four of these represent the foliage biomass of the two species in the herbicide section and two represent the litter. The unit of the state variable for biomass is milligrams of dry-weight biomass per square meter of soil surface.

Table 1
List of compartments for both the pesticide and the biomass submodels

Pesticide compartments	Symbol
Primary leaf surface	HPLSUR
Primary leaf interior	HPLINT
Dead primary leaf surface	HDPLS
Dead primary leaf interior	HDPLI
Secondary leaf surface	HSLSUR
Secondary leaf interior	HSLINT
Dead secondary leaf surface	HDSLS
Dead secondary leaf interior	HDSLI
Stem surface	HSTSUR
Litter, L layer	HLIT
Litter, F-H layer	HFH
Soil, A-1 layer	HA1
Soil, A-3 layer	HA3
Biomass compartments	
Litter, L layer	LMASS
Litter, F-H layer	FHMASS
Primary leaf biomass	PLMASS
Primary dead leaf biomass	PLDEAD
Secondary leaf biomass	SLMASS
Secondary dead leaf biomass	SLDEAD

The connectivity of the model is shown in Table 2. The herbicide section has 33 transfers out of a possible 156, or a connectivity of 21.2%. The connectivity in the biomass submodel is slightly lower at 16.7% (5 transfers out of a possible 30).

The interaction of the two submodels occurs at several points. It is worthwhile to illustrate two of these. In the first, the concentration of herbicide in the litter is calculated by dividing the amount of herbicide in the litter (mg/m^2) by the litter biomass (mg/m^2), expressing the result in parts per million (ppm). A transfer of herbicide into the litter may or may not be accompanied by a corresponding biomass transfer into the litter, e.g., sprayed leaves falling to the litter as compared to rainfall washing the unused herbicide off the leaves and onto the litter. Similarly, a transfer of biomass into the litter is not necessarily accompanied by a transfer of herbicide, e.g., second-year foliage dropping in the autumn season.

In another interaction between the biomass and herbicide submodels, the concentration of the herbicide in the foliage is computed from both the amount of herbicide that has been absorbed into the leaf-interior compartment and the biomass of the foliage. This is an important control that regulates the amount of foliage killed, which then determines the transfer of dead foliage to the litter.

DESCRIPTION OF THE MODEL

A major objective was to structure the model with enough flexibility so that the same structure could be utilized for a variety of pesticides and forest systems. For this reason, the model is very mechanistic and detailed. Transfers are related to well-known processes that occur within the structure of the vegetation, such as absorption from leaf surface into the leaf interior, as well as transfers between different entities in the system, such as from the upper forest canopy to the litter on the forest floor. Losses from the compartments are associated with processes such as volatilization to the atmosphere or decomposition to an inactive compound.

An explanation of the compartments and processes of the herbicide transfer follows. The amount of material applied to the system, or the simulated rate of field application, is specified. A computational process distributes the chemical to various compartments in the system. Thirty-five percent of that applied is lost through drift; the remainder is intercepted on the primary foliage, the stem surfaces of the primary foliage, the secondary foliage surfaces, the undecomposed layer of the litter ("L" layer), the decomposed layer of litter ("F-H" layer), and the first layer of soil, the A-1 horizon. The computational process is general to the extent that interception is proportional to the amount of intercepting surface. If a particular biomass compartment is empty, the sprayed material passes to the next compartment in which it can be intercepted. For example, if a recent fire had removed the primary and secondary foliages and most of the

Table 2

Connectivity matrices for both the pesticide and biomass submodels. Nonzero elements (X) show pesticide or biomass transfer from row compartments to column compartments (after Patten[7]).

PESTICIDE SECTION

	HPLSUR	HPLINT	HDPLS	HDPLI	HSTSUR	HSLSUR	HSLINT	HDSLS	HDSLI	HLIT	HFH	HA1	HA3
HPLSUR													
HPLINT	X											X	X
HDPLS	X												
HDPLI		X											
HSTSUR													
HSLSUR	X		X										
HSLINT						X						X	X
HDSLS						X							
HDSLI							X						
HLIT	X		X	X	X	X		X	X				
HFH	X		X		X	X		X		X			
HA1	X		X		X	X		X		X	X		
HA3												X	

BIOMASS SECTION

	PLMASS	PLDEAD	SLMASS	SLDEAD	LMASS	FHMASS
PLMASS						
PLDEAD	X					
SLMASS						
SLDEAD			X			
LMASS		X		X		
FHMASS					X	

L layer of the litter, an herbicide application to control resprouting vegetation would be intercepted principally by the F-H layer and by the soil layer if the F-H layer did not completely cover the soil.

Chemical material intercepted by the leaf surfaces is either lost from the surface or transferred to the leaf interior via the process of absorption. Losses from the leaf surface are broken down into two processes, volatilization, which is temperature dependent, and washoff, which is related to the precipitation pattern. When the applied chemical is an ester, hydrolysis changes the ester to an acid. The model assumes that this change is completed within one day. Only the ester is considered volatile and only acid is considered soluble in water (only it can be easily washed off by rain).

Transfer from the leaf surface to the leaf interior (leaf absorption) is a donor-controlled process, and there are two transfer coefficients, one each for the ester and the acid. The rate of absorption of the ester was assumed to be four times the rate assigned to the acid form. Chemical material washed off the leaf surface to the litter layer is a function of the precipitation rate. The rate that the ester is washed off the leaves is considered five percent of that for acid. Chemical transferred to leaf interior is often metabolized to an inactive form by the plant. This loss rate is a function of the amount of chemical in the leaf interior and temperature. Any translocation from the leaf interior to the rest of the plant is treated as a loss from the system.

The toxicity of different herbicides (the internal concentration required to kill the leaf) varies widely for a given species. The lower-threshold concentration is defined as that at which some kill begins to occur. From this threshold up to the maximum value where 100 percent of the foliage is killed, the percentage of kill is assumed to be linearly related to the increase of internal concentration. When the leaf is dead, this change of state is represented by chemical transfer to a corresponding dead-leaf compartment. The material in dead-leaf surface and dead-leaf interior compartments is ultimately transferred to the litter compartment. The rate of transfer is dependent upon a specified delay function that simulates dead leaves remaining on the branches for a period before they fall to the litter.

The material deposited on the stem surfaces is lost or transferred to the litter in essentially the same manner as that from the leaf surfaces.

In the L layer of the litter, losses are caused by either temperature-dependent volatilization of esters or microbial breakdown, which is also temperature dependent. Transfer from the L layer to the F-H layer occurs as litter is broken down and changes state from undecomposed to decomposed. Transfer of chemical from the L layer to the F-H layer also occurs as a result of leaching.

Losses from the F-H layer are largely the result of microbial degradation. Transfer to the A-1 soil horizon comes as a reclassification or change of state from litter to organic matter in the soil. Transfer also occurs as a result of leaching and is therefore proportional to the precipitation rate, although the transfer coefficients between the L and F-H layer and between the F-H layer and the A-1 soil are different. Material entering the A-1 soil compartment is lost from the system as a result of microbial activity. The transfer to the next soil layer, the A-3 horizon, is only weakly related to precipitation, as most of the chemical is not available for leaching because it is adsorbed onto exchange sites of the soil particles. Losses from decomposition by microbial activities in the litter and soil compartments are controlled by temperature.

As the dynamics of the biomass transfers are closely intertwined with the herbicide dynamics of a particular ecosystem, a somewhat smaller submodel of biomass was developed. In this system, two species were specified. Either can be considered as deciduous or evergreen, and the two can be either a dominant-subordinate pair with regard to their position in the canopy, or they can be codominate species. Only the foliage biomass per unit of soil area is necessary for the model. Leaf fall proceeds as the phenology (interaction of plant and climate) of the species requires. In evergreen species, the percentage of leaf-fall per day is constant throughout the year. For deciduous species, there is leaf drop at a particular time in the year, usually in the autumn for temperate-zone species.

The total litter biomass is separated into two compartments, the L layer, which is identified as the raw litter that is not decomposed, and the F-H layer, which is decomposed to the point of having lost its original identity. In the L layer, the turnover rate (loss from this compartment) is dependent on temperature. Two-thirds of the biomass is lost by microbial respiration and one-third is transferred to the F-H layer. Biomass is not traced in the underlying layer of soil. For each biomass compartment, the initial conditions (the biomass of the standing crop) is specified according to the data from the site to be sprayed.

The air-temperature function used in this model is composed of several sinusoidal components: the mean daily temperature, the daily temperature range, and the daily temperature excursion. The first two components have a period of 360 days; the third component has a period of one day. As an example, the three components for one study area are:

$$\text{(mean daily temp)} = 10 + 8 \sin(2\pi(t - 105)/360)$$

$$\text{(daily temp range)} = 7 + 2 \sin(2\pi(t - 105)/360)$$

$$\text{(temp excursion)} = \sin(2\pi(t + 0.125)$$

The air temperature function is

$$\text{(air temp)} = \text{(mean daily temp)} + \text{(daily temp range)}\ \text{(temp excursion)}$$

In these equations, temperature is in degrees centigrade and time is in days after noon of January first. The temperature parameters for these simulations have been derived from monthly average maximum and minimum temperatures. Litter temperature is approximated as having 10% of the daily air-temperature excursion. Soil temperature is assumed to have a negligible daily excursion. These temperature functions can be represented as

$$\text{(litter temp)} = \text{(mean daily temp)} + \text{(daily temp range)}\ \text{(temp excursion)}/10$$

$$\text{(soil temp)} = \text{(mean daily temp)}$$

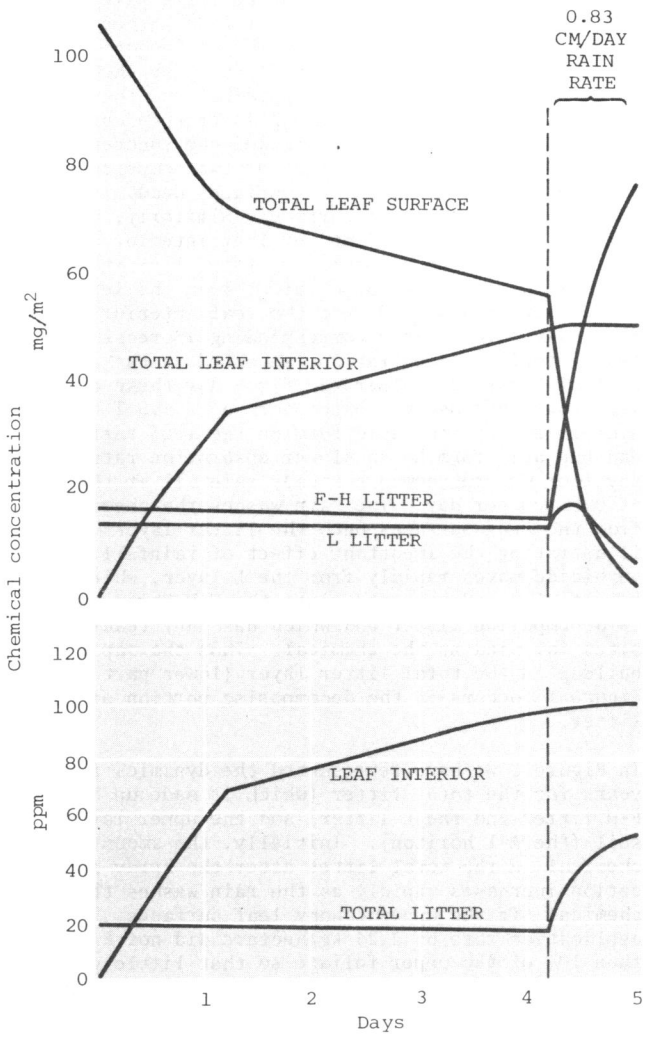

Figure 2 - Simulations of short-term dynamics of 2,4,5-T in a red-alder stand after an aerial application of 2.24 kg/hectare

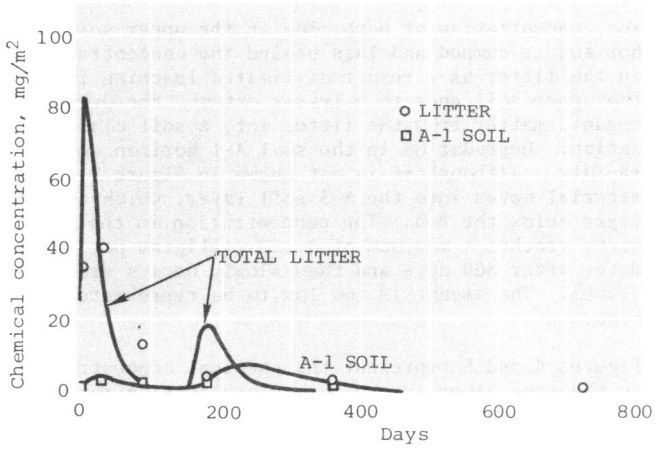

Figure 3 - Simulation of long-term dynamics of 2,4,5-T in a red-alder stand after an aerial application of 2.24 kg/hectare. Data in Figure 2 are means of nine observations.

The model includes the effect of temperature upon biological degradation processes, such as those occurring in the litter layer. Temperature coefficients derived from the temperature functions have unity value at a temperature of 20°C and change by a factor of 2 for every 10-degree difference in temperature.

$$(\text{temp coef}) = 2^{(T - 20)/10}$$

PARAMETERIZATION

Parameter values such as transfer coefficients and empirical constants ideally should be taken from measurements representing a time-series for each compartment. Detailed information such as this is not usually available for large-scale models. For this simulation, many coefficients for transfers and losses from compartments of the foliage were derived from individual studies reported in the literature. Where no studies have been undertaken, estimates were provided by scientists actively engaged in this field of research. When lack of information was considered critical, small experiments were designed and carried out. For instance, an experiment established the relation between precipitation rate and the washoff of herbicides from the leaf surface and the ensuing transfer to the litter.

The best data was from field studies of 2,4,5-T and picloram residues in the litter and soil. This work was done by the US Forest Service and encompassed several sites extending from the mild, wet climate of northwest Oregon to the hot, dry region of southern California (personal communication). In some instances, these studies spanned two years and provided excellent data from which to derive parameters for the litter and soil compartments. They also provided needed information for adjusting parameters representing chemical dynamics in the foliage compartments. The technique of adjustment was after Patten where, essentially, the input to the litter and soil was the output of the behavior in the canopy foliage.[7]

Base values for losses and transfers were determined for 2,4,5-T. As the behavior of different herbicides can be described with similar processes, it was not necessary to restructure the model for picloram. Instead, the base values were changed with ratios that reflected differences in the rate of loss or transfer of picloram relative to 2,4,5-T. Other chemicals can be programmed in the same way.

Precipitation and temperature data were taken from weather stations near the residue study sites and were used in determining the parameters of the functions representing these two independent variables. Initial estimates of biomass were obtained from values given in the literature for the study sites. As the simulations did not cover more than 800 days, the biomass remained fairly constant and the minor changes that actually may have occurred will not invalidate the output of the simulation.

DYNAMO

The model was programmed in DYNAMO, a simulation language that utilizes different equations. We used time steps of 0.1 day, and simulations were characteristically less than two years.

OUTPUT

The output can be varied by changing any number of a wide range of ecosystem state variables, herbicide variables, and the temperature and precipitation regimes. We chose four specific examples for simulation, and their outputs are illustrated in Figures 2 through 9. The results of each simulation are

shown by a pair of figures, one covering the first five days and the other covering a period of two years. Only the outputs of particular interest are shown.

The simulations represent two types of habitat or ecosystems. One is a pure stand of red alder of the type commonly found in northwest Oregon. Herbicides are often used to reduce this weedy species to allow the conifers in the understory to survive. The other habitat is in southern California and is a 3-year-old chaparral system that is recovering from a wildfire which removed all vegetation. At the dense alder site, we have simulated 2,4,5-T for two spray applications, one application at 2.24 kg/hectare, or two pounds per acre, which is the nominal rate, and the other at 22.4 kg/hectare, which is a high and seldom used rate. At the same site we have also simulated picloram at 2.24 kg/hectare. At the southern California chapparal site we have simulated consequences of applying 2,4,5-T at 2.24 kg/hectare. In all, we have simulated two ecosystem types, two chemical concentrations of a particular herbicide, and two different chemicals at a given concentration.

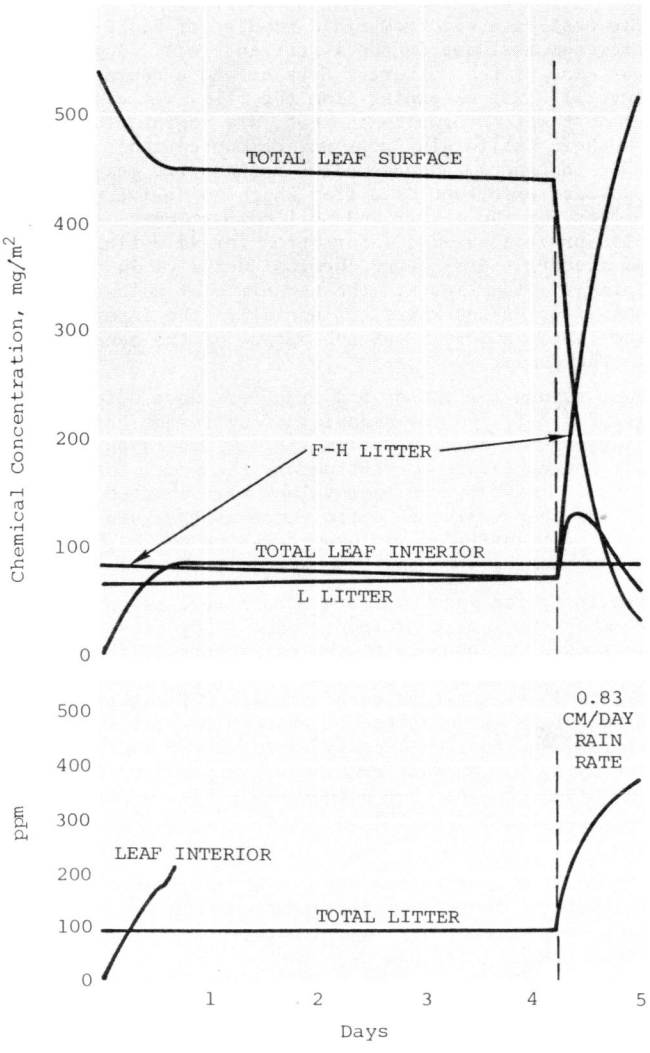

Figure 4 - Simulations of short-term dynamics of 2,4,5-T in a red-alder stand after an aerial application of 22.4 kg/hectare

Figure 2 shows what happens in the first five after a spray application of 2,4,5-T at 2.24 kg/hectare on a mature red alder stand in northwest Oregon. We see that immediately after the spray, the chemical is distributed among the leaf-surface and the litter layers, with the majority being intercepted by the alder canopy. (In this figure and the succeeding ones we have lumped the output of two compartments, leaf surfaces alive and leaf surfaces dead, into one compartment, total leaf surface. Similarly, we have lumped the two compartments of leaf interior, alive and dead, into one compartment, total leaf interior.) There is a rapid loss of chemical from the leaf surface as it is absorbed into the leaf interior in the first day. There is a corresponding increase in the leaf interior concentration, as noted in the lower part of Figure 2. After the first day these changes are slower because the ester form of 2,4,5-T has been hydrolized into the acid form on the leaf surface, and the acid form has a slower absorption rate. At day four we programmed a steady rainfall at the rate of 0.83 cm per day. The rain washes the chemical from the leaf surfaces onto the litter layers, illustrating the important effect of rainfall. The herbicide moves rapidly from the L layer, which is essentially undecomposed, into the F-H layer, which is decomposing litter and which has many reactive sites for binding the chemical. Thus the rapid buildup in the total litter layer (lower part of Figure 1) occurs in the decomposing portion of the litter.

In Figure 3 we have represented the dynamics for two years for the total litter (which is made up of the F-H litter and the L litter) and the upper layer of soil (the A-1 horizon). Initially, the amount of chemical in the total litter after the spray application increases rapidly as the rain washes the chemical off the upper canopy leaf surfaces. The application rate of 2.24 kg/hectare did not kill more than 10% of the upper foliage so that little chemical is transferred by herbicide-killed leaves falling into the litter. The second surge of chemical accumulation in the litter in Figure 3 is a result of the autumn leaf fall of the deciduous alder. The chemical decays rapidly after the leaf fall, but somewhat more slowly than the initial degradation rate because of lower temperatures in the late autumn and winter.

The concentration of herbicide in the upper soil horizon is damped and lags behind the concentration in the litter as a result of limited leaching into the upper soil and, to a lesser extent, the decay of organic matter from the litter into a soil classification. Degradation in the soil A-1 horizon occurs rapidly. Although it is not shown in Figure 2, some material moves into the A-3 soil layer, which is the layer below the A-1. The concentration in the A-3 layer reaches a maximum of 0.128 milligram per square meter after 360 days and then slowly decays from the system. The amount is too low to be represented in Figure 2.

Figures 4 and 5 represent the chemical concentrations in the same alder system for an application rate of 22.4 kg/hectare, or ten pounds per acre. (Note the scale difference between Figures 2 and 4, and between Figures 3 and 5.) At this high concentration, all the leaves are essentially killed before the end of the first day because the interior concentration in the leaf has exceeded the concentration required to kill the most resistant leaves. Therefore until the fourth day no transfers occur and the system is

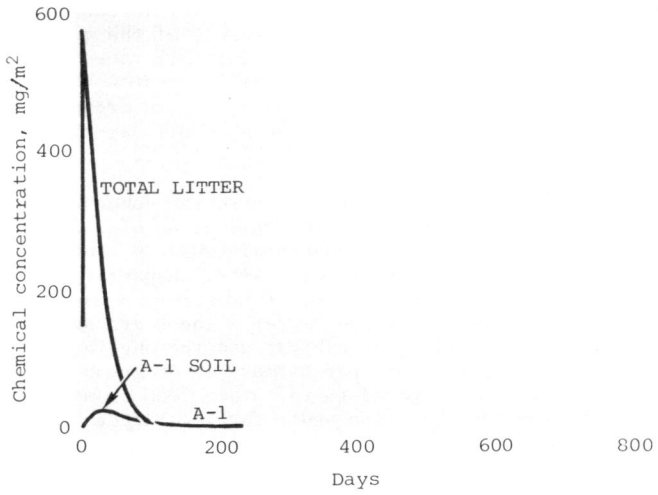

Figure 5 - Simulation of long-term dynamics of 2,4,5-T in a red-alder stand after an aerial application of 22.4 kg/hectare

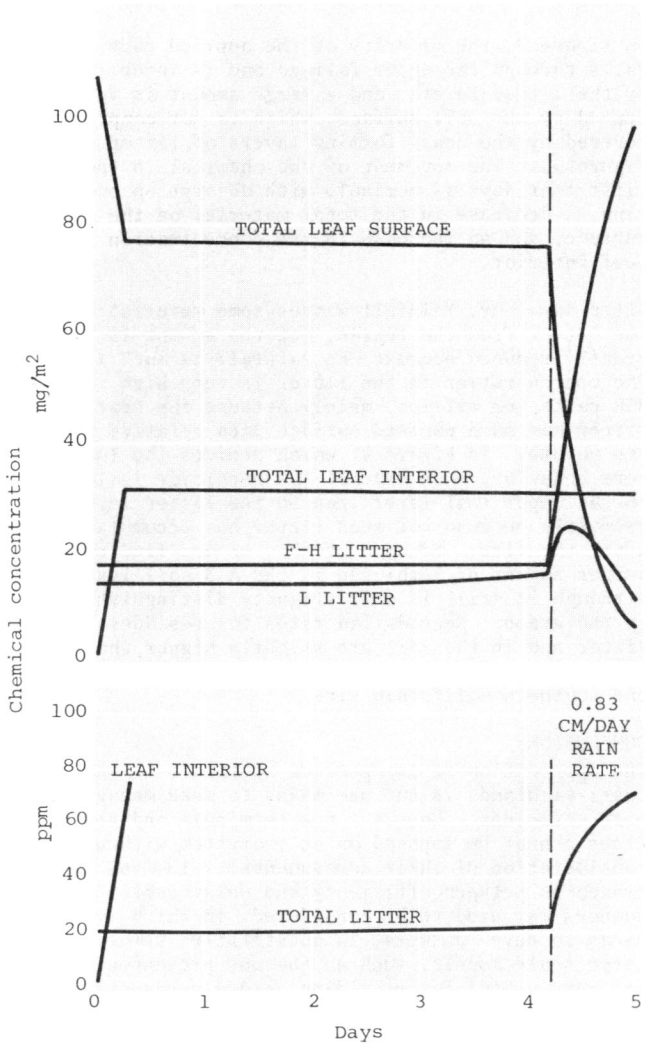

Figure 6 - Simulations of short-term dynamics of picloram in a red-alder stand after an aerial application of 2.24 kg/hectare

essentially nonresponsive. This is because the dead leaves will not fall immediately but "hang" and fall later. The concentration in the leaf interior is undefined after the first day because, once the leaves are dead, there is no live biomass on which to base a leaf-concentration calculation. After day four the system is responsive to the programmed rainfall rate, which is the same as for Figure 2.

The long-term behavior of the chemical concentrations for the 22.4 kg/hectare rate, illustrated in Figure 5, differs from the behavior for the lower application rate, Figure 3, in that the secondary surge of chemical into the litter that occurrred at the lower application rate at day 180 does not occur. All of the leaf material that would fall normally in the autumn of the year has already entered the litter layer, because it fell in the days immediately after the chemical kill. Again, as in Figure 3, there is rapid decay of the chemical in the litter because of microbial action in the warm summer months.

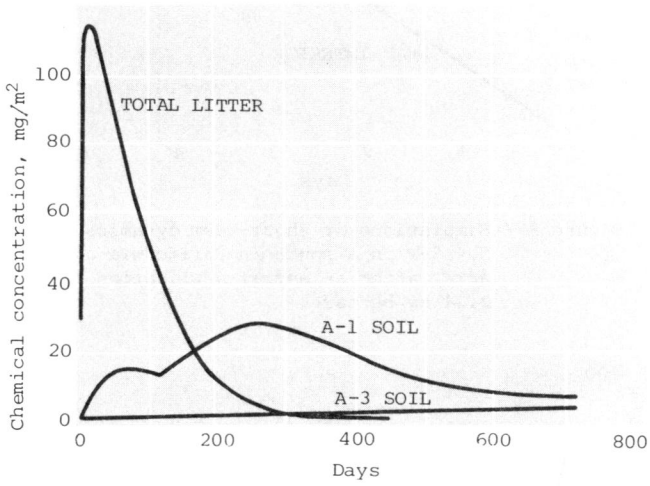

Figure 7 - Simulation of long-term dynamics of picloram in a red-alder stand after an aerial application of 2.24 kg/hectare

In Figures 6 and 7, we have represented the concentrations of picloram applied at 2.24 kg/hectare in the same red-alder stand. Picloram is much more active than 2,4,5-T, and 2.24 kg/hectare results in leaves being killed within the first day. This is primarily because of faster absorption into the leaves and the higher toxicity of picloram. After the killing action the system is nonresponsive until after day four when the rain washes the picloram off the dead leaves. During this period the changes are only slightly different from those in Figure 2 for the corresponding 2,4,5-T application at 2.24 kg/hectare. The amount of picloram in the litter is increased slightly over 2,4,5-T because more picloram is available for washoff onto the litter, as absorption stops when the leaves are killed during the first day. This did not happen with 2,4,5-T because 90% of the leaves were not killed and 2,4,5-T was absorbed continually during the four-day period.

In Figure 7, we see that the long-term behavior for picloram is considerably different than for either application rate of 2,4,5-T. The first peak of chemical concentration in the litter is essentially the same as that in Figure 5 for 22.4 kg/hectare of

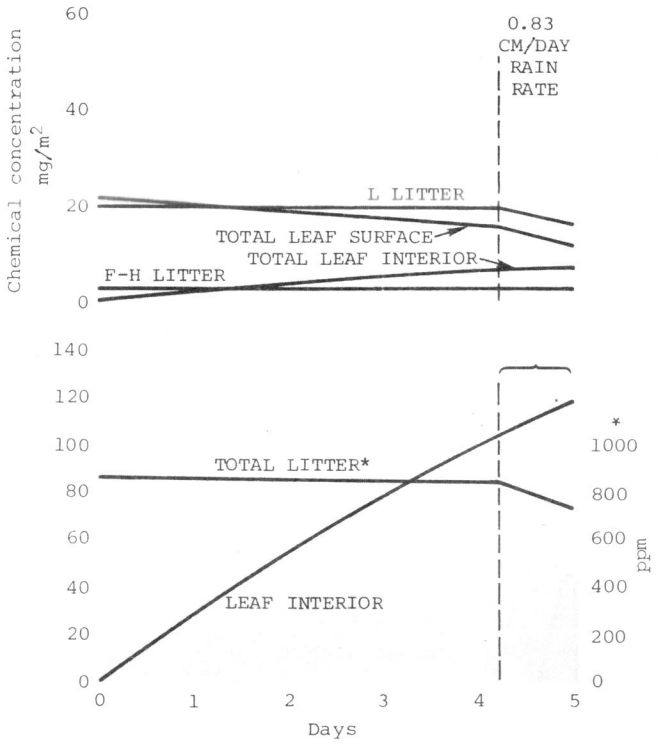

Figure 8 - Simulations of short-term dynamics of 2,4,5-T in a southern California chaparral after an aerial application of 2.24 kg/hectare

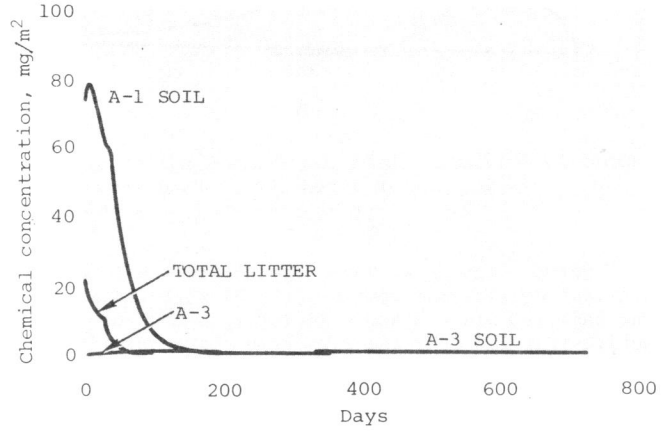

Figure 9 - Simulation of long-term dynamics of 2,4,5-T in a southern California chaparral stand after an aerial application of 2.24 kg/hectare

2,4,5-T, after normalizing to eliminate the difference in application rate. There is no secondary peak as in Figure 3 for 2.24 kg 2,4,5-T per hectare because all the leaves normally falling in the autumn have been killed and have fallen during the summer months. The decay of picloram from the litter is much slower than the decay of 2,4,5-T, principally because the degradation rate has been found to be about 0.2 that of 2,4,5-T.[4] There is considerably more picloram in the A-1 soil horizon, again because this chemical degrades more slowly in the litter and because picloram is more soluble and leaches more readily than 2,4,5-T. The discontinuity in the output at day 110 is essentially a result of the computer program, which changes the rainfall rate in the autumn abruptly by a factor of 5 to match the monthly changes that occur at this site in Oregon. Some picloram has moved into the A-3 soil layer; this does not normally happen with 2,4,5-T.

In Figures 8 and 9 we have simulated the concentrations of the herbicide for an application of 2.24 kg/hectare of 2,4,5-T in chaparral brush in southern California. On this particular site, chaparral occupies the site three years after wildfire has removed all vegetation and litter. There are several differences between this habitat and the one in northwest Oregon. The leaf biomass is 60 grams per square meter as compared to the alder-leaf biomass of 500 grams/meter^2. The newly forming litter layer is 26 grams/meter^2 compared to 1,560 grams/meter under the red-alder stand. The rainfall rate in southern California averages 36 cm per year. For northwest Oregon the annual rate is 151 cm per year. Temperatures are quite different. The annual mean in southern California is about 15°C compared to 10°C at the Oregon site. All these differences between habitats result in a marked change in the movement of 2,4,5-T residues in the southern California example.

In Figure 8, the majority of the applied chemical falls through the upper foliage and is intercepted by the litter layers, and a large amount is intercepted by the soil surface, which is not completely covered by the newly forming layers of litter (see Figure 9). The movement of the chemical in the first four days is nominal, with absorption occurring, a decrease in the total material on the leaf surface, and an increase in the concentration in the leaf interior.

After day four, rainfall washes some material into the litter from the leaves, but the amount is greatly reduced because the rainfall is much lighter. The concentration in the litter is very high, around 850 parts per million, mainly because the sparse litter has much exposed surface area relative to its volume. In Figure 9, which depicts the long-term behavior, much more of the herbicide is located in the upper soil layer than in the litter layer, primarily because not much litter has accumulated after the fire. Because of this we are finding a larger amount of herbicide in the A-3 soil layer, although it still is only slightly distinguishable in the graph. Degradation rates for residues in the litter and in the soil are slightly higher than for the Oregon cases due to the higher temperature at the southern California site.

CONCLUSIONS

The application of inexpensive chemicals to manage quasi-wildlands is but one means to make management more efficient. However, new chemicals and new practices cannot be imposed on an ecosystem without prior consideration of their consequences. In many instances tradeoffs between efficiency and unfavorable consequences may need to be considered, in which event one needs to have "answers" in quantitative terms. Large-scale models, such as the one presented here, are very useful for providing needed perspective, but in general they cannot provide reliable quantitative data. At this time, the major contributions of large models are to structure research and to place priorities on the experimentation that ultimately will lead to models that will yield quantitative data on which one can evaluate tradeoffs.

The model presented here is a mix of empiricism and theory. Its major contribution is the consideration, on a somewhat crude scale, of the interaction among normal seasonal changes of an ecosystem, the action of herbicides on rudimentary ecosystem functions, and the effect of the physical environment on the movement of chemical residues. Opportunities for supplementing this model are, seemingly, unlimited. Follow-up work on the toxicity of chemicals on the biota that occupy various compartments is needed. Output from models such as this one can be used to help specify dosage parameters that reflect the ecological context of toxic effects on biota.

ACKNOWLEDGEMENTS

During the construction of large-scale models many people people became involved, some intensively and some only slightly. We would particularly like to thank Michael Newton, Marvin Montgomery, Duane Moore, and Bob Loper, who contributed to this model, and to express our appreciation to the many others who helped on the project. This work was supported by a grant from the US Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

REFERENCES

1 NORRIS, L.A. FREED, V.H.
The Absorption and Translocation of Several Phenoxyalkyl Acid Herbicides in Bigleaf Maple
Weed Research vol. 6 1966 pp. 203-211

2 WOODWELL, G.M.
The Persistence of DDT in a Forest Soil
Forest Science vol. 7 1961 pp. 194-196

3 BARRIER, G.E., editor (Weed Science Society of America)
Herbicide Handbook 2nd edition WSSA monograph 3
Humphrey, Geneva New York
1970 367 pp.

4 NORRIS, L.A.
Degradation of Herbicides in the Forest Floor
In C.T. Youngberg and E.B. Davey, editors, *Tree Growth and Forest Soils* (Oregon State University Press, 1970), pp. 397-411

5 Forest Service--Pacific Northwest Region
Vegetation Management with Herbicides. Environmental Statement for Calendar Year 1973, Zone Vegetation Management Project Using Selective Herbicides, Siuslaw, Umpqua and Siskiyou National Forests
1973 73 pp. and appendices

6 LOOMIS, T.
Essential of Toxicity 2nd edition
Lee and Febigen Philadelphia 1974 180 pp.

7 PATTEN, B.C.
A Simulation of the Shortgrass Prairie Ecosystem
SIMULATION vol. 19 no. 6 December 1972
pp. 177-186