ENVIRONMENTAL SIDE-EFFECTS OF LARGE-SCALE CHEMICAL CONTROL OPERATIONS IN FORESTS

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Foreword

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INTRODUCTION

The North American economy, flush with technological prowess, has single-mindedly pursued goals of increased industrial growth in almost all fields of endeavour, including forestry. In Canada, about 9 million metric tons of wood products are harvested annually to meet the demand, mainly for paper. The chemical insecticides, herbicides, fungicides, and fertilizers which revolutionized agriculture now have an expanding role in forest management.

In the last decade, however, pushed by the spectre of Rachel Carson's "Silent Spring", the public has become alarmed over the environmental aspects of large-scale chemical application. Abundant wood and pulp resources are still taken for granted, but the public wants more of the other resources and facilities offered by woodland. These people contend that the forest environment is damaged by large-scale operations of all kinds, that chemicals bring hazards to human health, wildlife abundance, and ecological integrity, and that ultimately the general public will have to pay the bill in diminished resources and increased clean-up costs.

The forestry profession is reluctantly conceding that pesticides are a blunt weapon to control insect pests. Such chemicals are sometimes successful, but more often protect the forest by palliative action, delaying but not eliminating the pest threat. Their use reduces the rate of tree mortality, thereby giving more time for harvesting, but at an immediate cost to be born by the producer, industry, and consumer. Industry in turn demands subsidies or alternative strategies of protection from the governments.

Governments and their scientific branches sit uncomfortably on the fence, weighing on the one hand the social and economic impact of the pest, and on the other the environmental impact of protection. Is the environmental binge a global fad, or truly a ground swell of deep and justifiable concern? Is multiple use of woodland really diminished by current management techniques? How do we measure resources to monitor changes in yield? What criteria of environmental quality are needed as yardsticks of satisfactory management? What are these so-called side-effects, anyway?

The result of the environmental furor is a re-evaluation of land management practices. Various levels of government in North America are seeking to remove overt abuses of the environment by legislation and education, and to avoid more subtle ecological threats by anticipatory research. It is now recognized that forest industry is a large-area, high-volume influence on the natural environment and woodland resources such as water, wildlife, and recreational facilities; it is recognized that broadcast chemicals offer a means to tamper devastatingly with natural balance if we are indifferent to ecological processes. Forest industry itself is looking beyond the narrow technology of timber harvesting and is no longer so uncompromising towards government regulation. What is needed is a course that satisfies the legitimate interests of industry, government, science, and the public. What is new is that all parties have become sensitive to the long-term implications of today's actions and are determined to remedy environmental deterioration. Experience with chlorinated hydrocarbon insecticides, radioactive fall-out, heavy metals, and phosphorus-rich detergents and fertilizers has made a profound impression.

The components of the forest environment are air, water, soil, flora, and fauna. This paper will consider the impact of large-scale insecticide usage on each, following the sequence of chemicals used in measures against the spruce budworm, *Choristoneura fumiferana*, in eastern Canada. The side-effects are mainly population responses in non-target organisms which are themselves resources, or key ecological factors necessary to sustained resource yield. Other side-effects are the contaminant qualities of pesticides and their residues in air, water, and foodstuffs from the forest. I will not review environmental methodology but will suggest some ways of safeguarding the forest from adverse effects both by operational techniques and organizational approach.

THE SPRUCE BUDWORM PROBLEM

Outbreaks

The eastern spruce budworm is a native tortricid moth widely distributed in North American boreal forest west to the Rocky Mountains. It is the most important forest pest in eastern Canada, where it feeds on the buds and new shoots of several coniferous species, especially fir and spruce. Trees can tolerate about 3 successive years of heavy defoliation, but thereafter mortality is increasingly severe. The ravages of its outbreaks have been immense, a loss estimated at 700 million m^3 of wood this century, and salvage has rarely been practicable.

Periodic outbreaks and wholesale kill of mature stands are a natural and ecologically stable association between the spruce-fir forest and the budworm. One outbreak engenders the next, perhaps some 50 years hence, by a process of forest succession that leads irrepressibly to stands dominated by fir and spruce maturing simultaneously over very large areas. This is an evolutionarily cosy arrangement for both tree and budworm; only the forester objects - he wants his cut.

The problem is one of spruce budworm population dynamics. The insect has a high intrinsic capacity for reproduction, but its population increase is disputed by an array of biocontrol forces (predators, parasites, pathogens, and host synchrony) along with weather and dispersal. In the course of the rotation of a forest stand, these limitations on budworm populations operate with marvellous efficacy when the trees are young. The eventual outbreak occurs when age has accumulated a storehouse of budworm food in the deep canopy, and when cycles of warm dry weather trigger increased survival between generations of the pest.

Spray History

Up to the middle of this century, little could be done except to survey defoliation, warn of expected outbreaks and evaluate losses. Then came DDT, Muller's miracle. Large-scale aerial application was simultaneously promoted by the availability of war-surplus aircraft and pilots. Just at the right time, in the late forties, another budworm epidemic swept over eastern Canada. Aerial spray operations began in 1952, and they have continued in New Brunswick, the most affected province, almost every year since, accumulating to 20 million ha and a cost of $30 million; the world's largest aerial spray operation for forest pest control.

In any one year, the area sprayed has been substantially smaller than the area infested. The main criterion for deciding which stands would be sprayed has been the prospect for heavy mortality in repeatedly defoliated forest. This policy has minimized the area and cost of the annual operation. It has been unquestionably successful in preventing severe losses of trees. Forest industry has been able to continue to harvest pulpwood and sawlogs at the rate of market demand, and the urban and rural communities dependent upon such industry have continued to flourish. Thus the immediate benefits of forest protection have heavily outweighed the immediate costs to forest industry and the government.

Doubts

Nevertheless, governmental authorities in Ontario, Quebec, New Brunswick, Prince Edward Island, and Nova Scotia, faced with the expanding budworm outbreak, are yet again pondering the wisdom and long-term benefit/cost of large-scale spray operations. They are worried by the continuing evidence of unexpected side-effects in target and nontarget ecosystems. Moreover, there is the disquieting thought that chemical spraying may be prolonging the outbreak by preserving the pest's food supply. We cannot deny the evidence that the current outbreak has lasted twice as long as other recorded outbreaks, and that high populations continue to infest the repeatedly sprayed areas.

THE FOREST ENVIRONMENT

The spruce-fir biome in eastern Canada is distributed through a group of high-canopy forest ecosystems in which the dominant trees are balsam fir, white spruce, red spruce, and black spruce. These ecosystems are floristically and faunistically fairly simple, stable in long term, and ecologically resilient. A typical spruce-fir stand contains some 200 species of green plants, 500 species of fungi, 1000 species of insects, 200 species of mites, 100 species of spiders, and some scores of species of vertebrate animals. Some are key species characteristic of the habitat; others are non-specialized organisms tolerant of many habitats; a few are temporary drifters from other ecosystems. All are interrelated by food-web associations such that the rise or fall of one species populations exerts a tendency to change in most other species populations. Certainly the irruption of a key organism like the spruce budworm has dramatic effects on the abundance of many other denizens of canopy and soil. The interrelationships between defoliators, epiphyte browsers, predators, parasites, pathogens, pollinators, and plant hosts are infinitely variable.

Yet a forest stand looks much the same from year to year in spite of the fierce competition within its community. Generally we take such natural balance for granted - a gift of evolution. We fail to recognize that the dysfunction of the system may be caused by our management practices; indeed, hidden biocontrol mechanisms are revealed for the first time by our mistakes. Evolution has not prepared the forest for extraneous chemical influences such as pesticide application, and unusually drastic responses can ensue: direct, delayed and secondary mortality, altered reproductive capacity and behavioral routines; new patterns of dominance, distribution and density.

Such changes are a way of life in farming practice. In forestry, however, it is usually cheaper and more efficient to maintain natural biocontrol mechanisms because of the long rotation of crops. Thus the chemical suppression of forest pests has a long-term dimension that must be measured in benefit/cost equations.

So far we have considered only the target forest. But inevitably the area sprayed is a mosaic of ecosystems, some not susceptible to damage by spruce budworm (broad-leaved associations, pine, larch, and cedar stands, ericaceous shrubs, bog and swamp). In practice, spraying of the smaller patches of non-susceptible forest is unavoidable, and a chemical stress without benefit is imposed on a substantial area of woodland needing no treatment. These non-susceptible stands ordinarily have a self-regulating balance and healthy growth in the presence of many potential pests but few outbreaks. It is legitimate to be concerned about the effects of pesticidal stress on these non-target forests.

The ecological hazard from forest spraying arises from the large contiguous area, and from the repeated, perennial applications at the same time each year. In itself the application of 0.2 kg of insecticide per hectare is small compared with typical farm crop dosages in North America. But a farm crop is an ecological island surrounded by a sea of other habitats and vegetation covers. The farmer may extirpate most insects, pest and beneficial alike, from the foliage of his crop plant, yet almost immediately immigration from surrounding unsprayed lands will begin to re-establish the insect complex in more-or-less orderly proportions. However, in a million hectares of sprayed forest, redistribution by migration is necessarily slow, and ecological balance is not easily restored. Pest insects like spruce budworm are able to migrate in and rebuild populations from survivors faster than the non-specific predators and parasites.

The presence of an abundant, healthy, natural forest is a buffer against ecological disaster outside its own boundaries. Forests regulate waterflow, reduce erosion, and provide a source of biological control organisms to surrounding lands under other forms of management.

INSECTICIDES AS ENVIRONMENTAL POLLUTANTS

An insecticide has two merging effects on the environment; first as a pollutant over a period of time in air, water, soil, and resource organisms, with implications for human health; secondly as an ecologically disruptive agent with effects on natural balance. The importance of these two roles varies with properties of persistence and toxicology in the insecticides chosen.

The Choice of Insecticides

The petrochemical industry has developed four major groups of insecticide in the past 30 years - the chlorinated hydrocarbons, the organophosphates, the carbamates, and the plant derivatives and mimics. The marketed products have been developed for broad-spectrum toxicity within the class Insecta, which is an attractive sales character in agriculture. Their selection for use in forestry has depended upon supply, target efficacy, non-target toxicology, human health considerations, and aerial spray technology.

The general history of insecticide choice in North America has been to lean heavily on DDT in the fifties, then to turn to organophosphates in the sixties, and now to probe the potency of carbamates. DDT has been applied on a large-scale to gypsy moth, tent caterpillars, tussock moths, and spruce budworm (Williams and Shea 1971). Organophosphates were used against the spruce budworm in eastern Canada, jack pine sawflies in Ontario and Quebec, and hemlock loopers in Newfoundland. Carbamates have been used against gypsy moth in the New England states, and against spruce budworm in Maine and Montana.

In the campaign against the spruce budworm in eastern Canada, the chronological sequence of choice has been:

DDT	1952-1967	8,900,000 ha at 0.28 to 0.56 kg/ha
Phosphamidon	1963-1967	300,000 ha at 0.28 to 0.56 kg/ha
Fenitrothion	1967-1972	11,000,000 ha at 0.21 to 0.35 kg/ha.

The Persistence of DDT

Of the DDT formulation emitted by the spray aircraft, a large but variable proportion, perhaps averaging half, is dissipated into the air (Norris and Moore 1971; Yule and Cole 1969). This represents no hazard to human health and is rapidly diluted within a few hours. Most of the material reaching the target area is eventually adsorbed to soil colloids, where it remains in various isomers and metabolites, slowly disappearing by vaporization and degradation. The DDT remains in the surface organic layer and is not leached to the subsoil, at least during the first 10 years or so (Yule 1970; Yule and Smith 1971). DDT also enters water by spray droplets, soil wash, and falling leaves, where it is adsorbed to organic sediments with slow release and cycling in water (Yule and Tomlin 1971). However, it detoxifies more rapidly and persists in lower quantities in stream sediments than in forest soil. Residues persist in fir and spruce foliage for at least 5 years after last spray, and even new shoots carry burdens of DDT although they have never been exposed to spray. Thus in the target forests of New Brunswick, DDT persists in substantial quantity (around 0.07 to 0.7 kg/ha) 5 to 15 years after last application. This does not cycle through game animal tissues (deer, moose, grouse, salmon, trout, etc.) in sufficient quantities to represent foodstuff contamination, except in woodcock where concentration in the lipid tissues exceeds the permissible limit of 7 ppm.

The use of DDT was discontinued in operational forest use in 1968; it was generally curtailed in Canada in 1970 because of its chemical stability, its lipid solubility, its low water solubility, its vaporizing properties and because of biological concentration - all these properties resulted in uncontrolled redistribution in non-target biota including man.

The Persistence of Organophosphates

Organophosphates, like DDT, have two phases; initial movement in the air with dissipation; subsequent movement and persistence in the biota, soil, and water. Most have low to moderate persistence in soil and water, being oxidized then broken down to innocuous materials by the action of light, soil chemicals, and biological agents. Fenitrothion concentrations on foliage diminish rapidly in the first 4 days, but thereafter the residual material degrades more slowly until only a trace is detectable after 1 year (Yule and Duffy 1971). Little is known about its persistence in soil and water, but samples collected from stream water in sprayed forests have very low concentrations (< 50 ppb) at maximum. Fenitrothion penetrates insect bodies easily through skin contact, ingestion, and the respiratory tract (aquatic insects), and acts as a nerve poison. However, it does not persist or accumulate there because rapid degradation takes place; the insecticide has been detected only to the fourth post-spray day in analyses of field insects sprayed in New Brunswick.

Organophosphate compounds vary greatly in their toxicity to man. The proper use of fenitrothion, however, has brought no hazard either to spraymen wearing protective clothing, or to woodsworkers caught in the spray cloud, or to other people exposed to distant drift.

Third Generation Insecticides

Carbamates have a mode of toxic action similar to the organophosphates, while the toxicity of the pyrethroid chemicals is still unexplained. Other prospective insecticides being experimentally tested for forest use are synergist mixtures of chemicals, the combined use of pathogens and insecticides, and unconventional materials like juvenile hormones.

In theory, all chemical insecticides are evolutionarily obsolescent, fated to be increasingly ineffective with developing pest resistance; the literature is replete with examples. In practice, the continuing presence of unexposed individuals (immigrants from unsprayed areas) retards the development of genetic resistance in spruce budworm populations.

ECOLOGICAL DISRUPTION BY INSECTICIDES

I have noted that all insecticides have a wide spectrum of toxicity in the animal kingdom; but every insecticide has a distinctive spectrum, and every ecosystem has a different array of prospective victims. In practice, it has been difficult to determine side-effects and compare insecticides, because in all cases the defoliating impact of the spruce budworm causes population changes in the faunal community independently of spray stress. However, it is clear that DDT has ecologically disruptive effects by different pathways than are used by organophosphates like fenitrothion and phosphamidon. DDT is less potent, but much more residual, and is selectively severe along the food chain by accumulating higher concentrations in predatory animals. The organophosphates are more potent in immediate kill of insects, but have only brief persistence in general, and do not concentrate along the food chain.

More has been written about the biocidal side-effects of DDT than about any other pesticide (Woodwell 1967). Controversy has pitted conservationists who fear its redistribution in the biosphere, against agricultural and health authorities who have no other competitive chemical in the campaigns against disease and food shortage. Woodwell *et al.* (1971) are now less gloomy about its biospherical influence; the concentration of residues has not proceeded as far as was feared, and much of their residual potency has been diminished because they are being sequestered in substrates where toxins are not available for biological cycling.

Side-effects of DDT

My purpose now is to review side-effects as they were observed in spruce-fir forest and associated habitats during the successive spray seasons and in the subsequent years. The heaviest application occurred in New Brunswick forests but even there the maximum accumulative local dosage was no more than 5 kg/ha spread over 10 years, and most areas had much less. As noted before, much of the emitted insecticide was atmospherically dissipated without reaching the target.

The arthropod community on fir and spruce can be categorized as: - sap-sucking pests (aphids, thrips, scales, mites); defoliating pests (sawflies, beetles, and lepidopterous caterpillars including the budworm); epiphyte browsers (mites, psocids, flies); scavengers (mites, springtails); sugar and pollen gatherers (ants, bees); non-specific predators (spiders, syrphid-flies, ladybeetles, lacewings, mites); and the parasitoid insects (wasps, flies) attacking almost all other species. The susceptibility of each species to DDT poisoning depends upon its inherent resistance, its developmental stage, and to its exposure at spray time.

Measurement of the population response of all these species was beyond the capacity of the research force. However, some general observations were made by Macdonald and Webb (1963) during the spray years and by myself since the use of DDT was discontinued. The general result of spraying spruce and fir was an immediate reduction in insect faunal density; most species were able to recuperate and survive at a density two- to five-fold lower than normal. The results were descriptive rather than analytical, and there is no way of knowing how far changes in density should be ascribed to direct toxicity, food chain disruption, alteration of habitat by defoliation, weather stress or even sampling artifact. The exception was the target pest itself, of which the population dynamics were elaborately analyzed by life-table methods (Morris 1963). Certainly DDT was a good treatment for the spruce budworm with both immediate and delayed toxicity at light dosage. Some predatory insects recovered quickly from a single or few years of spraying; syrphid-flies, ladybeetles, and lacewings appeared to have densities higher than normal 2 to 3 years after spraying. The budworm's parasite complex - about 75 species - was not on the whole adversely affected by spraying, in so far as could be gauged by measurement of percentage parasitism (Macdonald and Webb 1963). Some of the lesser species, such as springtails and mites, made spectacular increases after DDT usage. A few species approached extirpation such as two common species of spiders (Renault and Miller, 1972). Populations of minor sucking pests were somewhat depressed. There was no evidence of minor pest irruption on the target trees, and the general effect was one of overall reduction in the arthropod community without severely upsetting relationships between trophic levels.

Here and there, interesting anomalies occurred. For example, one species of coccinellid appeared to increase its abundance, perhaps because its parasitic wasp became scarce. This ladybeetle had a high tolerance to DDT and stored it in its fat; the wasp larvae that fed on the fat lacked that tolerance, so the ladybeetle survival increased and wasp survival decreased.

No specific studies were made on the faunal communities of non-target trees exposed to spray. It is probable that most populations were mildly depressed without any significant population releases of minor pests. Macdonald and Webb (1963) noted that birch leaf miners were less numerous in spray years.

Somewhat similar studies were conducted in Oregon and Washington where western spruce budworm, *Choristoneura occidentalis*, was in outbreak from the late 1940's. Accumulatively, almost 2 million ha of defoliated forest were sprayed at irregular intervals between 1949 and 1958. There also, ecological effects to the community were temporary and generally minor: the stability of some parasites was disturbed, generally downward in population, but the complex as a whole continued to act effectively against the budworm. Three species of defoliators on Douglas-fir and true firs temporarily increased in the year after spraying, and disturbance of the biocontrol forces was probably involved, but the net result was not an irruption of non-target pests (Carolin and Coulter 1971).

The furor over DDT has been sparked by its effect on the reproduction of predatory birds. However, the extensive spraying over New Brunswick forests has had little effect on the survival of passerine birds which make an important contribution to biocontrol of pests. There was no acute mortality, only a tendency for birds to redistribute themselves in accordance with the post-spray survival of their insect prey (Macdonald and Webb 1963). However, it is possible that delayed mortality of migratory birds occurred when the stored DDT was mobilized with the fat after long flights. Adverse effects on the breeding success of grouse and woodcock was reported by Neave and Wright (1969). Moreover, high residues of DDT metabolites in woodcock in certain sprayed regions of New Brunswick led to a ban on hunting of that species in 1970, 3 years after last spray, although this concerned foodstuffs impurities rather than conservation of wildlife. It is probable that DDT will continue to be present in substantial concentrations in birds which feed on soil invertebrates; such residues are likely to cycle slowly in New Brunswick's forest soils for many years. Dimond *et al.* (1970) reported significant residues in forest robins 9 years after last spray, and the rate of diminution is slow.

DDT continues to cycle in other vertebrates to some extent. Dimond and Sherburne (1969) found traces in voles and higher concentration in shrews after a 9-year gap. However, in New Brunswick, frogs and salamanders appear to be free of such traces 4 years after last spray.

Undoubtedly the worst non-target side effects of DDT spraying in New Brunswick occurred in aquatic habitats. Elson (1967) and MacDonald (1971) reported substantial losses of young salmon, both immediate and delayed, and there is evidence of physiological disorders from sublethal doses. Adverse effects on other fresh water fish have been widely reported in the literature, but in fact rather high concentrations in water, prey organisms, and whole fish are necessary to produce acute or chronic toxicity. In general, such high levels have not persisted in forest streams. The effect of spraying operations on aquatic insects was also dramatic, producing immediate heavy mortality (Ide 1956), yet in general woodland streams were repopulated within 3 or 4 years. Low levels of residues have persisted in some predatory vertebrates, such as crayfish, for years after last spray date (Dimond *et al.* 1968). The total effect on game fish populations in long-term remains unsolved. DDT contributed immediate and chronic toxicity through contact effects and biological concentration along the food chain, but there are many other factors, such as pollution and overfishing, which enter into their population dynamics.

In summary, DDT was a mixed blessing. It was effective in saving trees from budworm defoliation, and apparently not seriously harmful to biocontrol mechanisms in the forest canopy and soil. However, it was damaging to end-chain organisms and thus affected sporting interests to some extent. It was also ecologically disturbing to parts of the food web and may continue to exert some influence on species population dynamics for many years post-spray.

In practice, DDT usage in North American forests proved reasonably safe, with benefits outweighing defects. Nevertheless, I do not consider it alarmist to describe its use as ecological Russian roulette. This compound has the potential for unexpected diaster. I believe that a resumption of large-scale, recurrent, high dosage spraying would reduce carnivore populations, weaken biocontrol mechanisms, and lead to increased survival of resistance-building pests with new equilibrium levels less favorable to the production of multiple forest resources. DDT may have a place as a useful palliative in forest protection, but not as an acceptable long-term solution.

Side-effects of Phosphamidon

I have remarked that the main adverse effect of spraying in New Brunswick was on salmon survival. On this account, the application of DDT along major water courses was suspended in 1964, and it was replaced by the organophosphate insecticide, phosphamidon, which is relatively harmless in aquatic environments. The latter was sprayed in 0.5-mile strips along hundreds of kilometres of rivers from 1964 to 1967. DDT was continued over the matrix between rivers, but its impact on water was minimized. Phosphamidon, which has useful sytemic properties, proved satisfactory for budworm control (Macdonald *et al.* 1968*)[1]. Its effect on the canopy fauna was to depress the abundance of most insect groups including parasites, predators, aphids and other defoliators in the years of spray. However, owing to the spray pattern of long isolated strips, its long-term influence could not be separated from that of adjacent DDT.

Phosphamidon was also applied as the sole insecticide for treatment of 55,000 ha of jack pine forest infested with sawflies. This treatment, 0.28 kg/ha, conducted in mid-August 1965 was spectacularly successful against the pest (McLeod 1968). It also killed a large proportion of the parasitic insects, but a reservoir of both pests and parasites survived in cocoons protected in the soil. During the next 4 years without further treatment, the pest population remained low, while in most areas the parasite fauna re-established a normal density. Locally, however, there was reduction in parasite species diversity, and it is feared that this may result in locally less stable balance between sawfly and its biocontrols; the extirpated parasite species presumably had special advantages in certain habitats, thus the sawfly might be more disposed to resurgence in the impoverished spots (Price 1972).

Unfortunately, a new side-effect emerged in New Brunswick, and was confirmed in Quebec. Songbirds, especially the insectivorous warblers, were found to be extensively poisoned by the spray, probably by perching contact (Fowle 1972). Although species population survival was not endangered, such bird mortality was unacceptable, and phosphamidon usage in forests ceased in 1967.

Side-effects of Fenitrothion

In 1968, the organophosphate fenitrothion replaced both DDT and phosphamidon in the New Brunswick spraying operations against spruce budworm. The reported toxicity to vertebrates was low, the needed dosage was low, and the price was competitive. At that time also, units of the Canada Department of the Environment intensified side-effects studies of arthropod communities, birds, small mammals, and fish, and initiated research on fenitrothion persistence in air, vegetation, and soil.

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1. Citations followed by an asterisk (*) are unpublished reports and are listed after the references.

During the 5 years of its forest application, fenitrothion has effectively prevented large-scale tree mortality by killing around 80% of the target budworm. The apparent disruption of the target ecosystem has been low because treatment has reduced the budworm's impact without causing excessive insecticidal stress on the associated community.

Nevertheless, the fauna has not gone unscathed. In the first week after treatment, there has been a dramatic mortality of non-target insects of many species. These included minor pests such as lepidopterous larvae, sawfly larvae, aphids in all stages; non-pests such as dipterous flies (various scavenging, necrophagous, blood-sucking, gall-making, fungus-eating, shrub-defoliating, or merely transient from other ecosystems); predatory insects (syrphid-flies, elaterid beetles, chrysopid larvae, hemipterans, and others); and parasitic flies and wasps in large numbers of species but small numbers of individuals. Altogether the insect kill exceeded 7 million individuals per hectare, including at least 150 species as estimated by sampling in research plots. The target pest made up about 15% of the numbers but 95% of the biomass of killed insects. Other arthropod fauna, such as spiders, mites and phalangids, suffered only light mortality (Kettela and Varty 1972).

Of course, in any insect control scheme, it is the rate of survival of pest and community, not the rate of kill, that counts in evaluation of ecological integrity. Studies of seasonal trends in the balsam fir faunal community, conducted over several years, show that populations of many insect species become less stable when exposed to fenitrothion in spring. Spraying for spruce budworm is generally conducted in early June in New Brunswick, when many insects are at the peak of their reproductive behaviour. In general those insects whose population consists of reproducing adults and very young offspring are more profoundly disturbed than populations of insects in other stages of development.

The following trends are apparent in the arthropod communities in the target conifers: (1) The spruce budworm continues to maintain high populations from year to year in spite of fenitrothion's toxic efficacy. (2) A few minor defoliators (e.g. tortricids, aphids) appear to have rising populations, and may be approaching major pest status in combination with the budworm. (3) Some minor pest species (e.g. thrips) may be greatly diminished, while others ((scales, spider mites) appear oto be stable. (4) Fungus-browsing mites which proliferate greatly on budworm-infested foliage, maintain population densities larger by two or three orders of magnitude than their normal density. (5) The insect predators are usually fewer in sprayed forest, but not uniformly so; thus one ladybeetle species, common in unsprayed forest, has been drastically reduced in sprayed areas; mirids and lacewings are lower in numbers, but there is no consistent pattern for syrphids, pentatomids, and nabids. Spider populations are strikingly stable in the presence or absence of fenitrothion, and predatory mites (of at least one species) are far more abundant in sprayed forest. (6) The budworm parasites are fewer, but not uniformly among species; the parasites of eggs and small larvae appear to have a fairly stable abundance, but the parasites of large larvae and pupae are strongly reduced (Varty *et al.* 1971). (7) Little is known about the survival of less abundant species, even though they may have important ecological roles, such as pollinators and soil-dwelling predators.

These trends suggest that the biocontrol mechanisms in the spruce-fir ecosystem have been damaged. The ecological integrity of the community should be conserved because predators and parasites may be the key factors preventing the epidemic rise of minor pests; because kill of predators and parasites partly negates the target efficacy of the insecticide. A proper diversity and abundance of beneficial insects should be maintained so that biocontrol of the budworm can be quickly re-established when the pest finally returns to endemic status.

The influence of the spray treatment on non-target trees in spruce-fir and other stands has not been deliberately investigated, but ground and aerial surveillance of defoliation is maintained by the Canadian Forestry Service. It is possible that the indiscriminate kill of beneficial insects may permit opportunistic minor pests to rise to new and higher levels of population equilibrium or to outbreak, following several years of pesticide application. Thus the current increase of at least one species of maple pest, hitherto scarcely known, may be a forerunner of more problems to come.

The ecological impact of fenitrothion on the soil has not been gauged. Typically, only low concentrations of spray filter through the canopy, and the rate of degradation is not well known. Salonius (1968*) showed that massive experimental doses applied to soil did not upset the microflora or soil respiration. However, Freitag and Poulter (1970) recorded a marked reduction in litter-dwelling beetles and spiders after a single spary operation at conventional dosage; the persistence of this shift is not known.

The drift of fenitrothion poses a potential hazard to non-target ecosystems both inside and outside the spray block. In New Brunswick, litigation concerning alleged damage to blueberry crops is now in process. The growers claim that spray drift caused such mortality to wild bees that fruit set was reduced. In consequence, the spray operators have modified their techniques to minimize the hazard to pollinators.

The effect on vertebrate animals has been slight. Field operations at 0.56 kg/ha caused frequent toxic symptoms and some mortality to warblers and other passerine birds, but the standard dosage of 0.21 kg/ha resulted in only slight mortality (Pearce and Teeple 1969*). The increased use of ultra low volume spraying techniques - the emission of a very fine penetrating mist - may be partly responsible for the unexpected toxicity to active, canopy-dwelling, insectivorous birds. However, the rate of kill has no significant effect on songbird population survival.

The effect on stream fauna is not well defined. Phytoplankton were apparently unaffected, but the biomass in invertebrate animals (the food supply of trout and young salmon) has been depressed by a factor of three to seven in experimental streams in the spray year. No toxic mortality of any fish species was observed, yet under-yearling trout have suffered substantial reduction in density (Elson 1972*). One feature of newly sprayed streams has been the aberrant downstream movement of young salmon, which may be a behavioral abnormality induced by insecticide. In practice, the concentration of fenitrothion is extremely low, far below the laboratory levels needed to induce abnormality (Wildish *et al.* 1971*). In Newfoundland, Hatfield and Riche (1970) concluded that the effect of fenitrothion spray operations on salmon and trout mortality was inconsequential.

MINIMIZING SIDE-EFFECTS BY OPERATIONAL METHODS

The approaches to reducing the unwelcome side-effects of chemical control operations are reductions of dosage and area, isolation of the target pest in space or time, and selectivity of the insecticide.

The best method is to prevent large-scale outbreaks from arising. In the case of the spruce budworm, much current research is being directed to the concept that epidemics arise in small discrete hot-spots or epicentres where qualities of stand structure and microclimate predispose the resident budworm to especially rapid increase. If such epicentres can be characterized and the outbreak predicted, then it should be possible to control the local budworm population with an arsenal of weapons, including insecticides, before the surrounding, less susceptible stands are flooded with an outflow of surplus moths. The side-effects of such treatment would be rapidly diluted and corrected by faunal immigration from the untreated matrix.

The reduction of dosage is a feature of the spray history in the forest operations in New Brunswick. Initially guided by agricultural practice, the dosages of the various insecticides were unnecessarily high, and were reduced with experience. In forestry, we can tolerate a higher survival of pests than in agriculture.

The second group of methods is to isolate the target pest in space or time. This is the method so successfully used in treating migrant locust swarms in the Afro-Asian arid lands. We are now groping with its possible application to spruce budworm moths. Owing to the female's flight behavior, it might be technically possible to drift a spray cloud at low concentration through the thinly dispersed moth swarms, when enough is known about their migratory patterns. A lower insecticidal efficacy would be acceptable because such a technique would leave the predators and parasites intact in the forest canopy.

Isolation of the pest in time may be partially effective when young larvae are the target. Thus phosphamidon was used in early spring in the belief that its systemic properties would enable it to reach the mining larvae, before the associated fauna had emerged from winter diapause. Fenitrothion has also been used in the early spring to kill the budworm in the migrating and mining stages (a more difficult target than the later stages) with compensating safety for torpid pollinators and parasites, and migratory birds. Spraying in the vicinity of blueberry fields was conducted only on cool still mornings so that the drift would dissipate before the day was warm enough for bees to begin to forage.

The method can find weak spots in the pest's defence. For example, two chlorinated hydrocarbon insecticides used against pine sawflies, were absorbed in the foam covering of pest eggs inserted in the leaves. The sawfly hatchlings died when they hatched soon after spray; but minute parasite adults, emerging from the eggs later, were unharmed (Franz 1971).

The third group of methods concerns the choice and specificity of insecticides. The toxicological qualities of a candidate insecticide must be checked by large-scale field experiments in advance of operational use. Ideally, we need a budworm-specific insecticide, or a lepidoptera-specific insecticide, but such sharp-honed materials do not exist, nor is there an adequate profit inducement for chemical companies to underwrite the massive investment needed for such development. Nevertheless, there are prospects for narrowing the specificity of available insecticides by design or accident. The Canadian Forestry Service is researching the advantages of mixing pathogens and insecticides; the idea is that sublethal doses of insecticide may increase pest susceptibility to virus and bacterial disease. Alternatively, when a latent virus is naturally present on a pest population, low dosages of insecticide might trigger an epizootic (Franz 1971).

Specificity in insecticides might also be acquired by exploring the properties of the chemical, the formulation and spray physics, and by utilizing the behaviour of pest and non-target organisms. For example, it is possible that a systemic insecticide applied in a large-droplet spray might be quite effective as ingested poison to defoliating pests. The current trend to small droplet size distributes the insecticide primarily for contact toxicity; active searching and exploring parasites and predatory insects are more exposed to skin contact than slow-moving defoliators. On the other hand, fine atomization of the spray cloud has resulted in high efficacy to pests at lower dosage. In large-scale spraying of budworm infestations, this conflict between kill of parasites and pest has not yet been fully evaluated or resolved.

Another avenue is modification of the spray pattern. It is possible, but untested, that occasional unsprayed swathes, or use of two different insecticides in alternate swathes, might preserve a higher proportion of the resident beneficial insects, without lowering budworm mortality too much over the whole block. It is possible that an imperfect pattern of spray swathes - an untidy job - might be ecologically preferable to a technically perfect one.

As to the decision to initiate spraying in a rising infestation, consideration of the status of parasitism should be a preliminary. When a pest has a very high rate of parasitism, it might be preferable not to spray at all. This kind of judgment can be most competently made when the status of the pest is seen in the context of life-table studies.

RESEARCH ORGANIZATION TO GUARD AGAINST SIDE-EFFECTS

In eastern Canada, the practice of large-scale aerial spraying for forest protection is only about 20 years old. The spray operators, although commendably sensitive to ecological considerations, have been preoccupied with operational and logistic problems. Awareness of the ecological consequences has grown slowly in governmental and research circles, and development of administrative regulations and research methodology lagged at first.

Most of the spraying in eastern Canada has been conducted by a corporation representing the province of New Brunswick and the major pulp companies of that province, with some financial support from the Government of Canada. This corporation has extended its services under contract to the governments of neighboring provinces. It has collaborated closely with the various governmental research services monitoring the operations.

Within the Government of Canada, interdepartmental consultations on the ecological and public health aspects of the operations have been conducted for 20 years. Already by 1958, these relationships were formalized by the establishment of an Interdepartmental Committee on Forest Spraying Operations, combining representatives of forestry, fisheries, wildlife, agriculture, and health. This committee formulates research policy; for example, it advised on discarding DDT 4 years before use of the insecticide was restricted legislatively.

The conduct of research is the responsibility of individual government services aided by universities in voluntary projects and research contracts. Such research has been favored with increasingly better direction, staffing and finance over the years, but it has been largely inward-looking to the discipline. Cross-disciplinary collaboration has been weaker; in recent years, however, scientists have channelled their findings through the annual meeting of a Pesticides Ecology Research Group. The work of the Canadian Forestry Service's Chemical Control Research Institute has also become far more comprehensive as its program evolved. Finally, all the services concerned with ecology have been grouped since 1970 under the new Canada Department of the Environment.

Methods for investigating environmental change have evolved quite rapidly in the past decade. Pesticide ecologists working on the aerial spray operations have drawn heavily on the research results and services of taxonomists, toxicologists, pollution chemists, spray technologists, systems ecologists, population ecologists and others; such an array of specialists is essential to research in side-effects. However, field behaviour of pesticides does not always run parallel to laboratory expectations. The problem is that most ecosystems are too complex and variable to be adequately modelled by the research staff yet available. Monitoring has been largely short-term, and methods of measuring long-term impact are still imperfect.

The large-scale use of insecticides is hedged by several governmental regulations and protocols designed to protect public health and safeguard the environment. Any insecticide which reaches the field has cleared an impressive line up of regulative hurdles (Fettes 1971*).

Finally there is the question of public acquiescence to the policy and practice of large-scale spray application. The criticism can be fairly made that the public lacks ready access to information on the environmental impact of such practices. However, the governments of both the U.S.A. and Canada recognize that the environment is a public affair, and are putting effort into the communications gap. There is much merit in the U.S.A.'s Environmental Policy Act of 1969, which requires the agency proposing the spray operation to file a detailed statement on environmental impact and responsibilities. Such statements have already been produced for proposals to spray spruce budworm in Maine and the gypsy moth in the New England states. They are costly to prepare and pre-empt the time of scientists already busy with the spray operation itself. Nevertheless, such statements present factual information in one document for the perusal of legislators, the news media, environmental councils, conservation groups, the general public, and not least the spray agency itself. Such statements define pollution effects in various substrates; the expected ecological consequences; responsibilities for research, funding, operational decisions, policy decisions, and public health; legal aspects and regulative restrictions; priorities and problems. They ask such pointed questions as; "What happens if the spraying is not carried out?", and "Is the supposed problem really a problem, and is the action a solution?".

Impact statements are not mandatory in Canada, but scientists are called upon at times to advise legislative commissions on environmental policies and affairs. In public relations, scientists have much to learn in the presentation of results. The public is distrustful of such terms as "chemical control", "breakthrough", and "promising development". Public statements should be screened for jargon and technical shorthand, and mistakes should be openly acknowledged. Scientists and forest managers need the confidence of the general public.

Looking Forward

In its research direction, Canada is heading towards integrated resource management and integrated control procedures. It is not too deeply committed to chemical control methods at the expense of research diversity. However, research must develop greater predictive capacity; we need greater strength in simulation studies of ecosystem interactions, with emphasis on outbreak prevention, biocontrol mechanisms, and insecticidal stress. We are especially weak in monitoring the impact of chemicals on the ecological integrity of non-target ecosystems within the spray blocks. Such research will also help to define sensible standards for the regulation of pesticide usage. In future, the introduction of new pesticides will be more difficult because experimentation will be more exacting.

The forest manager must develop environmental ethics that balance current production of fiber with future multiple use of the forest estate. To quote Canada's Minister of the Environment, Mr. Jack Davis, "The environment has an engineering facet, an economic facet, and an ecological facet ... but it is the ecological determinant which must be right".

SUMMARY AND CONCLUSIONS

Large-scale spraying of insecticides to protect forests from defoliators has been in progress for 20 years in North America, especially against the spruce budworm epidemics in New Brunswick. Such operations have accumulated to 20 million ha. These operations have been technically successful, but brought unwanted side-effects, and authorities are again pondering the advisability of such practices.

The forest susceptible to spruce budworm attack is dominated by spruce and fir; its foliage supports a complex community of vertebrate and invertebrate animals and microflora, all linked by food-web relationships and population interactions. Insecticides act as an unpredictable stress on the balance in this community, but in general their impact is not as severe as the predictable stress imposed by defoliation.

The target forest incorporates extensive areas of non-susceptible trees and stands not endangered by the budworm; in such stands insecticides are an unwanted disruptive influence. The danger of ecological disruption stems from the huge area of sprayed forest, so big that animal migration is too slow to reestablish quickly the balance between pests and beneficial organisms.

From 1952 to 1967, DDT was the main insecticide employed in eastern Canada. Much of the emitted material was dissipated in the atmosphere, but thousands of tons were distributed on the target area. These residues have been innocuously adsorbed to the humus fractions of the surface litter, where they still persist and cycle slowly in the fauna. Smaller quantities persist in foliage but are rapidly being lost to the soil. Some residues remain in stream sediments but the rate of degradation is faster than in the soil.

The organophosphate insecticides have been used since 1963, first phosphamidon, now fenitrothion. The latter degrades rapidly, losing most of the potency in the first week. There is no sign of developing insect resistance after 5 successive years of treatment.

DDT did not appear to be seriously disruptive of the community in fir and spruce stands in spite of a satisfactory reduction of defoliation and pest density. Populations of beneficial insects were reduced but not disastrously. Minor pest irruptions did not occur on target or non-target trees. Moreover, DDT did not severely disturb survival of most bird species, although it did affect hunting interests. Its effects on aquatic habitats were more drastic and large losses of game fish resulted, causing a ban on its further use.

Fenitrothion has not so far been observed to cause serious dislocation of natural balance in the tree-dwelling communities, but populations of several groups on fir appear to be unstable, and there is concern over mortality of parasites. No minor pest species has responded to lowered biocontrol forces by assuming outbreak status, but incipient irruptions of defoliators on spruce and maple are suspicious portents. The effects on vertebrate animals have been insignificant at the time of spray, but there is some concern over unexplained reduction of game fish density in sprayed streams.

Some operational methods of minimizing side-effects are proposed: (1) reducing spray dosage and area, (2) isolating the target pest in space and time, (3) the specificity of insecticides.

The development of the research organization in Canada to monitor side-effects is discussed. The Government of Canada conducts most of the research on the environmental impact of the spraying but it is much assisted by the collaboration of provincial governments, the spray agency, and universities. Cross-disciplinary investigation has been weak, but the research effort is now more comprehensive and sophisticated. It is essential that research information be communicated to the general public if forestry practices are not to be hindered by public antipathy and misunderstanding.

This paper has been largely concerned with adverse side-effects, but I would like to conclude by putting them in perspective. The careful use of insecticides, as practiced in the forests of eastern Canada, has not only prevented economic losses and sociological disturbance, but also has prevented environmental degradation from the defoliating impact of the pest. These positive benefits of the spray program overwhelmingly outweigh the environmental costs resulting from side-effects so far recorded. The dilemma is that governmental authorities are reluctant to cease further use of chemicals because of the pest's persistent infestation, but are apprehensive of yet more spraying lest side-effects extend and intensify.

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