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Use, Ecotoxicology, and Risk Assessment of Herbicides in the Forest

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Present risk assessment strategies are oriented to single organisms, and they do not evaluate risks at the ecosystem level. An ecotoxicological risk assessment requires information from studies of environmental chemistry (for evaluating exposure to specific organisms), toxicology (for determining the direct toxic effects of exposure to specific organisms), and ecology (for integrating the consequences of both direct and indirect effects of herbicides and projecting them to the ecosystem level). The National Research Council, Committee to Review Methods for Ecotoxicology, proposed a system for assessing ecotoxicological effects for use in administering the Toxic Substance Control Act. Most aspects of this system are already in use in forestry, but integration among disciplines and a mechanism for making risk assessments at the ecosystem level are lacking.

The predominant use of herbicides in forestry is for weed and brush control, both for establishment of young tree seedlings and for their later release from competing species. Other uses include vegetation control on rights-of-way, timber stand improvement through the removal of defective or non-commercial trees or through thinning in overstocked stands, range improvement for grazing of domestic animals, improvement of animal habitat, control of poisonous and noxious weeds, and maintenance of fire breaks.

Decisions about the use of herbicides in forests customarily take into account social and political considerations. In addition, they must include technically sound assessments of risk (1). Traditional risk assessments are basically assessments of single organisms, however, not of an ecosystem (2).

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Ecotoxicology is a relatively new term used to describe the field of study that integrates the behavior of chemicals in the environment, traditional toxicity testing, and the response of communities of organisms. For perhaps the first time, it integrates the efforts of environmental chemists, toxicologists, biologists, and ecologists and may enable assessments of risk to an ecosystem to be made. Ecotoxicology is not a new field of study, but until recently it had relatively few practitioners and lacked an easily identifiable title. It gained some prominence when the National Research Council, Environmental Studies Board, appointed the Committee to Review Methods for Ecotoxicology in 1979 (3-4).

Although the committee specifically addressed the Toxic Substance Control Act (TSCA), the recommendations of the committee can lead to better risk assessments for forest herbicides as well. In many respects it may be possible to perform ecotoxicological risk assessments much sooner for herbicides and forestry than for the many chemicals and environments covered by TSCA. The reason is that the pesticide registration process already requires much of the basic chemical and biological data needed for single-organism assessments, and forestry research already has in place many of the studies needed for estimating the integrated response of ecosystems.

The purpose of this paper is to (1) clarify the distinction between traditional risk assessments involving single species and assessments that integrate effects among species, including both direct and indirect effects; (2) show the kinds of information needed for ecosystem assessments at the forest watershed level; and (3) review the recommendations of the National Research Council Committee in terms of the type of information needed and its availability for herbicides and forestry.

Herbicide Risk Assessment at the Ecosystem Level in Forestry

Assessments of environmental impacts from herbicides are usually done at the single-species level. These assessments use toxicological data from laboratory bioassay tests and estimates of exposure from laboratory or field studies of environmental chemistry. Few tests have assessed the impacts of herbicides on organisms in the field and few, if any, at the ecosystem level. There are two main reasons why there have been so few field or ecosystem tests: They are exceedingly difficult and costly, and the current philosophies of risk assessment have evolved from classical toxicology and the federal regulatory framework that covers pharmaceuticals, food additives, and pesticides.

Techniques for evaluating impacts of herbicides at the ecosystem level are needed because traditional methods of risk assessment emphasize direct effects of chemicals on selected species. Indirect effects have been largely ignored, and they may be of equal or greater importance in maintaining the structure and function of an ecosystem and the well-being of its inhabitants.

Direct Effects, Indirect Effects, and Types of Toxicity Testing. Direct effects.--Direct effects of herbicides on organisms are those that result from the direct contact of a specific organism with an herbicide. Direct effects can be studied and evaluated in terms of currently accepted dose-response theory. The characteristics of exposure (magnitude, frequency, and duration) are one of the two essential ingredients of risk assessment. Toxicity, an intrinsic property of the chemical, is the other. The nature of the response of an organism depends on the basic properties and characteristics of the chemical and organism, and the characteristics of the exposure the organism receives.

Testing for direct effects.--The theories applicable to direct chemical effects on one organism are applicable to all organisms in an ecosystem because the direct interaction between the organism and the chemical is a one-on-one process. The difficulty is that ecosystems have many kinds of organisms, most of which are not likely to be involved in traditional programs of toxicological testing. Through careful selection of representative test species, however, it is possible to estimate direct toxic effects on many organisms through classical dose-response experimentation on traditional test species.

I do not mean that more accurate estimates of toxicity to squirrels or ptarmigans could not be obtained by including these species in testing, but the expected gain in accuracy over testing with rats and chickens is probably not worth the added expense. Furthermore, the number of species in the forest is large, and it is impossible to test them all. Therefore, the use of representative species in traditional testing is a reasonably accurate and efficient means of estimating the inherent toxicity characteristics of a specific herbicide. Because this system is not foolproof, it is important that researchers and herbicide users be alert for unusual effects of herbicides on non-target species.

There are some aspects of toxicity testing that should be improved. Toxicological testing has traditionally evaluated only a few responses of organisms, like survival or pathological responses. Recently there has been more study of other parameters, such as growth and reproductive success; however, these tests all focus on the well-being of the individual, not on communities of organisms and their interactions. The consequences that accrue to an ecosystem from changes in the numbers or activities of all the directly affected organisms should also be assessed.

Blanck and Gustafsson (5) said that "ecological and pollutant realism" are necessary in testing toxic effects. Ecological realism is attained when the test conditions reflect important characteristics of the natural environment. To a major degree, both of these characteristics are lacking in single-species testing. Tests of single species cannot delineate the complexity of the structure and function of the ecosystem; therefore, they lack ecological realism. For example, although there are numerous studies that include the effects of a chemical on the survival or growth of individuals of various fish species, measurements of behavioral or interspecific effects are uncommon. Alteration of predator-prey interactions, for instance, can markedly alter survivability (of either species) in a way not predicted by traditional testing procedures (6).

Pollutant realism is achieved when the test system includes sufficient diversity of components and the physical and chemical properties so that the pollutant behaves in the test system as it would in nature. Pollutant realism is lacking because, in most test protocols, the pollutant does not interact with any part of the environment, except the organism. A lack of pollutant realism in traditional tests may result in overestimates of risk. As an example, substantial information is now available about the toxicity of TCDD to numerous species when they are exposed via injection, incubation, diet, or dermal application. At Times Beach, Missouri, the TCDD is in the soil, and because it has apparently been there for some time, it is probably tightly bound to the soil. Little is published about the toxicity of TCDD bound to soil, for any means of exposure. Intuitively, I suspect the TCDD is less toxic when bound to soil than in the forms commonly used in toxicity testing. Thus, the risks of TCDD-induced toxicity to humans at Times Beach may be much smaller than would be suggested by the results of traditional testing which lacks this aspect of pollutant realism.

As another example, traditional testing with aquatic species relies on constant levels of exposure (for example, 10 mg/liter for 24, 48, or 96 hours). In the forest, exposure levels of herbicides in streams will never be constant over time. Virtually all the research on herbicides in forest streams shows that the residue levels reach a maximum shortly after application and then decline rapidly. Although the instantaneous maximum concentration may be 0.037 mg/liter, the concentration 1 hour later may be 0.010 mg/liter, 0.002 mg/liter at 24 hours, and below the detectable level after 48 hours. The problem is to evaluate this type of dynamic exposure in terms of the type of information that is available from traditional testing (2). The approach often taken is to assume that the maximum concentration defined in field monitoring was present for a full 48 or 96 hours, and to estimate toxic effects based on 48- or 96-hour toxicity tests. The consequence in almost every case is an overestimate of risk as shown for some aquatic invertebrates and methoxychlor (7-8).

Overestimates of risk may lead to the imposition of unnecessarily restrictive policies or procedures. Although this conservative attitude is attractive in many respects, it is important to determine what is going to be gained in terms of protection of the species involved (another form of benefits), and what is going to be lost in terms of resource production (another form of risk).

Does this mean traditional testing of the direct effects of toxicity is no longer valuable? Certainly not, but it does need to be expanded and modified to include aspects of ecological and pollutant realism. Single-species-testing will continue to be the predominant form of testing because it can yield a great deal of information, quickly, at minimum cost. Ecological realism cannot and need not be part of every test. Specific tests can be designed to provide ecologically relevant information within the framework of traditional dose-response relationships. Examples are dose-response tests of predator-prey interactions, and intraspecific and interspecific tests of competition for food, space, and other requirements. Tests can also be designed to be pollutant relevant within the framework of traditional dose-response relationships. Examples are dose response testing where the concentration of chemical is varied over time (and some alternative expressions of exposure developed--perhaps the integral of concentration over time), exposure via weathered substrates (containing known levels of chemical), and exposure in dynamic rather than static systems.

It is not realistic to expect that all relevant combinations of chemicals and organisms can be included in the tests which are designed to attain ecological and pollutant realism described above. What is needed is a research effort, not a regulatory effort. By this, I mean the tests I have described should not be made part of the pesticide registration process. Research is needed to develop more fully the concepts embodied in these tests and to test the concepts to determine their scope of inference. This will provide a better basis for evaluating the potential for direct effects of herbicides in the forest, both for management and regulatory purposes.

Indirect effects.--Indirect effects are those that do not require a direct interaction between the herbicide and an organism. As an example, herbicides, because they directly influence plant cover, result in modification of animal habitat (food, cover, microclimate) which, in turn, influences carrying capacity for specific wildlife species. As a result of the interrelations within food chains, direct effects on relatively minor species can be transferred indirectly to organisms at higher trophic levels. Other examples of indirect effects are those that result from the alteration of vegetation density and species composition. For instance, severe and prolonged deforestation can substantially alter the nutrient cycling relationships for an entire forest watershed (9).

Indirect effects can be substantially more far-reaching (in an ecosystem perspective) than direct chemical effects. Most herbicides used in the forest are not likely to directly affect many organisms in any ecosystem because few herbicides used in forestry are so inherently toxic or so widely distributed that the avoidance or detoxification mechanisms of all organisms would be overwhelmed. On the other hand, severe deleterious direct effects on only a few key organisms or ecosystem processes can have far-reaching (indirect) effects for many other components of the ecosystem.

A key point is that all indirect effects are the result of a direct effect on some aspect of the system. This is extremely important in planning methods for assessing indirect effects. Because the direct effect can be evaluated by use of established dose response theory and by tests, many of the indirect effects can be evaluated by use of the existing ecosystem data bases and current studies of ecosystem processes without a large amount of specific testing (10).

Testing for indirect effects.--In studies of indirect effects, it may be possible to examine the processes involved and to manipulate them by a variety of techniques, some of which may not involve the chemical in question at all. For instance, if a non-chemical technique produces the same effects on primary productivity as the herbicide does, it is useful for studying the effects of reduced primary production on higher trophic levels.

Testing for Effects of Herbicides at the Watershed Level

Many chemicals are regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), and their properties are as diverse as the properties of ecosystems. In forestry, however, relatively few herbicides are used very much. In fiscal year 1981, for instance, the USDA Forest Service used more than 25 different herbicides in the National Forests, but 2,4-D and picloram alone and in combination accounted for 70% of the total amount of herbicide applied. Atrazine, glyphosate, dalapon, simazine, fosamine, and hexazinone accounted for an additional 18% (2).

The properties or characteristics of chemicals that influence their behavior in the environment and can be used to focus attention to those most likely to cause changes in ecosystems at the watershed level of resolution (4) these are: compounds that contain heavy metals; and compounds with low water solubility and high fat solubility, high equilibrium vapor pressure, high degree of stability, or a high degree of mobility in soil. With the possibile exception of mobility in soil for one or two compounds, none of the herbicides in the top 88% of the amount used in National Forests in fiscal year 1981 have these characteristics.

Forest watersheds are made up of diverse and complex subsets of interacting systems. There are some major processes, however, that involve or affect all or most of the subsets and that can be studied or measured as indicators of change in ecosystems at the watershed level. These processes include carbon fixation by primary producers, transfers of energy, nutrient cycling, and the decomposition of various kinds of organic substrates. They are often measured in ecosystem studies at the watershed level (11). To determine if changes are occurring in ecosystem processes or watershed responses, it is necessary to have systems for accumulating long-term baseline data, including measures of the variation of systems over time. The use of paired watersheds (control and treated) is necessary. Unfortunately, there are few forest watersheds that can be used in assessments of this kind.

The number of such watersheds is vanishingly small compared to the matrix of herbicides (even groups of herbicides) and environments pertinent to the use of herbicides in the forest. For this reason and because watershed level studies are extremely expensive and take a long time, they should be part of a research program and not part of the pesticide registration process. Research needs to be done to establish the relationships between small-scale, process studies (such as carbon or nitrogen fixation) and the watershed response studies of water, nutrient, and sediment yield (12-13). By testing the direct effects of herbicides on these processes, and coupling them with the indirect effects as measured by or inferred from studies of other types of changes (often from ecosystem response studies that do not involve herbicides at all), reasonable estimates of the effects of herbicide use at the watershed level can be made.

A Proposed System and a Procedure for Assessing Ecotoxicological Effects

In most cases I have abstracted the essential points of the Committee's recommendations for assessing ecotoxicological effects (3), and then added (in parentheses) my comments and evaluation of the relevance to herbicides and forestry.

Types of Tests. The Committee identified the following types of tests as needed in a system for assessing ecotoxicological effects:

1. Single-species-tests (single-species-testing, both traditional tests and tests modified to include ecosystem and pollutant realism are needed).
2. Population tests (population tests proposed by the Committee include construction of actuarial life tables

and survivorship curves and changes in population gene pools, migratory behavior patterns, and food preferences. This approach is still in the research stage, and more research will be needed before suitable test procedures can be developed. It should continue to be important more as a research tool than as part of the pesticide registration process for herbicides in forestry).

3. Multi-species tests (these should include many types of interactions, such as competition, symbiosis, parasitism, host-plant relationships, and predator-prey interactions. As with the population tests, the multi-species tests may have greater value as a research tool than as an across-the-board regulatory tool for herbicides in forestry).
4. Ecosystem tests. These are needed at several levels; for example, laboratory microcosms, greenhouse studies, field enclosures, and field tests in natural ecosystems. (These represent three levels of the same type of testing, but they have different emphases. The microcosms are most easily managed, and they can be replicated and can test a wide range of experimental variables. Field enclosures have a higher degree of ecological and pollutant realism, and opportunities for replication exist, but they require more intensive study and fewer experiments like this can be conducted; thus, few variables can be examined. Field tests in natural ecosystems are the most realistic but the most difficult to control and conduct; there would likely be few of these.)
5. Models. Both empirical and simulation models are needed. (Models can help bridge the gap between experimental conditions and the real world and between actual observations and predictions. Obviously, models can be no better than the data used to construct them, and much of these data will come from the tests described above. The tremendous advantage of models comes as increased experience and better data bases permit their refinement to the degree that they can be used in place of, or to guide some of the more complex testing described above. Well-validated models can be a powerful research and regulatory tool.)

A System for Assessment. Improvement and expansion of specific tests as discussed are important, but equally so is a system or procedure for making ecotoxicological assessments from the information from these tests. The Committee proposed both a system for evaluating effects and a procedure for implementation. Evaluating environmental effects of herbicides in the forest requires two subsystems, a multi-level integrated test system and a system of baseline and experimental ecosystems for monitoring and study.

The integrated test system approach is proposed as an alternative to the more traditional hierarchical testing approach (14), although many of the elements in the hierarchical approach remain. The difference is that in the hierarchical approach, individual tests tend to stand alone with little overlap. The Committee recognized that no one type of test can produce the diversity of information needed and some overlap among tests is good. Therefore, integration of results and an analysis of combined results were proposed as a more effective scheme. These would ultimately require fewer, not more, costly and difficult field tests. The integrated system needs to produce data on:

1. The characteristics of the chemical and its behavior in the environment. (This is traditional environmental chemistry (15-16) and, for herbicides in forestry, requires little change.)
2. The physiological responses of species related to the presence of the chemical. (This is traditional single-species testing (14) but with some additional tests to improve ecological and pollutant realism.)
3. Changes in species interaction.
4. Changes in the functional processes of the ecosystem (like mineralization; and nutrient, soil, water, and energy fluxes).

Baseline ecosystems are undisturbed systems used for monitoring and studying the structure and function of the ecosystem. Experimental ecosystems, paired with undisturbed baseline ecosystems, are used to determine the specific effects of herbicides on ecosystem dynamics. Mathematical models to facilitate understanding of the interactions among system components and the effect of the use of herbicides in the forest on these components should be developed from this system of study.

Implementation. Implementation of this assessment strategy sounds formidable when viewed from the perspectives of TSCA, but for herbicides in forestry, much of the work is already underway. The Committee identified the following steps in implementation, and I have commented (in parentheses) on the status of each step:

1. Select baseline ecosystems. (Much of this is already done via Ecological Reserves established by the "Man and the Biosphere Program" and the system of experimental forests maintained by the USDA Forest Service.)
2. Characterize each baseline ecosystem. (Much of this is already done or is being done under research efforts funded by various groups, such as the National Science Foundation and USDA Forest Service.)

3. Establish experimental ecosystems. (Much work remains to be done. Monitoring and experimental systems need to be established in connection with each baseline ecosystem. The concept is that the monitoring and experimental systems could be disturbed and studied, and the findings related to the characteristics of the baseline ecosystem. The monitoring and experimental systems may vary in size from petri dish microcosms to full-scale field sites, although there are likely to be few of the latter.)
4. Develop models of the dynamics of the baseline ecosystems. (Much of this is already underway via the research programs identified in 2. Models of pesticide behavior have been developed, but they are based primarily on agricultural uses. They need to be modified and validated for herbicides in the forest.)

Assessment. The material presented thus far explains the basis and structure of an assessment system and the steps needed to implement it (have it ready to use).

The following steps (proposed by the Committee) show how the information for assessment of ecotoxicological risks is developed once a system is in place:

1. Characterize the physical-chemical properties of the chemical and how it is used to determine which ecosystems may be the direct recipient of the chemical. (This information is already available as part of the FIFRA registration.)
2. The key species and processes of the ecosystem in question, as identified in the baseline ecosystem, are used in single-species and microcosm tests to determine the potential points of chemical entry and impact. (The single species test procedures are already well developed and are used in the FIFRA registration process. They need some modification, however, to achieve ecological and pollutant realism, and they need to be expanded to include some types of organisms not included in testing strategies at present. The microcosm tests are not part of the registration process and are intended to test for effects on the interactions of key species or the processes of key ecosystems.)
3. With the information from these tests, the models are used to predict both direct and indirect responses of the ecosystem.
4. The model outputs are then checked experimentally by manipulating the experimental baseline system to simulate the impact of the chemical. (The opportunities for this type of testing are limited

because of the scarcity of baseline forest ecosystems. The need for this step for herbicides and the forest may not be great because of the relatively small impact of herbicides in the forest ecosystem compared with some other types of perturbations such as logging, burning, landslides, and debris torrents. Experimental manipulation may be called for if the models indicate that some extraordinary response may occur, such as elimination of nitrogen-fixing organisms or the loss of an organism essential in the processing of stream detritus. Otherwise, use of the models to identify points for study during pilot scale field testing for efficacy may be sufficient.)

5. The final step is to test for anticipated effects of the chemical using a multi-species integrated approach. (Because the list is in steps, it may appear that this integrated testing is done last, but in fact it is done concurrently with steps 3 and 4. Much of the basis for the integrated testing is already in place in FIFRA.)

The information from these five steps can be used to make accurate assessments of ecotoxicological risk, but it will require a different mix and emphasis of disciplines than are presently involved. Assessments of risk for herbicides in forestry have usually been done by those with traditional training in toxicology and environmental chemistry. Unfortunately, neither of these disciplines have developed an "ecosystem" perspective. They tend to focus narrowly. Those trained in ecology (and its associated specialties) must be added to this process to achieve the integration of thinking and study necessary for risk assessments that focus beyond individual organisms. Fortunately, in forestry many ecologists and ecosystem specialists are already at work in research, although their attention has not yet included herbicides to any great degree. With some refocusing of their efforts (or with additional efforts), it will be relatively easy to integrate the efforts of toxicologists, environmental chemists, and ecologists for accomplishing ecotoxicological risk assessments for herbicides in forestry.

Conclusions

It may appear to be a nearly overwhelming task to conduct ecotoxicological risk assessments for herbicides in forestry. But much of the basic ecological work is already being done and more sophisticated toxicological test protocols are being developed to improve the validity of test results by achieving a higher degree of ecological and pollutant realism. What is most seriously lacking at this point is integration of the information developed by environmental chemists and toxicologists with information developed by biologists and ecologists. In addition, ecologists need to include herbicides as a method of perturbation in their ecosystem studies (at some normal level of use, not to create ecological extremes as was done in the Hubbard Brook studies [9]). The ecotoxicology testing strategies proposed by the Committee may be most important used in connection with the Toxic Substances Control Act, but they can also be used to help improve the quality and accuracy of the risk assessment process for herbicides in forestry.

When priorities are developed, the need for implementing a formal strategy for ecotoxicological assessments of herbicides in forestry may not be as pressing as it is for other chemicals in other areas because: (1) In forestry, there are relatively few chemicals that receive sufficiently wide use that they need detailed attention; (2) less than 1% of the forest land is treated with pesticide of any kind in any one year (less is treated with herbicide); (3) large, contiguous forest areas are not treated with herbicides (typically treated areas are widely scattered and range from less than 2 ha to 200 ha in size); and (4) areas that are treated are usually treated only once, twice, or perhaps three times early in the 30- to 50-year growth cycle in the Southeastern United States, or the 70- to 120-year growth cycle in the Western United States.

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