Proceedings of the CARNATION CREEK Herbicide Workshop
Proceedings of the Carnation Creek Herbicide Workshop

December 7 - 10, 1987

P.E. Reynolds, Ed.

Forest Pest Management Institute
Forestry Canada
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Sault Ste. Marie, Ontario
P6A 5M7

March 1989
Partial funding for the research project and the cost of printing this publication was provided by the Canada-British Columbia Forest Resource Development Agreement - a five year (1985-90) $300 million program cost-shared equally by the federal and provincial governments. Additional funding was provided by Monsanto Canada.

Canadian Cataloguing in Publication Data

Proceedings of the Carnation Creek Herbicide Workshop

(FRDA Report, ISSN 0835-0752 ; 063)

Issued under Forest Resource Development Agreement.
Co-published by B.C. Ministry of Forests.
"Canada/BC Economic & Regional Development Agreement".
ISBN 0-7726-0917-9


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This is a joint publication of Forestry Canada and the British Columbia Ministry of Forests.

Produced and distributed by the Ministry of Forests, Research Branch.

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Victoria, B.C. V8W 3E7
(604) 387-6719
FOREWORD

The Carnation Creek Herbicide Workshop was held on December 7-10, 1987 in Nanaimo, B.C. Over 150 people attended the workshop, which featured two days of oral presentations and a wrap-up one day discussion session. At the discussion session, workshop attendees divided up into various working groups to address special topics arising from the oral presentations. The workshop was the third Carnation Creek Workshop to be held.

The objective of the present workshop was to facilitate discussion of ROUNDPUP research conducted at Carnation Creek, and elsewhere within B.C., by operational and regulatory personnel. The wrap-up discussion sessions allowed environmental and fisheries regulatory personnel to interact with operational foresters in addressing problems and opportunities of mutual interest. Both groups are responsible for managing or regulating forest vegetation control treatments within coastal B.C. The discussion groups attempted to evaluate what is currently known based upon research presented at the workshop, what sorts of regulatory or operational policy changes are warranted based upon the conclusions of this research, and what additional research would be desirable based upon data gaps identified by the participants. Publication of the proceedings was delayed until after the workshop to allow for inclusion of these important deliberations.

Special thanks are extended to the many people who contributed to the organization and running of the workshop and to the countless hours of editing, word processing, and graphic art necessary to produce this proceedings in a final camera-ready version. Kathy Banky, Dan Lousier and Rick Ellis were responsible for organizing the workshop and for transcribing the deliberations of the discussion groups. Following the workshop, FPMI's word processing unit worked for nearly 15 months to produce this proceedings; I am grateful to Joanne Theriault, Donna Weeks, Judy Novick and Edna Morningstar for their untiring devotion to this project. The drawings in the various FPMI papers are the work of Sandra Mantulak. I reserve special praise and thanks for Karen Jamieson, FPMI's Scientific Editor, without whose able stewardship this proceedings would not have been possible. While Karen was away on maternity leave, Fiona Ortiz worked closely with me as Acting Scientific Editor. Finally, I thank Steve Chatwin for his assistance in preparing to go to press with this proceedings.

Often research papers do not bear the names of those who worked very hard to collect the data. Results presented in this proceedings would not have been possible without the efforts of Bruce Andersen, Jim Beveridge, Brent Birkedal, Tom Brown, T. Buscarini, A. Carter, Liesbet Croockewit, Dana Dekoven, Wayne Enlow, W.W. Kay, Herb Klassen, P. Klueckner, A. Langston, Dick Leahy, G. Lough, Linda MacDonald, Virve Manniste-Squire, Kevin McCullough, P.C.K. Pang, R. Rowswell, Bozena Staznik, K. Stephen, John Studens, Dal Travnick, Min Tsze, and Ann van Niekerk.

For me, completion of this project is a dream come true. Many thought the project was worth doing, but few felt it could be done. This proceedings is a tribute to those who believe dreams can come true. Two individuals deserve special mention and recognition for their efforts. Henry Benskin shared the dream from inception; I shall always be grateful for his untiring devotion to the success of this project. Charlie Scrivener, one of the founding fathers and guiding lights of the Carnation Creek research, has been a true delight and inspiration to work with. I am honoured to have had the opportunity and the privilege to work with Charlie.

Funding for a significant portion of the research, for the workshop and the proceedings was provided by the Canada-British Columbia Forest Resource Development Agreement (FRDA).

Phillip Reynolds
Editor and Coordinator of Herbicide Research
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CARNATION CREEK HERBICIDE WORKSHOP

OPENING REMARKS

Les Carlson
Director, Research and Development
Canadian Forestry Service
Ottawa, Ontario
K1A 1G5

I am happy to be here with you this morning, although I must confess that at times I wasn’t sure that I would make it—between getting travel authorization and then working around the Air Canada strike. It is my pleasure to be with a group of interesting people working on an important forestry and environmental problem such as the use of herbicides in the forest.

This morning, in addition to a little commercial background on the CFS, I would like to cover three other specific points regarding herbicide research: a) the problem and the initial approaches by the CFS; b) a little about our overall approach to research in this area; and c) herbicide research in context of the National Forest Sector Strategy.

This workshop represents a significant effort and contribution by all of the agencies involved, particularly the CFS and DFO. Equally recognized are the contributions of the B.C. Ministry of Forests and Lands, the B.C. Ministry of Environment and Parks, and the forest industries in the province, in particular MacMillan Bloedel Limited. While the workshop is focussed on the use of glyphosate, its approach to the overall problem involved in the use of herbicides in our forests will be useful for future research programs.

First of all, for those of you who don’t know who we are, the Canadian Forestry Service is part of Agriculture Canada. We hold a unique position within the Department in that we are represented by a Minister of State (Forestry and Mines) in the Government’s Cabinet. This is an administrative arrangement that allows us to develop and carry out our own programs without having the political domination of Agriculture, yet allows us to use their political strength in support of our programs. Like all marriages, it takes a lot of effort to make the arrangement work.

The Service will be 90 years old in two years and for most of that time it has been specifically oriented toward research. We have, however, at several different times in our existence, been involved in the delivery of joint federal/provincial forestry agreements. We are in that mode at the present time. In fact, the Canada/British Columbia forestry agreement is involved in funding this workshop.

The scope of our research, for example, ranges from this project on application and environmental affects of glyphosate to micropropagation of conifers to remote sensing technology. And like K-Tel records, many, many more activities in support of forestry and the forest interests of the people of Canada.

The second point I want to make is that we got into herbicide research because there was a need for the forest sector to have a variety of weed control options if they were going to be able to successfully put back those trees that they had taken in the harvesting process. We were aware of the need before, but it wasn’t until 1980 that the issue became more pressing. The CFS, while we were with federal Department of the Environment, in cooperation with Agriculture Canada and other federal agencies involved in the registration of pesticides, then organized a steering com-
mittee to review the work needed to complete the registration of several herbicides, i.e. glyphosate, hexazinone, and others. The Forest Pest Management Institute has been the CFS lead in the federal registration process for forest pesticides and therefore plays an important role in all pesticide research in forestry across Canada.

Now that you are aware of how we got into programs such as the Carnation Creek study with glyphosate, my third point is that you should be aware of the extent of CFS involvement in herbicide research. The Forest Pest Management Institute established a series of studies across the country that were designed to answer some of the more important concerns raised with the use of herbicides. Those concerns have been articulated very well by knowledgeable biologists, environmentalists, citizens and politicians.

Our research programs involving herbicides have been limited to the Institute, but have had a definite regional orientation. There has been work in Newfoundland, Ontario, the prairies and here in British Columbia.

The CFS research program, recognizing the concerns for the environment, is focused toward developing ecologically sound forest practices using herbicides and alternatives to herbicides in forest weed control. We have done this through various programs in some of our regional centres.

More specifically, here in B.C., the Pacific Forestry Centre has six scientists working on topics related to weed control such as weed autecology, as related to site preparation methods, and manual weed control methods (including the recent demonstration to contractors near Nelson on the use of brush saws). Included in this group are two researchers the Centre has brought in from other parts of the Canadian Forestry Service to work on the biocontrol of weeds using plant pathogens. This is the first effort of its kind in forestry in Canada, although work on biological control of weeds has been going on for some time in agriculture using insects and pathogens.

I want to issue a warning here. Biological controls are to be considered the ultimate in our fight against pests of all kinds. With insect control we have had some very good successes, but we face some extreme difficulties with weed control. It is high risk research, yet we intend to move forward in this area. In the meantime it will be necessary to have other tools in our hands for the management of the forests. Therefore, we will continue to develop methods that use safe chemicals and that allow us to safely apply effective chemicals.

Having seen how we got involved in the problem and some of the responses the CFS has taken, I would like to take up my fourth point of how these actions fit in with the context of the National Forest Sector Strategy for Canada.

Many of you may be aware that during the past two years the forest sector in Canada has been meeting in a series of four forums designed to thrash out the sector's problems. This series culminated last July in a meeting in Saint John, New Brunswick that developed a National Forest Sector Strategy for Canada. The strategy was approved by the Canadian Council of Forest Ministers in September. The full text of the strategy can be found in the October 1987 issue of The Forestry Chronicle.

Protection of the forests and reforestation were high on the list of priorities in the strategy. Two recommendations have to be considered in context of the program of research on herbicides and weed control.

Recommendation #9 reads: "It is recommended that all elements of the forest sector recognize that pesticides are among the legitimate means of effective forest management in specific areas, that their use continue to be regulated; and [that the forest sector]
- ensure that all pest management operations are ecologically and economically justified;
- encourage development and use of effective alternative methods of pest control, including integrated pest management;
- accelerate research into the environmental effects of pesticides; and
- ensure that the process for registration of pesticides for forest use is not cost prohibitive and is open to public scrutiny."

The second recommendation I want to bring to your attention is Recommendation #7 which reads: "It is recommended that foresters and wildlife managers cooperate in the review and development of forest, fisheries, wildlife, and integrated management." I also read this to include fisheries managers.

As we go through the next few days we should keep the spirit of these recommendations in mind. It is the latter that calls us to muster our resolve to work collectively and I see in this workshop a real opportunity to do so.

Thank you for listening and I hope you have a very profitable meeting.
INTRODUCTION: COOPERATION IN RESOURCE MANAGEMENT

Bill Bourgeois
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

Today I would like to talk to you briefly about cooperation in resource management. In the late 1970s the attitude for cooperation began to build momentum in resource management in coastal British Columbia. The economic downturn accentuated the need for this approach. All organizations and agencies found themselves in the position of not having or expecting to have the resources necessary to conduct priority activities. It was quickly accepted by many people that we needed to work together. Moving in this direction has not been without its problems. An example of this was the coastal fisheries/forestry guidelines. Fortunately, we have benefited from this experience with acceptance of the guidelines as a final result.

The guidelines contain a statement agreed to by all agencies and COFI that should serve as a basis for the approach to fisheries and forestry management. The statement is: "the objective of the coastal fisheries guidelines is to maximize the net benefits of the combined fisheries and forestry resources while minimizing time and cost." To satisfy this objective a cooperative approach is essential.

The economic and social world we live in today demands we manage our natural resources in truly an integrated manner. We cannot tolerate unjustified single use management. I recognize there are instances where the only known way to satisfy the guidelines objective is for single use management. However, we must strive to obtain information and tools that will keep these situations at a minimum. It is in this area where the work being discussed over the next three days is a prime example.

The challenge before you and other research and operations people is to conduct this work in a cooperative way. If we are to be successful in meeting this challenge, we cannot tolerate people or organizations that are not willing to work cooperatively towards the objectives of integrated resource management. We all know there are insufficient people and dollar resources available to conduct all the needed activities. If our objective is to use the available resources efficiently and effectively, a cooperative approach is the only way. It's easy to say "let's do the project or activity cooperatively"; it's more difficult to actually do it. It requires the individuals have skills to work as a team. It is also necessary that all parties agree on a common goal and be willing to deal with the differences of opinion in an objective and up front manner. The approach is not easy. We will all have to work hard at developing the cooperative approach.

The Carnation Creek program is a good example of a successful cooperative approach. I think all participants have gained over the years from this synergy. The herbicide project that you will be discussing is a challenge to all of you to continue the positive attitude and approach taken in the Carnation Creek program. We all know the herbicide issue is emotional and politically sensitive. This is an added challenge to the cooperative approach. How do we deal with the forestry concerns of productivity declines due to lack of vegetation control, costs of leaving pesticide free zones, and approval for use of safe and effective chemicals? At the same time we
have to consider the fisheries concerns of toxicity of chemicals to fish, accumulation of chemicals in the fish eaten by humans, and removal of required streamside vegetation. In addition we have to consider the political and emotional concerns of "chemicals are bad" and the pollution of domestic water supplies. Although it is not easy, we must insist on a cooperative approach to both research and operations activities involving the herbicide issue.

In summary, I would like to leave you with the following comments: we must manage resources in an integrated manner; our objective must be to maximize net benefits of the combined fisheries and forestry resources; available people and dollar resources are and will continue to be insufficient; the cooperative approach and attitude is essential if we are to use these resources effectively and efficiently. There are great challenges confronting us in conducting our business in this manner, especially in the areas such as herbicides. In the 1980s and 90s, there is no room in resource management for people or organizations that do not accept the cooperative approach. I leave you with this challenge and hope that the next three days assist you in meeting it.
INTRODUCTION: ISSUES AND CONCERNS RELATING TO THE USE OF HERBICIDES

Peter Ackurst
B.C. Forest Service
Vancouver Region
4595 Canada Way
Burnaby, B.C.
V5G 4L9

I think this workshop is a very important contribution to our knowledge of the use of herbicides in the forests of British Columbia. I would like to comment on several issues and concerns that the forest service and the forest community in general has with regards to use of herbicides in our forests.

Research: More research in the field of vegetation management and herbicides and more research into the interaction between our various resources is needed. We do not know all of the answers yet and research projects must continue in search of this knowledge. The Prime Minister and Provincial Premiers acknowledged this fact last week at their first ministers conference when they agreed to greater research and development efforts across Canada. Canada is not keeping up with the rest of the industrialized world in research and development and we in the natural resources sector must strive to keep our research expanding.

New provincial policy initiatives: The initiatives that were announced in September 1987 have had a big impact on the forest service and the forest industry. There are really two new policies, one on stumpage and one on reforestation. I don’t want to talk about stumpage at all and I hope no one else talks about stumpage at this workshop. But the second one, on reforestation, makes industry responsible for achieving free-growing status on all regenerated areas both operationally and financially. The forest service also has the same responsibility for large areas under the new policy. The latest quote from the forest service executives is that “the forest service is now the largest licensee of the Province.” This means that the forest service manages 16% of the allowable cut of the Province or over 12 million m³, or approximately 30,000 hectares of area logged per year.

The aim of both industry and the forest service is to put all harvested areas back to a free-growing status as soon as possible. These new policies mean that industry and the forest service will be looking at the most cost effective methods to achieve free-growing plantations. In many cases, this means the use of herbicides, but not in all cases. In many situations, if we do a good job of reforestation we can get a successful plantation without the use of herbicides. We should be striving to do this wherever possible. On some sites there will always be a need for herbicides. And when we deal with the backlog situation we’ll have to use herbicides more frequently. I think that it is an important point that we are striving not to use herbicides, but if necessary we will make use of them. The public is very concerned about us using herbicides all of the time.

Public concerns: We have a problem with public concerns over the use of herbicides in the forest. We must be sensitive to the public’s concern. The forest service is attempting to deal with these concerns through education programs and further studies. The forest service has a
small committee, called the "Forest Issues Steering Committee." It deals specifically with pesticide issues. To date it has been education-oriented, providing pamphlets, slide shows, information centres, demo forests, etc. Our future direction is more towards such things as risk management studies, cost-benefit studies, and other kinds of studies.

Before I leave the topic of public concerns, I would like to just comment that we should not overreact to the public pressure. In 1987, 488 pesticides permits were applied for, some of which have a three-year duration. Only 22 of these permits were appealed, the board denied 5 permits, amended 2, and there are still 15 permits pending. So 22 out of 488 is not a huge concern.

Staff training: We must keep our staff well-trained on technical facts and figures and with what is happening with current research. In addition, our staff must also be trained in the skills of dealing with the public and the media. Training is a constant concern and it must be kept up and maintained at all times. Certainly, this workshop is a good training session. To carry this point on, I feel there is a need for interpretation of research results to the field practitioners. This workshop is a good example of highly technical research papers that must be translated into field guides and operational principles that field staff can understand and follow. We must go the extra step to technology transfer. The new fisheries/forestry guidelines are just out, and we're all anxiously waiting to see what they are. But these guidelines are a good example of technology transfer. We must be constantly working to transfer new research results to the field.

Finally, cooperation (Bill's theme): We must continue to cooperate on the integrated management of fish and forestry. We can make more progress by cooperatively managing all resources rather than fighting with each other. This year, provincial government money has been allocated to the Ministry of Environment to monitor herbicide use and projects in the field. The forest service feels that it was our money that went from our budget to the Ministry of Environment, but it was all provincial government money given to manage our resources. These monies, if well spent, can contribute to the improvement of integrated management of all resources and I look forward to the results of these surveys and the projects that were carried out in 1987.

To finish up, I would just like to show you what was accomplished province-wide this year (Table 1).
Table 1. Vegetation management activities: 1987 estimates (Ministry and licensees) of hectares treated

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<th>Region</th>
<th>Chemical*</th>
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<td></td>
<td>Aerial</td>
<td>Hack and</td>
<td>Backpack</td>
<td>Other</td>
<td>All</td>
<td>Non</td>
<td>Total</td>
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<td>1,866</td>
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<tr>
<td>Kamloops</td>
<td>230</td>
<td>2,380</td>
<td>1,117</td>
<td>311</td>
<td>4,138</td>
<td>1,257(^c)</td>
<td>5,395</td>
</tr>
<tr>
<td>Nelson</td>
<td>265</td>
<td>216</td>
<td>329</td>
<td>10</td>
<td>820</td>
<td>542</td>
<td>1,362</td>
</tr>
<tr>
<td>Total</td>
<td>14,254</td>
<td>10,182</td>
<td>5,032</td>
<td>1,247</td>
<td>30,715</td>
<td>6,729</td>
<td>37,444</td>
</tr>
</tbody>
</table>

*Includes some site prep/rehab.
**Includes non-chemical site prep (over 110,000 ha).
\(^a\)All ground except H&I.
\(^b\)Includes 350 ha of grazing.
\(^c\)Includes 100 ha of grazing.

Table 2 is just a different breakdown that shows you the area treated by the Ministry and by licensees.

Table 2. 1987 vegetation management activities: hectares treated by Ministry and licensees

<table>
<thead>
<tr>
<th>Region</th>
<th>Ministry</th>
<th>Licensees</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vancouver</td>
<td>2,184</td>
<td>2,341</td>
<td>4,525</td>
</tr>
<tr>
<td>Prince Rupert</td>
<td>5,939</td>
<td>1,736</td>
<td>7,675</td>
</tr>
<tr>
<td>Prince George</td>
<td>5,107</td>
<td>11,534</td>
<td>16,641</td>
</tr>
<tr>
<td>Cariboo</td>
<td>1,473</td>
<td>373</td>
<td>1,846</td>
</tr>
<tr>
<td>Kamloops</td>
<td>5,362</td>
<td>33</td>
<td>5,395</td>
</tr>
<tr>
<td>Nelson</td>
<td>1,147</td>
<td>215</td>
<td>1,362</td>
</tr>
<tr>
<td>Total</td>
<td>21,212</td>
<td>16,232</td>
<td>37,444</td>
</tr>
</tbody>
</table>
Table 3 gives a cost comparison of the different vegetation management methods. The last one (Table 4) shows that the people who make ROUNDUP are doing quite well in the province of British Columbia. The use of herbicides is 94% ROUNDUP this year. And finally, in summary, I would just like to make the following points:

1. Herbicides are very important to foresters who have the responsibility to establish a new crop of trees on the ground; this is a tool that we must have.

2. This workshop is important to foresters for the purpose of communication and technology transfer.

3. Research into these complex interactions is important so that we can increase our knowledge and thus improve our management.

4. And, finally, cooperation is important between all agencies if we are to progress in the management of our collective resources.

Table 3. Vegetation management activities: 1987 treatment costs ($/ha)* by method

<table>
<thead>
<tr>
<th>Method</th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>$/ha</td>
<td>$/ha</td>
</tr>
<tr>
<td>Cutting</td>
<td>340-1,200</td>
<td>620</td>
</tr>
<tr>
<td>Girdling</td>
<td>45-820</td>
<td>375</td>
</tr>
<tr>
<td>Herbicide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spot gun</td>
<td>150-400</td>
<td>320</td>
</tr>
<tr>
<td>Hack and squirt</td>
<td>11-905</td>
<td>260</td>
</tr>
<tr>
<td>Ground</td>
<td>250-760</td>
<td>490</td>
</tr>
<tr>
<td>Aerial spray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- fixed wing</td>
<td>155-180</td>
<td>165</td>
</tr>
<tr>
<td>- helicopter</td>
<td>180-350</td>
<td>255</td>
</tr>
</tbody>
</table>

* Included direct on-site costs plus overhead and supervision
Table 4. 1987 vegetation management activities: percent of area treated by chemical (Ministry and licensees)

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vision (glyphosate)</td>
<td>93.9</td>
</tr>
<tr>
<td>Velpar L (hexazinone)</td>
<td>3.5</td>
</tr>
<tr>
<td>Forestamine (2,4-D amine)</td>
<td>2.6</td>
</tr>
</tbody>
</table>
INTRODUCTION: FISHERIES ISSUES

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Vancouver, B.C.
V6B 5G3

I intend to provide a quick overview of the fisheries issues associated with pesticide use in forestry. The three major areas I will touch on are mandates, protection strategies, and problems and solutions.

1. Mandate

The federal mandate for fisheries management is the Constitution Act (originally the BNA Act of 1867), which gives the federal government the authority for managing seacoast and inland fisheries, marine science and the administration of the Fisheries Act. Elements of the Fisheries Act predate confederation; today it continues as the principal federal pollution control instrument. Section 31 is concerned with the protection of the physical habitat of fish. The definition of habitat given in the Fisheries Act is all encompassing, including: spawning grounds, nursery areas, rearing areas, food supply and migration areas. Section 33 is the pollution prevention section of the Act and it states that no person shall deposit a deleterious substance in water frequented by fish.

In 1986, the DFO Minister presented the department’s Policy for the Management of Fish Habitat. This is a national document with the overall objective of a net gain in the productive capacity of fish habitat. The document points out that habitat damage should be avoided, mitigated or finally compensated for; but that compensation is not an option in the case of chemical pollution and contamination. The Policy states that mitigation must be practised to abate chemical pollution.

DFO inputs to Agriculture Canada in the registration of pesticides federally under the Pest Control Products Act.

The Province manages recreational fisheries, wildlife. and, because of ownership of Crown land and water, also manages waste discharges and pesticide use in British Columbia. Permit appeals under the Environmental Management Act are a provincial responsibility.

2. Protection Strategies

How are fisheries protected when pesticides are used? Nationally, as stated, DFO inputs to the registration process. On a regional level under the auspices of the B.C. Pesticide Control Act, a Pesticide Control Committee oversees a federal-provincial referral process for pesticide use on Crown Land. The DFO has input into that process through the Environmental Protection Department of the Environment.
A key fisheries protection strategy in the review of pesticide use near fish habitat is the application of the ten metre pesticide-free zone around waterbodies. This is a management strategy unique to B.C. in Canada. The ten metre pesticide-free zone, can be used to protect both potable waters and fisheries waters. It protects both water quality and riparian areas, or streamside zones.

The riparian zone of streamside vegetation along watercourses, provides five major items for fish: food, cover, shading, bank stability and sediment trapping, all of which are essential to fish production. The riparian zone also provides critical wildlife habitat. Another indirect benefit of the ten metre pesticide-free zone is that it may serve to minimize public appeals of permits through the Environment Management Act's Environmental Appeal Board.

To reiterate, the ten metre pesticide-free zone is a basic requirement around fish habitat and it is a technical as well as administrative management strategy unique to B.C.

A buffer zone, which is a recommendation in B.C., exists outside the ten metre pesticide-free zone, and is measured in addition to the pesticide-free zone. Buffer zones are usually used with the broadcast application of pesticides, as opposed to individual tree treatment methods. Buffer zones serve to protect the integrity of the ten metre pesticide-free zone: their size is determined through agency input and the professional judgment of the applicator. Buffer zones are site specific. The ten metre pesticide-free zone may be waived on a site specific basis where nonbroadcast techniques are used on a small scale.

3. Problems and Solutions

Regarding pesticide registration, there is a need for more region-specific toxicology data, to ensure the specific needs of Pacific salmon species are fully addressed. Salmon, because they are seagoing, have different physiological requirements than the commonly tested rainbow trout or fathead minnow. A promising area of testing in toxicology is the rapid sublethal trial. Information is inexpensive to develop but most useful. Also in a strong positive sense is the emerging improved dialogue and working relationship with pesticide manufacturers. Finally, the FRDA toxicity trials that are ongoing funded through CFS and BCFS, dealing with herbicides' sublethal effects on Pacific salmon, are very positive developments.

A second problem area relates to agricultural pesticide use. The agriculture industry is the major pesticide user in Canada. However, there are many applicators using toxic insecticides, without necessarily adequate pesticide-free zones on streams. Potential solutions to agriculture pesticide use problems perhaps lie in the training of farmers as certified pesticide applicators, similar to forestry applicators. Perhaps there is also a need for tighter restrictions on agricultural pesticides available. We are monitoring agricultural pesticide runoff and attempting to characterize problem usage.

A third problem area is the constant pressure to relax the ten metre pesticide-free zone. With broadcast pesticide application, the ten metre pesticide free zone around fish habitat is, as I have stated, a requirement, it is not negotiable: whereas the buffer zone is a recommendation, it is flexible and it is based on site specific conditions. The ten metre pesticide-free zone is a technical and administrative strategy. It’s a risk management tool. It protects not only water quality but as well, riparian vegetation. Finally, it appears that the ten metre pesticide-free zone is working well to protect fish and wildlife and their habitats. Solutions to the ten metre pesticide-free zone wrangle seem to be: an improved dialogue such as this meeting, to promote better understanding of our management philosophies, and to allow regulators and researchers to discuss their respective views.
In summary, there are federal/provincial mandates to protect fish and wildlife and their habitats. Objectives are achieved through a combination of technical and administrative strategies, supplemented by research, including that directed at minimizing off-target pesticide losses, which may allow smaller buffers outside the ten metre pesticide-free zone.
AN OVERVIEW OF CARNATION CREEK HERBICIDE STUDY: HISTORICAL PERSPECTIVE, EXPERIMENTAL PROTOCOLS, AND SPRAY OPERATIONS

P.E. Reynolds\textsuperscript{1}, J.C. Scrivener\textsuperscript{2}, L.B. Holtyb\textsuperscript{2} and P.D. Kingsbury\textsuperscript{1}

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P6A 5M7

\textsuperscript{2}Department of Fisheries and Oceans  
Biological Sciences Branch  
Pacific Biological Station  
Nanaimo, B.C.  
V9R 5K6

ABSTRACT

Research objectives, proposals and protocols for assessing the environmental impacts of applying ROUNDPUP (glyphosate) as a control of forest brush species at Carnation Creek were agreed to in 1984 by the British Columbia (B.C.) Ministry of Forests, B.C. Ministry of Environment and Parks, Canadian Forestry Service, Fisheries and Oceans Canada, and the Council of Forest Industries. Carnation Creek is a 10 km\textsuperscript{2} watershed in the high rainfall cedar-hemlock zone of coastal British Columbia, where the impacts of forestry practices on salmonids have been studied since 1970 under the Carnation Creek Experimental Watershed Project. Project objectives were to improve our understanding of any impacts and the relative magnitude of clearcut logging and post-logging forestry practices on salmon and trout populations and their stream habitat. The Forest Pest Management Institute coordinated and administered the herbicide study as a component to the overall Carnation Creek Experimental Watershed Project. ROUNDPUP was applied aerially at 2.0 kg/ha to 41.7 ha of the watershed in September 1984. A 10-m pesticide free zone was maintained along the stream, but two tributary swamps were oversprayed as part of the study design. Short-term direct impacts to stream water, vegetation, soils and stream biota were assessed. Long-term indirect impacts on water quality, erosion processes, and stream biota were studied until at least June 1986.

INTRODUCTION

In September 1983, the Forest Pest Management Institute (FPMI) of the Canadian Forestry Service (CFS) visited British Columbia (B.C.) to examine forest weed problems in five of the six B.C. forest regions. The visit was sponsored by the B.C. Ministry of Forests (MOF). Following the visit, the MOF proposed that the CFS undertake cooperative research in the province to expedite registration of new forestry herbicides and to assess possible environmental impacts associated with operational use of these herbicides. Use of herbicides was anticipated on productive forest sites within the B.C. coastal zone and a major environmental concern potentially preventing that use of forestry herbicides was possible impacts on salmonids and their habitat. The Carnation Creek Experimental Watershed located on the western side of Vancouver Island was suggested as a prime location for evaluating possible herbicide impacts.

Since 1970, the Carnation Creek Watershed has been an active research site for evaluating the impacts of forest harvesting and other forest practices on salmon and salmon habitat in studies carried out by CFS, by Fisheries and Science branches of Fisheries and Oceans Canada (DFO), and by Water Survey of Canada. Thus, the watershed offered an ideal, extensively studied location, where existing forestry impact studies could be expanded by evaluating the impact of forestry herbicides on fish and fish habitat.
In December 1983, a planning session was held in Victoria, B.C. to discuss research needs with federal and provincial environmental regulators, to solicit their views on study objectives, and to invite their active participation in any future research. Out of this meeting was born the support and the cooperation for the current Carnation Creek Herbicide Study. When the MOF quickly followed through with financial support for the proposed research, other agencies also began contributing resources to the study. Major funding was provided via Monsanto Canada, the manufacturer of ROUNDUP™ (glyphosate). FPMI was designated as the lead and coordinating agency for carrying out the research and for administering research funds associated with the project.

WATERSHED DESCRIPTION

Carnation Creek is a small watershed (10 km²), which drains into Barkley Sound on the west coast of Vancouver Island. Annual precipitation is 210-480 cm (Hetherington 1982), 75% of it falls between October and March, and 95% of it falls as rain. Stream flow is highly variable, ranging from .025 m³/s in summer to 33 m³/s during winter freshet. Peak flows of 37, 44, and 64 m³/s with return periods of 5, 12, and 50 years respectively have been observed during the study.

The topography of the basin features rugged terrain of steep slopes to 700 m elevation and a narrow valley bottom through which the stream meanders. The area was heavily glaciated during the Pleistocene period. Slope soils are shallow, coarse textured and highly organic (Oswald 1973). Bedrock is mainly of volcanic origin. Soils in the valley bottom are derived from recent alluvium, which is underlain by gravel deposits (as deep as 4 m), bedrock, and some silty clay deposits.

The pre-harvest vegetation and soils in the drainage were described at the 1982 workshop (Oswald 1982). The primary forest trees in the Carnation Creek drainage basin are western hemlock _Tsuga heterophylla_ [Raf.] Sarg., western redcedar (_Thuja plicata_ Donn), amabilis fir (_Abies amabilis_ [Dougl.] Forbes), Douglas-fir (_Pseudotsuga menziesii_ [Mirb.] Franco), Sitka spruce (_Picea sitchensis_ [Bong.] Carr.), and red alder (_Alnus rubra_ Bong.). The predominant shrubs are salal (_Gaultheria shallon_), stink current (_Ribes bracteosum_), salmonberry (_Rubus speciosus_), and four species of _Vaccinium_.

Originally, the main channel and tributaries were bordered by red alder, western red cedar and Sitka spruce. This canopy and its thick understory shaded the stream so that light intensities were one sixth of those of adjacent areas with no trees (de Leeuw 1982). By 1984, red alder and salmonberry again shaded the tributaries, but not the main channel.

Anadromous fish use the lower 3.2 km of Carnation Creek and its tributaries. In the mainstem, mean gradient is 0.9% and the bed is characterized by gravel with few particles greater than 100 mm in diameter (Scrivener 1975). Numerous accumulations of fallen trees and buried logs occur in the channel. Extensive gravel bars indicate considerable gravel movement. Valley-wall tributaries, which include Tributaries C, J, and H, and three unnamed tributaries, have gradients ranging from 16.5 to 49% (Fig. 1). These tributaries descend all the way to Carnation Creek or descend for most of their length before crossing a short distance of floodplain. They contain bedrock and boulder bottoms and many fallen trees, some of which store gravel. Often, they also contain cutthroat trout (_Salmo clarki_). The valley-floor tributaries or wall-base channels (Peterson and Reid 1984), which include Tributaries 750, 1600, and 2600, have gradients of <1.5% and are fed by groundwater and ephemeral seepage channels along the valley walls (Hartman et al. 1987). They flow among fallen trees and their beds are organic muck which contain rooted aquatic plants (Brown 1985). Some lower reaches contain sandy gravel bottoms. These valley-floor tributaries are used extensively by salmon and trout.

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1 Registered trademark of Monsanto, Inc., St. Louis, MO.
Figure 1. Map of Carnation Creek Watershed showing the locations of glyphosate spray blocks.
HISTORICAL PERSPECTIVE

Pre-herbicide Studies

In 1970, forest and fishery managers were growing concerned about the potential impacts of clear-cut logging practices on salmon stocks of western North America. Logging practices were major topics of a salmon and trout symposium in 1968 at the University of B.C. (Northcote 1969) and in 1970 at Corvallis, Oregon (Krygier and Hall 1971), but little detailed information was available from B.C., or from cedar-hemlock watersheds (Narver and Chamberlin 1976). These old-growth forests are typical of coastal North America from the Olympic Peninsula in Washington State to southeast Alaska and the Queen Charlotte Islands (Krajina 1969). During the summer and autumn of 1970, DFO examined fish populations in a number of coastal streams (Narver 1972; Narver and Andersen 1974). Carnation Creek was chosen as the site for a study of the influences of watershed processes on streams and their fish and how these processes are affected by forestry practices. The varied expertise that was required to quantify these processes was obtained through the cooperation of DFO, MOF, CFS, B.C. Ministry of Environment and Parks, Water Survey of Canada, B.C. Universities and MacMillan Bloedel Ltd. Component studies of the pre-herbicide research have been described in detail elsewhere (Scrivener 1988).

Important objectives of the Carnation Creek Project included assisting managers developing resource management strategies for forests and fisheries and communicating results to the scientific/technical community. Technical input during development of the new Coastal Fisheries Forestry Guidelines was continuous (BCMFL et al. 1987). Results have been reported previously during two major workshops (Hartman 1982; Chamberlin et al. 1988), and in 147 articles or reports through a variety of media (Polin and Scrivener 1988).

As initially planned, the Project had a pre-logging stage (1970-1975), a logging stage (1976-1981) and a post-logging stage (1982-1986). During the logging stage, 41% of drainage area was clearcut in winter as 13 cutblocks using high lead systems (Dryburgh 1982; Hartman et al. 1987). The cutblocks were burned, scarified or left untreated and tree seedlings were planted on the valley bottom and lower slopes. Tributary C and the drainage above E-weir were untreated and served as internal control watersheds (Fig. 1).

The logging plan contained three streamside treatments along the area of stream that was used by salmon and trout. The undisturbed portion (58.4 ha) left the lower 1300 m of Carnation Creek with a variable width strip of deciduous vegetation and some merchantable trees along its banks. This area included the mouth of Tributary 750 (Fig. 1). In the intense streamside treatment (1300-2200 m), streamside alder were girdled and injected with TORDON 22K herbicide, and all merchantable timber was harvested. Timber was either felled away from the channel, or if leaning heavily, across it, and then yanked away from the stream to roadside landings. Streambanks and large debris in the channel were damaged. This area (102.7 ha) included Tributaries J and 1600 (Fig. 1). In the careful streamside treatment (2200-3200 m), minor vegetation such as salmonberry was left along the stream and only six merchantable trees that could not be jacked or cabled were felled across the channel and removed. Streamside alders were felled, and during scarification, the logging debris was piled for burning. This area (76 ha) included Tributary 2600. Operationally, treatments two and three are no longer permitted along stream segments that contain salmon.

Herbicide Study

At the herbicide research meeting in December 1983, the major concern that was expressed by provincial and federal managers of fishery resources involved potential impacts to salmonids or

2 Registered trademark of Dow Chemical Co., Midland, Mich.
riparian habitat that was oversprayed with herbicide. A policy of maintaining a 10-m pesticide
free zone along all fisheries sensitive streams had been established to protect riparian vegeta-
tion and water quality. Operational forest managers and spray applicators at the meeting indi-
cated that deliberate overspray of streams visible from the air was not likely, since avoidance of
such streams was both feasible and accepted practice. However, possible overspray of tributary
back channels that were overgrown by vegetation and used mainly as overwintering habitat for sal-
monids, was considered unavoidable and probable. The potential impacts of such oversprays, direct
or indirect, were unknown and unquantified. Hence, the herbicide research at Carnation Creek was
concentrated in these overwintering tributaries. Previous research at Carnation Creek, aimed at
assessing logging impacts, had focused more on the main channel.

The proposed herbicide research both redefined and expanded the 5-year post-logging stage
of the Carnation Creek Project. Originally the post-logging stage was to end in 1986, and no
post-logging use of herbicides was envisioned. Since post-logging use of forest management
practices such as site preparation, scarification, prescribed burning, or herbicides have been
routine, expanding the Project provided an opportunity to examine the potential impacts and rela-
tive magnitude of these practices.

Following the December 1983 meeting, key researchers met at Carnation Creek in March 1984
to define the research objectives and experimental protocols that were released in April 1984.

STUDY DESIGN OF HERBICIDE RESEARCH

A decision was made to design a herbicide environmental fate/impact study at Carnation
Creek which would:
(1) maintain a 10-m vegetation buffer along the main creek, but
(2) allow for an overspray of certain floodplain tributaries used as overwintering habitat
by salmon and trout.

Debate among researchers included whether the herbicide would complicate interpretation of
ongoing or future research and what herbicide should be chosen for study, triclopyr (GARLON3 ) or
glyphosate (ROUNDUP). After the study began, glyphosate was the herbicide selected because:
(1) the Carnation Creek Steering Committee decided to forego triclopyr testing due to un-
certainties in relation to environmental impact and
(2) regional environmental impact data was needed for glyphosate, one of only two herbi-
cides presently federally registered for forestry use.

Concerns about potential herbicide impacts focused on direct or indirect effects. Direct
impacts concerned short-term (96 hours) toxicity to fish or stream invertebrates, resulting from
overspray or off-target drift, or long-term (up to one year) toxicity resulting from herbicide
residue inputs, from winter fresnets into side channels used by overwintering salmonids or emer-
ging fry. In general, regulators wanted information on short-term impacts, while researchers
designing the study were more concerned with long-term impacts. Researchers were concerned that
the long-term fate of herbicide residues in a coastal watershed had never previously been quanti-
fied, and did not know if toxic levels would enter the tributaries during and following winter
fresnets. Other regulators were concerned about sublethal effects, a longer-term impact of the
herbicide, on fish movements, reproduction, etc. However, researchers concluded that long-term
fate of herbicide residues had to be properly quantified before any sublethal effects could be
assessed.

3 Registered trademark of Dow Chemical Co., Midland, Mich.
Indirect impacts were accorded greater importance by researchers designing the experiment. These impacts on salmonids were likely to be far more significant than direct effects because herbicides are used to reduce brush species that maintain stability of the stream channel and quality of salmonid habitat (Gregory et al. 1987; Hartman et al. 1987). Indirect impacts concerned long-term habitat (i.e., riparian or stream) changes resulting from overspraying overwintering tributaries.

Objectives:

With this background, the objectives of the Carnation Creek ROUNDUP Study were defined to include:

1. Monitoring off-target glyphosate deposit;
2. Monitoring short-term glyphosate residues in oversprayed tributaries and those entering Carnation Creek from these tributaries;
3. Monitoring short-term, immediate effects of aerial ROUNDUP application on salmon fry behavior, movements and mortality in relation to measured glyphosate residue levels in flowing tributaries and isolated pools in the experimental area;
4. Monitoring short-term aquatic invertebrate drift resulting from ROUNDUP exposure;
5. Monitoring the movement of glyphosate residues into side channels following major fall and winter storm events;
6. Measuring the persistence and dissipation of glyphosate in riparian foliage and soils;
7. Assessing habitat changes induced by glyphosate (water temperature, changes in riparian vegetation, erosion, sediment inputs, stream chemistry, algal populations, aquatic and terrestrial invertebrate fish-food, litter inputs, etc.) in stream and side channels; and
8. Monitoring fish utilization of side channels for 2 years following glyphosate application relative to habitat changes or relative to glyphosate residues in water and stream sediment.

EXPERIMENTAL PROTOCOLS

Specific protocols called for the following:
1. Maintenance of a 10-metre vegetation buffer on either side of Carnation Creek;
2. Overspray of two side channels designated as 750 and 1600;
3. A third side channel, designated as 2600, to serve as a control side channel for 1600 and 750 (2600 is located above the portion of the watershed to be aerially treated with herbicide);
4. Mortality and/or movements of fish to be recorded for 1600, 750 and 2600 during and immediately after spraying (96 hours);
5. Invertebrate drift to be quantified for 1600 and 2600 during and immediately after spraying (96 hours);
6. Streamwater samples to be collected from Carnation Creek, 1600, 750 and 2600 during and immediately after spraying (96 hours) for residue analysis;
7. Off-target deposit samples to be collected from within the 10-metre vegetation buffer and from within the main channel of Carnation Creek following the herbicide application for residue analysis;
8. Soil samples to be collected periodically for one year after herbicide treatment for residue analysis;
9. Erosional changes affecting Carnation Creek to be measured periodically prior to and after herbicide treatment;
(10) Streamwater and stream sediment samples to be collected from 1600, 750 and 2600 after major storm events (freshets) for the first six months after herbicide treatment for residue analysis;
(11) Streamwater and stream sediment samples to be collected twice monthly from 1600, 750 and 2600 for seven through twelve months after herbicide treatment for residue analysis;
(12) Streamwater samples to be collected periodically from Carnation Creek, 1600 and 2600 prior to and for 2 years after herbicide treatment for analysis of dissolved ions;
(13) Stream temperature to be monitored continuously in 1600 and 2600 tributaries until October 1986;
(14) Periphyton samples to be collected periodically from Carnation Creek, 1600 and 2600 prior to and after herbicide treatment for analysis;
(15) Alder and salmonberry leaves to be collected periodically prior to and after herbicide treatment for residue analysis;
(16) Detrital inputs to be measured periodically for 1600, 750 and 2600 prior to and after herbicide treatment;
(17) Aquatic invertebrate samples to be collected periodically from Carnation Creek, 1600, 750 and 2600 prior to and after herbicide treatment for identification and quantification;
(18) Input to the stream of terrestrial insects to be measured periodically for 1600, 750 and 2600 prior to and after herbicide treatment;
(19) Long-term fish mortality and utilization of 1600, 750 and 2600 to be monitored periodically after herbicide treatment, and compared with pre-treatment utilization patterns; fish mortality and utilization to be studied in reference to long-term residues and habitat changes; and
(20) Herbicide efficacy, crop tolerance and crop growth to be evaluated periodically after herbicide treatment.

**SPRAY OPERATIONS**

Carnation Creek watershed was aerially treated with ROUNDDUP in early September 1984 using an Alpine Helicopter Bell-47 helicopter equipped with a MICROFOIL BOOM⁴ to minimize aerial herbicide drift into fish-bearing waters. Spraying was carried out by Rotor Vegetation Control of Calgary under the direction of the FPMI. A map showing actual spray blocks is presented in Figure 1 and hectares, spray dates, spray times, air temperature, wind conditions, etc. are presented in Tables 1-3.

**Protocol Deviations and Their Rationale**

Research was carried out as described in the April 1984 protocols with only minor deviations. The watershed was treated at 2.0 kg a.i./ha of ROUNDDUP versus 1.7 kg a.i./ha to more closely approximate the maximum recommended label rate and to enhance herbicide efficacy (spraying was late season and some of the vegetation was already senescent). However, it should be noted that previous MacMillan-Bloedel data supplied to FPMI indicates that an application rate of 1.7 kg a.i./ha is optimal for coastal weed control.

Tributaries C and 1450, side channels of Carnation Creek, were not oversprayed as originally planned. These areas were known or found to contain salmonids. The study thereby

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Table 1. Treatment conditions (all meteorological data was obtained from recording instruments at Station A; Scrivener 1988)

<table>
<thead>
<tr>
<th>Herbicide (a.i.)</th>
<th>glyphosate (356 g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment rate</td>
<td>2.0 kg a.i./ha</td>
</tr>
<tr>
<td>Spray volume</td>
<td>258.25 L/ha</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Bell-47 helicopter</td>
</tr>
<tr>
<td>Boom and nozzles</td>
<td>MICROFOIL BOOM, 7.9 m in length, .060 hayrake nozzles</td>
</tr>
<tr>
<td>Orientation of nozzles</td>
<td>180°</td>
</tr>
<tr>
<td>Boom pressure</td>
<td>172.5 kPa</td>
</tr>
<tr>
<td>Airspeed</td>
<td>40.2 km/h</td>
</tr>
<tr>
<td>Swath width and altitude</td>
<td>12.1 m; 6-18 m</td>
</tr>
<tr>
<td>Weather (prior)</td>
<td>Sunny and calm winds immediately prior to Sept. 6; intermittent showers on Sept. 7 and each day from Sept. 9 through Sept. 12; sunny with NE winds to 22 km/h on Sept. 13</td>
</tr>
<tr>
<td>(at times of spraying)</td>
<td>Sept. 6 – time: 1900-2005 h; air temperature: 15°C; wind conditions: 7 km/h E to W; skies: cloudy, overcast, intermittent sun; precipitation: none</td>
</tr>
<tr>
<td></td>
<td>Sept. 8 – times: 1416-1445 h and 1913-1940 h; wind conditions: 7-10 km/h E to W; skies: overcast, black clouds, threatening showers; precipitation: none</td>
</tr>
<tr>
<td></td>
<td>Sept. 14 – time: 1430-1931 h; air temperature: 21°C; wind conditions: 5-11 km/h E to W; skies: sunny, overcast, white clouds; precipitation: none</td>
</tr>
<tr>
<td></td>
<td>Sept. 15 – time: 1041-1101 h; air temperature: 14°C; wind conditions: &lt; 5 km/h E to W; skies: sunny; precipitation: beginning at 1345 h</td>
</tr>
<tr>
<td>(after)</td>
<td>Winds increasing in speed and changing direction (W to E) by 1130 h on Sept. 15; cloudy and overcast, with rain clouds moving in from sea by 1200 h; rain showers began at 1345 h on Sept. 15, and heavy rain continued through 1500 h on Sept. 16</td>
</tr>
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</table>
Table 2. Spray Data for Carnation Creek Watershed

<table>
<thead>
<tr>
<th>Spray block</th>
<th>Spray date (Sept.)</th>
<th>Time period</th>
<th>Application rate (kg. a.i./ha) (Glyphosate)</th>
<th>Tank mix</th>
<th>Spray volume (I.G.)</th>
<th>Block size (ha)</th>
<th>Air temp. (°C)</th>
<th>Wind conditions km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1900-1925</td>
<td>2.0</td>
<td>1</td>
<td>140</td>
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<td>≤ 7</td>
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<tr>
<td>2</td>
<td>6</td>
<td>1935-2005</td>
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<td>1</td>
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<td>3.1</td>
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<td>7</td>
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<tr>
<td>3</td>
<td>8</td>
<td>1416-1445</td>
<td>2.0</td>
<td>1</td>
<td>300</td>
<td>5.3</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>1913-1940</td>
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<td>1</td>
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<td>3.2</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>1430-1539</td>
<td>2.118&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2</td>
<td>505</td>
<td>8.9</td>
<td>21</td>
<td>10</td>
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<td>6</td>
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<td>1646-1715</td>
<td>2.118&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>235</td>
<td>4.1</td>
<td>21</td>
<td>&lt; 7</td>
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<tr>
<td>7</td>
<td>14</td>
<td>1730-1814</td>
<td>2.118/2.125&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2/3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>290</td>
<td>5.1</td>
<td>21</td>
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<td>8</td>
<td>14</td>
<td>1840-1849</td>
<td>2.125</td>
<td>3</td>
<td>63</td>
<td>1.1</td>
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<td>100</td>
<td>1.7</td>
<td>14</td>
<td>&lt; 5</td>
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<tr>
<td>11</td>
<td>15</td>
<td>1053-1101</td>
<td>2.125</td>
<td>3</td>
<td>100</td>
<td>1.7</td>
<td>14</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based upon spray volume and calibration of spray system (56.8 I.G./ha).

<sup>b</sup> Residual spray solution in the tank and pumping system was assumed to be 50 Imperial gallons (I.G.) after each tank mix was used. Therefore, the concentration of active ingredient (a.i.) remaining subsequently changed the rate for tank mix #2 and tank mix #3.

<sup>c</sup> In spray block #7, the area closest to Carnation Creek received 100 I.G. from the 2nd tank mix while the area farthest from Carnation Creek received 190 I.G. from the 3rd tank mix for a total of 290 I.G.
Table 3. Spray data for specific Carnation Creek sprayblocks

<table>
<thead>
<tr>
<th>Spray period</th>
<th>Spray Block 5</th>
<th>Spray Block 6</th>
<th>Spray Block 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tributary 1600</td>
<td>Connection with 1600</td>
<td>Tributary 750</td>
</tr>
<tr>
<td>Time</td>
<td>Duration (Min)</td>
<td>Time</td>
<td>Duration (Min)</td>
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<tr>
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<td>1433-1438</td>
<td>5</td>
<td>1646-1652</td>
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<tr>
<td>2</td>
<td>1443-1445</td>
<td>2</td>
<td>1654-1659</td>
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<td>3</td>
<td>1451-1453</td>
<td>2</td>
<td>1703-1707</td>
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<td>4</td>
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<td>1709-1715</td>
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<td>1507-1510</td>
<td>-</td>
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<td>6</td>
<td>1514-1518</td>
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<td>7</td>
<td>1522-1526</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>1530-1534</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Spraying began closest to Carnation Creek and moved upslope away from Carnation Creek.
conformed more closely to the regulatory policy of DFO. Because of reduced spraying near 1450, tank mix solution was left over at the conclusion of spraying. This mixed solution was sprayed onto an adjoining portion of the watershed (spray block 11) and one original spray block (spray block 9) was enlarged (spray block 10) to accommodate the left over solution. Rinseate from the helicopter spray tanks and boom was sprayed onto portions of the adjoining spray block (Number 11).

LITERATURE CITED


CARNATION CREEK FLOODPLAIN HYDROLOGY

SEPTEMBER 1984 - SEPTEMBER 1985

Eugene D. Hetherington
Pacific Forestry Centre
Canadian Forestry Service
506 West Burnside Rd.
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V8Z 1M5

ABSTRACT

The precipitation, streamflow, and groundwater regimes in the lower Carnation Creek floodplain are described for the 1-year period encompassing the application and monitoring of the environmental behaviour of the herbicide glyphosate. Rainfall just prior to the first herbicide application on the floodplain moistened the soil on well-drained areas and initiated ponding and flow of water in side channel depressions and swamps. The next rainfall on blocks containing monitored tributaries and seasonally flooded soil residue sampling sites came within 24 hours after herbicide application. Rainfall during the next 10 weeks was above average, providing ample opportunity for off-site movement and leaching of any mobile herbicide residues. However, precipitation then remained below average for the rest of the study period. Surface water was continuously present in floodplain depressions and side channels until the following summer, with groundwater levels rising and falling in response to rainfall events. Surface soil layers on well-drained soil sampling sites would have remained moist but unsaturated and above the groundwater table throughout most of the study period. Of the three seasonally flooded soil sampling sites, two remained saturated and were frequently flooded until the following summer, while the other experienced unsaturated periods, particularly during the first 3 weeks after application, and only occasional flooding. The implications of these soil water regimes are that any mobile herbicide residues would have leached vertically downward on well-drained sites and under non-saturated soil conditions, but would have tended to move laterally from seasonally flooded stations during flooding and saturated conditions.

INTRODUCTION

The information presented herein provides an a posteriori description of the floodplain hydrology to aid other workers in interpreting the environmental fate of glyphosate and its major metabolite aminomethylphosphonic acid (AMPA). Precipitation and streamflow data were collected during the 1984-1985 herbicide study period as part of the regular Carnation Creek Project monitoring program. In addition, some groundwater measurements were taken from June to early October 1984 and 1985 as part of another study. However, direct on-site measurements of groundwater levels during the residue sampling period are lacking. The nature of the floodplain microroughography makes it difficult to generalize about off-channel flooding on the basis of information available, but some reasonable speculations can be made about specific sites. Probable groundwater and flooding conditions within soil sampling stations at sampling times have been estimated by piecing together the hydrological data that are available for the period of interest, anecdotal comments from field notes (H. Klassen, V.A. Poulin & Assoc., Vancouver B.C., personal communica-
have been particularly helpful. Additional surface water observations and groundwater measurements were also collected in 1987 at soil residue sampling sites to provide further clues.

The objectives of this paper are to present precipitation and streamflow data for September 1984 to September 1985, describe the nature of groundwater behaviour in the Carnation Creek floodplain and evaluate probable hydrologic conditions at soil residue sampling sites for the specific days of sample collection.

**STUDY AREA**

**Floodplain**

The lower floodplain of Carnation Creek (Fig. 1) is about 3000 m long, 50 ha in area, and has an average channel slope of 1.9% (Brown 1985). In the past, the stream has moved back and forth across the floodplain, leaving numerous old channels separated by slightly raised sand and gravel beds. Vegetation has occupied the raised areas while many of the old channel depressions have become swamps or ephemeral stream channels which occupy about 1.3 ha at low winter flow periods (Brown 1985). These coarse alluvial deposits are as deep as 4 m (Scrivener and Brownlee 1980). In the depressions, accumulations of fine organic material have resulted in muck blankets as much as 1 m deep with a variety of ground vegetation described in detail by Brown (1985). The soils on the raised areas occupied by trees are alluvial regosols from about 0 to 60 cm deep with sandy loam textures (Oswald 1973). These coarse soils have high infiltration and percolation rates and allow rainwater to move quickly down to the groundwater table. The main channel

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**Figure 1.** Map of Carnation Creek floodplain showing locations of piezometers, rain gauges, soil and water sampling sites and approximate spray block boundaries (modified from Brown 1985).
morphology and debris accumulations determine where and at what flow levels the stream will overflow its banks and enter some of these old channels or simply cover the floodplain. The degree of overflow varies both along the length of the channel and over time as channel geometry changes due to shifting of gravel and debris during storm flows. During major rain storms, surface runoff in side channels will also increase, expanding the area of surface water flow and extending it beyond defined channel depressions.

The 750-m, 1450-m, and 1600-m side tributaries vary in size and flow, each having contributing side slope drainage areas that exceed those in the floodplain itself. The 1450-m tributary has a total drainage area of about 50 ha which includes the gauged 24-ha J Creek watershed. However, flow dispersal across and into an elevated alluvial fan results in only a portion of the flow occurring in the ephemeral channel from which water samples were collected for herbicide residue analysis. Drainage areas for the 750-m and 1600-m tributaries are approximately 9 and 13 ha and their channel lengths in the floodplain are about 100 m and 250 m, respectively. The 750-m channel carries water fairly directly from the side slope to the main Carnation Creek channel, while the 1600-m channel meanders across the floodplain and contains considerable amounts of woody debris. Water from Carnation Creek enters the 750-m channel when flows exceed 7 m$^3$ s$^{-1}$ and the upper 1600-m channel when flows exceed 20 m$^3$ s$^{-1}$ (Brown 1985). Carnation Creek water also enters the 1450-m channel in its lowest portion and the lower part of 1600-m channel at flows less than 20 m$^3$ s$^{-1}$, but the flows at which this occurs have not been evaluated.

The soil herbicide residue sampling stations #1 to #3 and #7 to #9 (S13 and S79 in Fig. 1) are located on raised well-drained sandy-gravel beds. More information on soil characteristics at these stations is given by Feng and Thompson (1989). Stations #4 and #5 (S46 in Fig. 1) are situated in a gently sloping ill-defined and seasonally flooded side channel, and station #6 (S46 in Fig. 1) is located downstream immediately adjacent to a more well-defined portion of the same channel.

**Climate and Streamflow**

The climate features mild summers and mild wet winters with frequent frontal rain storms. Annual precipitation on the floodplain occurs mostly as rain and has ranged from about 2100 to 3850 mm. Average precipitation for the total watershed is about 20% higher than on the low-elevation floodplain (Hetherington 1988). Maximum annual daily rainfall on the floodplain has ranged from 80 to 220 mm. Some snow occurs at higher elevations in the watershed almost every year but the snowpack is usually short-lived and probably represents less than about 5% of the total precipitation. Snow has occurred on the floodplain in 8 of 14 winters prior to 1985. Annual water yields (total streamflow) have ranged from 2100 to 4000 mm (depth over the drainage area) and measured flows from less than 0.03 to 65 m$^3$ s$^{-1}$. Both streamflow and groundwater levels respond rapidly to storm rainfall, rising and falling in concert with variations in rainfall intensity or cessation (Hetherington 1982). The frequency of major stormflow events (flows exceeding 6.7 m$^3$ s$^{-1}$ at weir B) has ranged from 7 to 21 per year with an average number of 14 (Hetherington 1988).

**METHODS**

A comparison of precipitation data from gauges at the main weather station (CDF), weir B, and weir C on the floodplain (Fig. 1) indicated that the daily station CDF data adequately represent floodplain precipitation. Hence, CDF data are used in this paper because they were readily accessible and had been verified. Hourly precipitation values recorded at the field camp
were adjusted using ratios of CDF/camp daily totals. Streamflow data from weir B were used to represent floodplain flow conditions.

Floodplain groundwater behaviour was assessed in several ways. Data from an on-going study of summer groundwater recession in the floodplain (Hetherington 1982, 1987) were used to study groundwater responses during rain storms and relationships to streamflow during part of the herbicide study period. In particular, recordings of water levels at stations #63 and #74 plus manual measurements at stations #62 and #63 were used (Fig. 1). Groundwater measurements were taken during the winter of 1983-84 at a different set of piezometers located throughout the floodplain (Brown 1985). One of these piezometer locations (#22) was chosen as the site for soil sample station #4, but water levels were not measured, while a second (#40) was situated only 13 m from my piezometer #62. Piezometers #62 and #40 are located in a drainage depression analogous to that at soil stations #4 and #6, piezometer #63 is in a depression near #62, and piezometer #74 is in a depression on a raised alluvial fan from the J Creek (1450-m) tributary.

Observations of groundwater levels and conditions collected subsequent to the 1984-85 study period were used to evaluate probable conditions during that time. Water levels were measured at piezometer #40 in 1986 and 1987. Additional measurements of groundwater levels and observations of surface water conditions were made from June to November 1987 at the soil residue sampling sites to supplement the 1983-84 data. Soil pits about 180 cm deep were dug in June 1987 near soil stations #1 to #3 and #7 to #9 to monitor groundwater levels at these locations. Photographs of the soil stations taken in 1984 indicated that field conditions in 1987 at the sites had changed very little since 1984. Brief field notes on soil station surface water conditions at times of herbicide residue soil sample collections were also used in this assessment (H. Klassen, personal communication).

The above information on groundwater and streamflow was used to select weir B stream discharge values which coincide with three water-related conditions at soil stations #4 and #6: (1) station completely flooded (flow 1.7 m³ s⁻¹ at #4 and #6); (2) soil not flooded but saturated to the surface (flow >0.085 m³ s⁻¹ at #4 and >1.13 m³ s⁻¹ at #6); (3) water content below saturation in the top 15 cm of soil (flow <0.051 m³ s⁻¹ at #4 and <0.17 m³ s⁻¹ at #6). Water begins to flow across one corner of station #4 when weir B flows exceed 0.085 m³ s⁻¹, whereas surface water enters station #6 only when flows exceed 1.13 m³ s⁻¹. Even for the non-saturated condition, the soils would have been wet to the touch (confirmed by H. Klassen, personal communication), but subsurface water movement or leaching would be slower than for saturated conditions. The derived groundwater conditions are only estimates. Actual measurements of water table and soil hydrologic properties would be needed to be more definitive.

All times indicated on the graphs and referred to in the text are Pacific Standard Time (PST).

RESULTS AND DISCUSSION

General Nature of Floodplain Groundwater Level Behaviour

During dry periods or several days after major rainfall, the groundwater table in the floodplain exhibits a general uniform rate of decline. Groundwater will naturally be closer to the surface in depressions than under raised areas. Contributing causes of groundwater rises are rainfall directly onto the floodplain, subsurface seepage from side slopes and water from the main channel at higher flows. Side slope seepage will be more rapid in winter under wet conditions and much slower during drier summer months. The groundwater table rises rapidly during storm events.
much slower during drier summer months. The groundwater table rises rapidly during storm events. Increases in groundwater level can range from only a few centimetres if water levels are already high or rainfall light to over 100 cm if levels are low and rainfall heavy (Fig. 2). In addition, infrequent light rains during the summer dry period may cause a slight change in groundwater levels with little accompanying change in streamflow (Fig. 2).

The rate of groundwater rise in side channel depressions decreases sharply once surface flow in these channels begins (Fig. 3). Changes in groundwater levels are fairly closely correlated with streamflow and the onset of side channel flow occurs when streamflows are still very low (Fig. 3). Relative changes in groundwater levels can also vary markedly over short distances as shown by a comparison between sites #62 and #40 only 13 m apart (Fig. 4). In this case, surface flow begins sooner at the upstream #40 site causing a drop in relative rates of water level rise until flow also occurs at site #62. These data highlight the difficulty of generalizing about floodplain groundwater levels during storms and the need for site-specific measurements.

Hydrologic Conditions Prior to Herbicide Application

Below-average precipitation during July and August 1984 resulted in the following conditions by September 4: very low streamflow (0.024 m³ s⁻¹), water table about 20 cm below the surface in side drainage channel depressions at soil station #4 (piezometer #22) and piezometer #62, and over 100 cm below at piezometer #74. The 39 cm of rain on September 4-5 increased streamflow (Fig. 5), brought the water table to the surface in drainage channels and depressions as indicated at piezometers #62 and #63 (Fig. 6), saturated the soil at sampling station #4 and moistened the soil at the other soil sampling stations prior to herbicide application on blocks 1-2 (Reynolds et al. 1989) on September 6. Surface ponding in drainage depressions was sustained through September 15. The 22 mm of rain on September 7-8, ending at 0600 PST September 8, resulted in a modest peak streamflow (Fig. 5), caused surface flow in drainage depressions, brought the water table temporarily to the surface at piezometer #74, and wetted vegetation just 11 hours prior to herbicide application on blocks 3 and 4 (Reynolds et al. 1989) on September 8. Light showers on September 9 and 10 kept the system moist. A further 17 mm of rain early on September 12 caused a small increase in streamflow (Fig. 5) and sustained ponding in drainage depressions, although groundwater levels at piezometer #74 dropped well below the surface by September 14 (Fig. 6). On September 14, the day of herbicide application on blocks 5-9 (Reynolds et al. 1989) and over 2 days since the last rain, streamflow had decreased (Fig. 5) but the soil was saturated at sampling stations #4 and #6, wet at other sampling stations and water was still ponded in depressions (Fig. 6), including most of the 750-m and 1600-m tributary channels. J Creek was flowing and some but not all of its ephemeral channels across the alluvial fan had surface flow. Streamflows at the time of herbicide application on September 14 were estimated at 0.001 m³ s⁻¹ for the 750-m tributary, 0.01 m³ s⁻¹ for the 1450-m tributary and 0.016 m³ s⁻¹ for the 1600-m tributary (Feng et al. 1986), and measured as 0.15 m³ s⁻¹ at weir B, 0.02 m³ s⁻¹ at weir J and 0.016 m³ s⁻¹ at weir C. The next rain on September 15 began after 1330 PST or within 3 or 4 hours after herbicide application on blocks 10 and 11.

Hydrologic Conditions During the Year After Herbicide Application

Weather during the year after herbicide application (September 1984 to September 1985) exhibited some interesting anomalies. The annual precipitation from October 1984 to September 1985 of 2307 mm was the third lowest recorded at Carnation Creek. Of particular importance for the herbicide study, however, is the fact that precipitation was actually above average during the first 10 weeks after herbicide application (Fig. 7). The maximum daily rainfall of 120 mm occurred on October 7 and the October total of 542 mm was the second highest on record for this
Figure 2. Relative comparison of site #63 groundwater and weir B streamflow fluctuations June to September 1985.
Figure 3. Relationship between storm peak groundwater levels at site #62 and peak flows at weir B.

Figure 4. Relationship between groundwater levels at sites #62 and #40 in the Carnation Creek floodplain.
Figure 5. Streamflow, precipitation and water sampling times from September 4-18, 1984.
Figure 6. Groundwater levels at site #63 and site #74 and times of soil sampling at sites #4 and #6 from September 3 to October 11, 1984.
Figure 7. Monthly precipitation on the floodplain for the period September 1984 to September 1985 in relation to long-term mean values.
month. Thus, there was ample opportunity for lateral movement and leaching of herbicide residue during this rainy period. Precipitation then remained below average through September 1985, with January and February 1985 values being the lowest on record (Fig. 7). The winter of 1984-85 was one of the two snowiest on record in terms of frequency of snowfalls and duration of the snowpack at higher elevations. Snow occurred on the floodplain on three occasions (Dec. 28-30, Jan. 5 and Feb. 8-9) but remained on the ground for only a short time. At higher elevations (stations D and L), snow occurred as early as October 24, 1984 and a snowpack persisted most of the winter and into April 1985, with maximum depths up to 40-50 cm.

For reference, daily precipitation and the streamflow hydrograph for the year after herbicide application are presented in Figures 8 and 9, respectively. During this year, there were seven rain storms of sufficient magnitude to produce streamflows exceeding 6.7 m$^3$ s$^{-1}$ (Fig. 9), the third lowest number on record and well below the average of 14 which meet this criterion. Storms for which water samples were collected for herbicide residue analysis (Feng et al. 1989) include six of these major events (Fig. 9). The highest peak flow of 28.1 m$^3$ s$^{-1}$ has a return period of about once every 2 years and is below the average annual peak of 35 m$^3$ s$^{-1}$ (Hetherington 1988).

**Hydrologic Conditions Relating to Water Sampling Times**

Sampling of stream water for herbicide residue analysis included a short-term intensive monitoring period from September 6-18, collection related to seven stormflow events (flows exceeding 3 m$^3$ s$^{-1}$) and bi-weekly collections from March to September 1985 (Feng et al. 1989). The times of water sample collection are indicated in Figures 5, 8 and 9 in relation to streamflow and precipitation. Precipitation and streamflow data for the seven sampled storms are summarized in Table 1. Flow values in the various streams at the time of herbicide application have been given above.

**Table 1. Summary of data for storms during which water samples were collected for herbicide residue analysis (flows exceeding 3 m$^3$ s$^{-1}$ at weir B) from September 1984 to September 1985**

<table>
<thead>
<tr>
<th>Storm event no.</th>
<th>Date after 14.09.84$^a$</th>
<th>Peak flow (m$^3$s$^{-1}$)</th>
<th>24 h total$^b$ preceeding</th>
<th>Storm total</th>
<th>Cumulative$^c$ from 14.09.84</th>
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<td>56</td>
<td>49</td>
<td>1532</td>
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</tbody>
</table>

$^a$ Date of second herbicide application.

$^b$ For the 24 h preceeding the time that threshold flow was attained.

$^c$ Up to 0800 PST on the day threshold was attained.
The first rainfall after herbicide application on blocks 5 to 9, which contain the side tributaries of interest, began at 1335 PST September 15 and ended 8 hours later at about 2145 PST with a total of 38 mm (Fig. 5). Thus, the rain started 21, 24 and 25 hours after spraying occurred on blocks 5, 7 and 8 containing the 750-m, 1600-m and 1450-m tributaries, respectively (Reynolds et al. 1989). Streamflows at weirs B, C and J increased modestly in response to this rainfall (Fig. 5). Further rain September 16, 17 and 18 sustained these raised flow levels during the remainder of the first 96-hour intensive sampling period ending in the evening of September 18 (Fig. 5). Water was also ponded and flowing in most side channel drainage depressions in the floodplain during this rainy period.

Water flow and ponding was sustained in the 750-m, 1600-m, and C Creek and most other drainage depressions in the floodplain through the winter until near the end of May 1985. Flow fluctuations in the side channels would have generally followed the pattern of flow in the main channel (Figs. 9, 10). Subsequent low precipitation during the summer (Fig. 8) resulted in many side channel depressions drying up in June 1985 and surface water was absent from most of the floodplain during August 1985 (Fig. 10). Pools enabled water samples to be collected from the 1600-m tributary during the summer, but surface channels of the 750-m and C Creek tributaries were dry at 4 and 5 of the last 8 sampling times, respectively. Water moves more quickly through the relatively short 750-m and 1450-m floodplain channels to the main stream than through the longer, more tortuous 1600-m channel.

Hydrologic Conditions Relating to Soil Sampling Times

Conditions at soil sampling stations #4 and #6 are described separately from those at stations #1 to #3 and #7 to #9 because of differing site characteristics and sampling times. The times of soil sample collection for residue analysis (Feng and Thompson 1989) for stations #4 and #6 are indicated in Figures 6, 8, 9 and 10 in relation to streamflow, precipitation and groundwater levels and listed specifically in Table 2. The times for the other stations are listed in Table 3. In Table 2, the data on the percentage of time streamflows exceed specified values were derived from flow duration curves.

On soil station #4, located partly in the drainage channel, surface water was flowing across the lower portion of the site at the time of herbicide application on September 14. This flow decreased during the next 24 hours but it is possible that some surface flow was sustained during this period. Surface flow across the station increased with the rain on the evening of September 15, with complete flooding of the station for at least 4 hours on September 16 and sustained surface flow until September 22. The water table remained within 10 cm of the surface at the highest part of the station from September 14 through September 22, sustaining water saturation to the soil surface. Under these conditions, water would have tended to move laterally over the station surface or through the top few centimetres of soil rather than downward into the soil. The top 15 cm of soil in station #4 would have subsequently remained saturated until the next summer (Table 2). A part of this station was subject to surface flow for a considerable portion of this time, which meant that soil samples were taken from one area of the station while the rest of the area was under water. These results suggest that water and any herbicide residue in solution or suspension in the water would have continued to move laterally rather than downward in the top soil layer.
Figure 8. Daily precipitation on the Carnation Creek floodplain from September 1984 to September 1985 plus indicated times of sampled storm events, water sampling and soil sampling at sites #4 and #6.
Figure 9. Streamflow at Carnation Creek weir B for September 1984 to September 1985 plus indicated times of sampled storm events, water sampling and soil sampling at sites #4 and #6.
Figure 10. Groundwater levels at sites #63 and #74 from June to September 1985 plus indicated times of soil sampling at sites #4 and #6.
Table 2. Hydrologic conditions related to times of soil sample collection at stations #4 and #6.

<table>
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<th>Date</th>
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<th>Weir flow (m³/s)</th>
<th>Flooded (%)</th>
<th>Sat. (%)</th>
<th>Non-sat. (%)</th>
<th>Sample time cond.</th>
<th>Flooded (%)</th>
<th>Sat. (%)</th>
<th>Non-sat. (%)</th>
<th>Sample time cond.</th>
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<td>N</td>
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<td>94</td>
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<td>9</td>
<td>14</td>
<td>47</td>
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</tr>
</tbody>
</table>

- Date of second herbicide application
- Cumulative precipitation
- Flow values for 1200 PST
- Flooded: completely saturated
- Sat.: saturated
- Non-sat.: unsaturated
- Sample time cond.: condition of the top 15 cm of soil
- F = Flooded, S = Saturated, N = Completely saturated

Note: Percentages for the three soil water condition categories do not total 100% because the saturated category includes the time the site was flooded and the intermediate stage between saturated and non-saturated is not included.

On soil station #6, the top 15 cm of the higher half of the station was in a non-saturated condition from the time of herbicide application on September 14 until near midnight September 15. The rising groundwater table and 1600-m tributary flow from the rain on September 15 then saturated the soil to the surface and completely flooded the station for at least 4 hours on September 16. The surface soil layer remained saturated until September 21. Thus, water would have tended to move downward into the soil during the first 24 hours after herbicide application and then laterally over the surface and through the top few centimetres of soil during flooded and saturated conditions over the next 5 days. The station would subsequently have been in a non-saturated condition for much of the time until the first major rain storm October 20, three weeks after herbicide application (Table 2). Water and any residue it contained would have tended to move vertically downward through the top soil layer during this non-saturated period. During the rest of the winter, site conditions fluctuated between saturated and non-saturated with occasional flooding (Table 2).
Groundwater data for piezometer #63 (Figs. 6, 10) and data presented by Brown (1985) support the idea that surface water was likely continually present in most side channel depressions during the fall and winter period. Under these conditions, even those sections of these channels temporarily without surface water would have remained saturated in the centre of the channel or depression.

At soil stations #1 to #3 and #7 to #9, it is highly unlikely that the top 15-30 cm of soil were flooded and they seldom reached the point of saturation. Rain water would have moved vertically downward through the soil profile to the groundwater table below, carrying with it any mobile herbicide residue. Cumulative rainfall at sampling times for these stations is summarized in Table 3.

Table 3. Cumulative precipitation at time of soil sample collection at stations #1 to #3 and #7 to #9

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<th>Date</th>
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*a Date of first herbicide application.
*b Cumulative precipitation.

ACKNOWLEDGMENTS

I wish to express my appreciation to R. Leahy, J. Lough and R. Rowswell for the many hours of taking measurements and observations of floodplain groundwater behaviour, often under adverse weather and field conditions, and to Tom Brown for his assistance.
REFERENCES


Feng, J.C. and D.G. Thompson. 1989. Persistence and dissipation of glyphosate in foliage and soils of a Canadian coastal forest watershed. This proceedings.

Feng, J.C., D.G. Thompson and P.E. Reynolds. 1989. Fate of glyphosate in a Canadian forest stream ecosystem. This proceedings.


FATE OF GLYPHOSATE IN A FOREST STREAM ECOSYSTEM

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ABSTRACT

Residues of glyphosate and its major metabolite aminomethyl phosphonic acid (AMPA) were monitored in stream water, bottom sediments and suspended sediments for a one year period following aerial application of glyphosate (2.0 kg/ha) to the Carnation Creek watershed of Vancouver Island, British Columbia. Analysis of deposit collector samples indicated an actual deposit of 1.88 kg/ha within the target zone and that less than 0.1% of the full rate impinged on surfaces beyond 8 m from the spray zone boundary. The highest concentrations of glyphosate (6.80 µg/g dry mass) were observed in bottom sediments of a directly sprayed tributary, with low residue levels (<0.2 µg/g) persisting in this substrate throughout the monitoring period. Suspended sediment samples collected from the main stream channel, indicated low levels of glyphosate input (0.10 µg/L) in conjunction with the first five storm events (23-66 days post application). The highest stream water residue observed (162 µg/L) occurred in a directly sprayed tributary, 2 h post-application and decreased rapidly to 37 µg/L after 16 h. Transient increases in glyphosate concentrations were associated with first rainfall event (39 mm) which occurred 23 h post-application. Subsequent dissipation of residues in the two tributaries receiving direct glyphosate applications was rapid, such that no quantifiable residues were found after 96 h post-application. No quantifiable residues were found in tributaries buffered with a 10-m vegetation strip during the monitoring period.

INTRODUCTION

Glyphosate (ROUNDUP¹) is a forestry herbicide recently registered in Canada for site preparation and conifer release (Malik and Vanden Born 1986). Federal and provincial regulatory agencies require further research on the aquatic fate and persistence relevant to the operational use of glyphosate under local geographical and climatic conditions. Although the behavior of glyphosate in aquatic systems has been investigated in the United States and elsewhere (Comes et al. 1976; Rueppel et al. 1977; Edwards et al. 1980; Ghassemi et al. 1981; Norris et al. 1983; Newton et al. 1984), this aspect has not been studied in Canada. Research on the aquatic fate and impact of glyphosate is of particular importance in coastal temperate rainforest ecosystems of British Columbia. In such areas a number of factors, including steep-sloped terrain, high rainfall (>2000 mm), and proximity of treatment areas to salmon spawning streams, combine to approximate a worst case scenario with respect to aquatic ecosystem impacts following silvicultural chemical applications. The aquatic persistence and transport patterns of glyphosate under these situations are unknown. Also, the relative degree of stream contamination resulting from input sources such as direct over-spray of stream channels, off-target deposit, lateral movement and mass transfer from surrounding treated areas have not been quantified under these conditions.

¹Registered trademark of Monsanto Co. Inc., St. Louis, Missouri
A vegetation buffer strip along streams may be used to reduce contamination via off-target drift and runoff. Current regulatory guidelines in British Columbia require the establishment of a 10-m pesticide-free zone with appropriate buffers, usually 100-m, to achieve this goal. These guidelines may unduly restrict silvicultural treatment of the highly productive forest lands that border the intensive network of streams in coastal regions.

Establishment of an effective buffer must balance environmental concerns with the need for maximum utilization of lowland forests. The goal of effective buffering has become feasible with the development of dispersal systems, such as the MICROFOIL BOOM\(^2\), which are designed to reduce chemical drift and the width of buffer strips required to protect streams and lakes (Payne et al. 1986).

**OBJECTIVES**

The specific objectives of this study were:

1. To assess the on- and off-target deposit of glyphosate following an operational application for conifer release in a typical, coastal British Columbia watershed.

2. To determine the residue levels and subsequent dissipation of glyphosate and its major metabolite AMPA during the initial 96 hour period in four dissimilar streams following aerial application with a MICROFOIL BOOM.

3. To compare residue levels and dissipation rates of glyphosate and AMPA in water, stream bottom sediment and suspended sediment, of buffered and directly sprayed streams during fall and winter storm events.

4. To assess the long term (1 year) potential for stream contamination resulting from lateral movement and mass transfer in four streams typical of a coastal forest watershed.

5. To evaluate the effectiveness of a 10-m vegetation buffer in protecting forest streams from contamination via off-target drift resulting from applications with a MICROFOIL BOOM.

**MATERIALS AND METHODS**

**Site Description**

The study site was located in the Carnation Creek watershed on the west coast of Vancouver Island, British Columbia (48°50’N, 125°2’W), approximately 200 km west of Victoria (Fig. 1). Carnation Creek has been the focus of a 15-year investigation of the effects of logging on fish (Hartman 1982). The main stream and side channels support populations of coho (*Oncorhynchus kisutch* Walbaum) and chum (*O. keta* Walbaum) salmon.

The 10-km watershed is within a coastal hemlock and cedar ecozone (Krajina 1969). Following clear-cutting in 1975, the study area was site-prepared and planted in 1976 (Dryburg 1982). Shortly after planting, thick vegetation, dominated by salmonberry (*Rubus spectabilis* Pursh) and red alder (*Alnus rubra* Bong.), covered the area (King and Oswald 1982). In September 1984, the ranges in height for salmonberry and alder were 1.5-2.5 m and 7-10 m, respectively. Weather stations and a broadcast weir (B weir) were established near the mouth of Carnation Creek to monitor precipitation and stream discharge (Fig. 1). The four tributaries involved in this study were

\(1\) Registered trademark of Union Carbide Inc., Ambler, Pennsylvania

\(2\) Registered trademark of Union Carbide Inc., Ambler, Pennsylvania
Figure 1. Location of the Carnation Creek Watershed Study Area and Stream Sampling Stations.
located at 750, 1450, 1600 and 2200 m upstream from the Carnation Creek estuary; they are referred to in this manuscript as tributaries 750, 1450, 1600 and C, respectively (Fig. 1). Annual precipitation at the study site ranges from 2500 to 3800 mm and occurs mainly from October through March (Hetherington 1982). Tributaries 750, 1450 and C are ephemeral and in 1984 started flowing with the first seasonal rainfall (35 mm) on September 04. Further details regarding site characteristics and description are reported by Hartman (1982) and King and Oswald (1982).

Herbicide Application

ROUNDUP (isopropylamine salt of glyphosate) was applied in the fall of 1984 at 2 kg active ingredient (a.i.) per hectare by a Bell-47 helicopter equipped with a MICROFOIL BOOM and 1.5-mm hayrack nozzles calibrated to deliver 258.25 L/ha. The main channel of Carnation Creek and tributaries 1450 and C (Fig. 1) were buffered with a strip of vegetation, approximately 10 m in width. Tributaries 750 and 1600 were directly treated. A total of 45 ha received herbicide application on four different days. Treatment Area I was sprayed on 06 September 1984 (1935 -2005 h), Treatment Area II on 08 September 1984 (1416 - 1940 h), and Treatment Area III received application on 14 September 1984 (1430 - 1930 h). Meteorological conditions for specific spray periods as well as application system specifications are reported in Reynolds et al. (1989).

Site Preparation for Deposit Study

The study area prepared for determination of initial deposit levels was located on the southern bank of Carnation Creek about 2000 m upstream from the estuary (Fig. 1). The deposit study area measured 100 x 20 m, including a vegetation-buffer strip 10 m wide by 100 m long, divided roughly in half relative to the two dominant vegetation types (salmonberry and red alder) (Fig. 2). Within the deposit-study area six transects, each 20 m apart and 20 m long, were established at right angles to the stream bank (Fig. 2). Three transect lines were located in the salmonberry area and three in the alder area. The deposit collectors were located at 5-m spacing from the stream bank at -5, 5, 10 and 15 m along each transect (Fig. 2). The outermost deposit collectors were located 5 m inside the stream channel.

Sampling Methodologies

Deposit collector sampling

Deposit collectors were arranged within the off-target deposit study site as described above. In open areas, deposit collection plates (400 cm²) were placed 20 cm above either ground or water level. In areas of vegetation, collectors were raised 170 cm above ground level, roughly corresponding to the height of salmonberry but below the alder tree canopy. The actual swath edge (Fig. 2) was determined by assessing phytotoxicity 10 months post-application. The swath edge was defined as the line demarcating the zone of 100% injury to salmonberry. The distances of the deposit collectors to the actual swath edge were measured and used for subsequent interpolation of glyphosate deposit at various distances from the target area. Detailed descriptions of deposit collection procedures have been reported previously (Feng and Klassen 1986).
Figure 2. Experimental Design of the Off-Target Deposit Study at Carnation Creek Watershed.
Initial (96-h) intensive sampling program for water residues

Water samples were collected intensively during the first 96-h period after treatment, at tributaries 750, 1450 and 1600 as well as in Carnation Creek (Fig. 1). The sampling stations for the three tributaries were located about 5 m from the confluence with the main channel of Carnation Creek. The sampling station for Carnation Creek was located at B Weir, 500 m upstream from the estuary and immediately below Treatment Area III. Water samples were collected using techniques described by Feng and Klassen (1986). The sampling protocol involved an initial, short-term, intensive sampling period during which integrated samples were collected hourly for the first 96 hours post treatment (Table 1). Integrated samples (IS) were obtained initially by collecting six samples of 150 mL at 10-minute intervals, thus yielding an hourly integrated sample with total volume of 900 mL. Following the intensive sampling period, point samples (PS) of 900 mL were collected according to the schedule as outlined in (Table 1).

Table 1. Sampling schedules for the Carnation Creek watershed study

<table>
<thead>
<tr>
<th>Sampling Site</th>
<th>Sampling Schedule (time post-application)</th>
</tr>
</thead>
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<td>Intensive (96-h) Sampling Schedule For Water (Time in Hours)</td>
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<td>(B weir)</td>
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<tr>
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<tr>
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Storm Event Sampling Schedule For Water, Bottom and Suspended Sediments (Time in Days - Bold Values Denote Major Storm Events)

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</thead>
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<tr>
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<tr>
<td>750, 1600 &amp; C tributaries</td>
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</table>

Long Term Sampling Schedule (Water and Bottom Sediments) (Time in Days)

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</tr>
</thead>
<tbody>
<tr>
<td>196 210 224 238 252 263 280 297 311 326</td>
</tr>
<tr>
<td>339 355 364</td>
</tr>
</tbody>
</table>

IS = Integrated Sample
PS = Point Sample

Storm event sampling

Water samples were collected in conjunction with major storm events at B weir in Carnation Creek, and at tributaries C, 750 and 1600. Suspended sediment samples were taken at B weir only, during and after major storm events (Table 1). Methods used to obtain suspended sediment samples are presented in detail by Feng and Klassen (1986). In brief, the technique involves collection and filtration of 20 L of water during each storm event; the residues in filtered sediments are quantified and reported on a µg/L basis. Storm event samples were obtained during a major storm
event when the instantaneous discharge of Carnation Creek at B weir reached a threshold level of 7 m³/s. Post-storm sampling commenced when the discharge decreased to below the same threshold, with collections at 1, 3, 7, 14 and 21 days after a storm or until a new storm began. Peak discharges were recorded in conjunction with each storm event, while daily rainfall and average discharge were measured throughout the sampling program.

Long term sampling

Long term water and bottom sediment point samples were obtained from Carnation Creek (at B weir) and from tributaries 750, 1600 and C. The sampling schedule was biweekly, totaling thirteen sampling dates. Methods used to obtain water and sediment samples were described by Feng and Klassen (1986).

Residue Analysis

Formulation analysis

Samples of RONDOUP formulation (356 g a.i./L) were collected before mixing for application and kept at ambient temperature. Quadruplicate 1 mL aliquots were serially diluted (10⁻¹ X) with KH₂PO₄ buffer solution (mobile phase) as described in Table 2. The diluents were filtered with Millipore filter units (Millex HV, 0.45 μm) and subjected to HPLC analysis for glyphosate and AMPA, as described above and in Table 2.

Table 2. Specifications of HPLC instrumentation

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPLC System:</td>
<td>Varian Model 5560 Ternary HPLC, Model 8085 autosampler</td>
</tr>
<tr>
<td>Detector:</td>
<td>UV-200 variable wavelength detector set at 570 nm</td>
</tr>
<tr>
<td>Derivatization System:</td>
<td>Ninhydrin post column reactor (100°C) System V Model 5000 (Varian Inc.)</td>
</tr>
<tr>
<td>Analytical Column:</td>
<td>Bio-Rad Aminex A-9 10 cm X 4.6 mm i.d.</td>
</tr>
<tr>
<td>Guard Column:</td>
<td>Bio-Rad Aminex A-9 (K⁺ from cartridge)</td>
</tr>
<tr>
<td>Mobile Phase:</td>
<td>0.005 M KH₂PO₄ buffer in 4% methanol pH = 1.9</td>
</tr>
<tr>
<td>Flow Rate:</td>
<td>0.5 mL/min (isocratic)</td>
</tr>
<tr>
<td>Column Temperature:</td>
<td>50°C</td>
</tr>
</tbody>
</table>
Tank mix analysis

Tank-mix samples (400 mL) collected immediately prior to application to Treatment Area III were stored frozen prior to analysis. Duplicate 1 mL aliquots were diluted (10⁻² X) in buffer solution and filtered and analyzed as described above.

Deposit collector sample analysis

Residues of glyphosate and AMPA were extracted from the deposit collecting sheet by a multiple rinsing/shaking and sonicating procedure using 0.1 N HCl as the extraction solvent (Feng and Klassen 1986). The extracts were then subjected to cation and anion exchange column cleanup prior to quantification by HPLC analysis (Table 2). Herbicide quantities (glyphosate plus AMPA as glyphosate equivalent) on the deposit plates, were converted to kg/ha rates using the equation:

$$
\text{kg/ha} = 2.5 \times 10^{-4} \times R
$$

where R = total residue (µg) per deposit collector (400 cm²). The off-target deposit residue data were subjected to linear regression analysis, using the logarithms of distance off-target in meters (X) and rate (kg/ha) of glyphosate deposited (Y) for both conditions (alder area and salmonberry area) and for the pooled data of the six replicates (log Y = a + b(log X)). Statistical differences between regression lines were determined by means of t-tests, comparing slopes (b) and elevations (a) of the lines as described by Zar (1984). Regression equations were used to interpolate distances at which deposit estimates were equal to 10, 1 and 0.1% of full deposit in the target area. Since deposit estimates were measured over a limited distance, and since distance to off-target deposit relationships are generally exponentially related over larger distances, regression equations could not be used for extrapolation beyond the furthest distance at which deposits were empirically determined. The regression equations developed to interpolate off-target deposit are specific for the application, meteorological and physical conditions of the Carnation Creek site. Since this off-target deposit study was conducted once only and conditions are not representative of worst-case scenarios, regression equations are neither accurate or useful models for purposes of prediction or establishment of buffer zone requirements.

Water samples

Frozen water samples were thawed, acidified with HCl to pH 2 and filtered through a Millipore filtering apparatus (0.45 µm HA disc filters), prior to concentration of the analytes on cation exchange resin (Chelex, Fe⁺⁺⁺ form) and subsequent cleanup on anion exchange resin (AG1-X8, HCO₃⁻ form). Extraction and cleanup procedures based on those of Cowell et al. (1986) were used, with slight modification to provide samples for HPLC analysis. The cleanup procedure was altered by increasing the concentration (6.0 to 6.5 N) of HCl used to elute the analytes from the cation exchange column. An additional modification involved final recovery of glyphosate and AMPA using mobile phase solution (as described in Table 2) rather than distilled water.

Bottom and suspended sediment sample analysis

Residues of glyphosate and AMPA in bottom and suspended sediments were quantified using the method as described by Thompson et al. (1989). The method involves extraction of the substrate with 0.5 M NH₄OH, pre-concentration on AG1-X8 (HCO₃⁻ form) anion exchange resin, cleanup via cation exchange (Dowex 50W-X8, H⁺ form) and HPLC analysis as described below and in Table 2.
For bottom sediment samples, aliquots (20 g, air dry mass) were taken for analysis. Percent moisture was determined in duplicate aliquots for each sample so that residue levels could be calculated on μg/g dry mass basis. For suspended sediment samples the entire sample (including filter paper), as obtained from the field was weighed, homogenized and extracted. Residue results were calculated as μg/L of filtered water.

High performance liquid chromatography

High Performance Liquid Chromatography (HPLC) coupled with post-column ninhydrin derivation and absorbance detection (specifications as listed in Table 2) was utilized for separation and quantification of glyphosate and AMPA. Use of the short (10 cm) analytical column resulted in short retention times (7 min), improved peak shape and increased sensitivity compared to systems employing a longer (30 cm) column (Cowell et al. 1986).

Validation data for analytical methods

Data indicating the accuracy and precision of analytical methods used for quantification of glyphosate and AMPA are presented in Table 3 for each substrate.

Table 3. Validation data for analytical methods

<table>
<thead>
<tr>
<th>Substrate Type</th>
<th>Fortification N</th>
<th>Analyte</th>
<th>Mean ± s.e. (cv%)</th>
<th>LOD ( ^a ) (ppm)</th>
<th>LOQ ( ^b ) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit Collector</td>
<td>1.0-4.0 μg/L</td>
<td>25</td>
<td>GLYH</td>
<td>99 ± x.x (5.0)</td>
<td>0.10</td>
</tr>
<tr>
<td>Bottom Sediment</td>
<td>0.05-0.8 μg/g</td>
<td>36</td>
<td>GLYH</td>
<td>79.7 ± 6.3 (7.9)</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AMPA</td>
<td>64.1 ± 10.1 (15.4)</td>
<td>0.01</td>
</tr>
<tr>
<td>Suspended Sediment</td>
<td>0.50-4.0 μg</td>
<td>14</td>
<td>GLYH</td>
<td>65.5 ± 9.1 (13.9)</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AMPA</td>
<td>54.3 ± 8.5 (15.7)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

\( ^a \) LOD = limits of detection = detector response equivalent to 2X S:N ratio.
\( ^b \) LOQ = limits of quantification = detector response 6X S:N ratio.
\( ^c \) ppm = ng/L for formulation, tank mix and water
\( ^d \) LOD and LOQ values for deposit collectors equate to 2.5 X 10\(^{-5}\) and 1.25 X 10\(^{-4}\) kg/ha respectively.

RESULTS AND DISCUSSION

Formulation Analysis

Analyses of the ROUNDUP formulation used for the herbicide application in this study indicated that the amount of active ingredient (glyphosate) was 363 g/L ± 2% cv. approximately 2%
in excess of the label concentration (356 g/L). No AMPA was detected in the formulation, which had been stored at ambient temperature for 3 months.

Tank Mix Analysis

Results of the analyses conducted on the tank mix showed concentrations of 7889 and 58 \( \mu g/L \) of glyphosate and AMPA respectively. There was a 6% v/v contamination of the tank-mix from a six-day old mixture used to spray adjacent areas of the watershed. The amount of AMPA detected (0.7% of glyphosate concentration in the tank mix), indicated a 13% degradation of glyphosate in the previous mixture after six days of storage at ambient temperature. The initial concentration of the tank mix was corrected by converting the AMPA concentration to a glyphosate equivalence. The corrected value was 103% of the concentration required to yield an application rate of 2 kg a.i./ha.

Off-Target Deposit Study Results

Analysis of 20 deposit collector samples indicated that the concentration of AMPA (relative to glyphosate) was 1.5%, slightly higher than the ratio for the tank mix. The highest deposit rate, which was found 2.9 m within the target area, was 1.882 kg/ha. This empirical value was 6% less than the nominal application rate for the study. The lowest quantifiable deposition rates (0.00155 and 0.000176 kg/ha) were found 17.2 and 23.1 m off-target for the salmonberry and alder areas respectively (Table 4).

<table>
<thead>
<tr>
<th>Distance (m) off-Target</th>
<th>Glyphosate deposit (kg/ha)</th>
<th>Distance (m) off-Target</th>
<th>Glyphosate deposit (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.9</td>
<td>1.8820</td>
<td>1.0</td>
<td>0.1786</td>
</tr>
<tr>
<td>0.2</td>
<td>1.5093</td>
<td>2.6</td>
<td>0.01687</td>
</tr>
<tr>
<td>2.1</td>
<td>0.01934</td>
<td>3.0</td>
<td>0.02096</td>
</tr>
<tr>
<td>2.8</td>
<td>0.01025</td>
<td>6.2</td>
<td>0.00383</td>
</tr>
<tr>
<td>7.2</td>
<td>0.00239</td>
<td>6.5</td>
<td>0.00145</td>
</tr>
<tr>
<td>7.8</td>
<td>0.000364</td>
<td>11.1</td>
<td>0.00162</td>
</tr>
<tr>
<td>10.0</td>
<td>0.00115</td>
<td>12.0</td>
<td>0.000281</td>
</tr>
<tr>
<td>12.9</td>
<td>0.000337</td>
<td>13.1</td>
<td>0.000351</td>
</tr>
<tr>
<td>17.2</td>
<td>0.00155</td>
<td>21.1</td>
<td>0.000600</td>
</tr>
<tr>
<td>20.0</td>
<td>&lt;0.000025</td>
<td>22.0</td>
<td>&lt;0.000216</td>
</tr>
<tr>
<td>22.9</td>
<td>&lt;0.000025</td>
<td>23.1</td>
<td>&lt;0.000176</td>
</tr>
</tbody>
</table>

Note: Limit of detection (LOD) = 0.000025 Kg/ha

Limit of quantification (LOQ) = 0.000125 Kg/ha.

Statistical analysis of the deposit data indicated a significant (\( P < 0.05 \)) correlation between the log of glyphosate deposited and the log of distance off-target. Linear regression on log-log transformed data yielded correlation coefficients of -0.95, -0.97 and -0.95 for the mean
data values of 3 replicate transects in the alder, salmonberry and for the pooled data, respectively. The corresponding regression equations accounted for 89%, 94%, and 91% of the variation within the data, respectively. Non-significance in differences between regression lines for the salmonberry and alder areas allowed calculation of a general extinction rate from pooled data. The general extinction rate was used to estimate distance downwind from the spray boundary at which 10%, 1% and 0.1% of the full deposit would be found (Table 5). The results show a very rapid decline in glyphosate deposit with increasing distance off-target.

Table 5. Glyphosate distance:deposit relationships as calculated for the Carnation Creek study site.

<table>
<thead>
<tr>
<th>Calculated Distance Off-Target (m)</th>
<th>Estimated Deposit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Kg/ha)</td>
</tr>
<tr>
<td>Alder Area 0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Salmonberry Area 0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Alder Area 0.6</td>
<td>0.02</td>
</tr>
<tr>
<td>Salmonberry Area 0.9</td>
<td>0.002</td>
</tr>
<tr>
<td>Alder Area 2.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Salmonberry Area 2.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Alder Area 7.2</td>
<td>7.8</td>
</tr>
<tr>
<td>Salmonberry Area 7.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Note: Off-target deposit estimates as shown in Table 5, were interpolated using the regression equations:

Alder: $\log Y = a + b (\log X)$; $r^2 = 0.89$
where: $X =$ distance off-target (m)
$Y =$ amount of glyphosate deposited on collectors (kg/ha)

$a = -1.17$
$b = -1.82$

Salmonberry: $\log Y = a + b (\log X)$; $r^2 = 0.94$
where: $X =$ distance off-target (m)
$Y =$ amount of glyphosate deposited on collectors (kg/ha)

$a = -0.82$
$b = -2.13$

Vegetation assessment indicated the average off-target distance between spray boundary and zone of 100% healthy salmonberry was 2 m. However, several pockets of partially damaged salmonberry were found up to 5 m from the spray boundary in association with scattered clumps of alder. Results of the vegetation assessment indicated that deposit rates of <0.02 kg/ha (i.e., approximately 0.01% of full application rate) would be required to ensure no phytotoxicity to salmonberry.

Dissipation of Glyphosate and AMPA in Stream Water and Sediments

Results of short-term intensive sampling program

Initial residue response differed in buffered and unbuffered streams. Rainfall (39 mm) occurred one day after treatment of Treatment Area III and lasted for 8 h. In streams receiving
direct application, stream response was characterized by rapid decrease in residue concentrations, both immediately post-application and in response to the rainfall.

Direct treatment of tributary 750 resulted in quantifiable glyphosate concentrations (1.5 μg/L) at 1 and 2 h post-application (Fig 3). Glyphosate concentrations rose to 144 μg/L at 27 h post-application in response to the rainfall event and decreased rapidly to 22.1.3 μg/L and nondetectable levels at 36, 72 and 96 h post-application, respectively. Tributary 750 was a small, ephemeral stream covered by riparian vegetation for most of its length. At the time of application it exhibited a slow flow rate (0.001 m³/s). As compared to the initial stream response to direct over-spray, longer periods of time (>0.5 h vs. <45 h) were required for residues to dissipate below detectable levels. The 100-fold increase in concentrations of glyphosate in stream water following the first rainfall event may have been the result of several sources of input including mobilization of residues in ephemeral stream channels feeding the tributary (Norris et al. 1983), washing of residues from leaves of overhanging vegetation, surface movement and subsurface flow. Norris et al. (1983) noted that mobilization of residues in runoff may yield longer lasting effects than direct application. In a study of agricultural watersheds, Edwards et al. (1980) showed that residues of glyphosate were transported mainly via overland (surface) runoff, rather than through subsurface flow.

Tributary 1600 received direct chemical application for about 600 m of its 800 m length. At the time of application the stream was fast flowing (0.02 m³/s) and contained pools ranging from 0.5 to 1 m in depth. Stream banks were covered with salmonberry and alder vegetation. Residues were detected in water samples immediately following direct deposit of glyphosate, concentrations peaked at 152 μg/L within 2 h and decreased rapidly to 54.4 and 36.5 μg/L at 7 and 16 h, respectively (Fig. 3). The magnitude of the initial concentrations and rate of residue dissipation in this stream were comparable to those observed in a similar forest stream in Oregon (Newton et al. 1984). Following the first rainfall, concentrations of glyphosate in the water rose to 109 μg/L at 28 h and decreased rapidly thereafter to 1.3 μg/L at 96 h (Fig. 3). Concentrations of AMPA found in both tributaries 750 and 1600 were about 2% of corresponding glyphosate concentrations.

The buffered tributary 1450 was selected to represent a worst-case situation for operational spraying and to determine the accuracy of aerial application while maintaining a designated buffer without an intensive boundary marking system. This tributary consisted of a network of branching stream channels, mid-portions of which either flowed underground or were covered with dense 2 m high salmonberry. The stream boundary of these sections could not be clearly identified from the air. About two-thirds of its length (600-800 m) were adjacent to Treatment Area III (Fig. 1). Stream flow at the time of application was 0.01 m³/s. No quantifiable residues were found in the first 7 h of the intensive sampling program. The rainfall that occurred at 20 to 28 h post-application did not mobilize significant quantities of glyphosate into this stream during the first 16 to 96 h post-application. These results indicate that a 10-m wide vegetation buffer is adequate to prevent stream contamination from either direct aerial application, drift or from subsequent inputs in the first 96 h. One anomalous sample (10 h post-application) was identified, having a concentration of 2.5 μg/L of glyphosate. This delayed response may be the result of an accidental spray over a middle section of the tributary, which eventually flowed underground. The slower water velocity, which would be expected in subterranean flow, may be responsible for the delay of residue response to 10 h post application.
Figure 3. Short-term Streamwater Residues of Glyphosate in Carnation Creek Watershed Tributaries 750 and 1600.
The buffered main stream (Carnation Creek) was monitored at B weir, both following application to Treatment Area I and Treatment Area III. No residues were found in any of the 12 samples collected after application to Treatment Area I. Results of samples associated with application to Treatment Area III, showed that the main stream responded with quantifiable glyphosate concentrations only following the direct treatment of tributary 1600. Glyphosate (1.5 µg/L) was found in only two samples, 4 and 6 h after treatment. In general, these results corroborate other studies, which indicate rapid dissipation of glyphosate in both lentic surface waters (Legris et al. 1985) and lotic systems (Comes et al. 1976; Norris et al. 1983; Legris et al. 1985). In lotic systems such as Carnation Creek, this effect may be the result of degradation, dilution, adsorption to organic substrates or uptake by biota. Glyphosate concentrations in five samples collected between 29 and 33 h rose to 1.7-3.2 µg/L in response to the rainfall. The 2-fold increase in main stream water residues further indicated input of chemical from non-point sources such as charged ephemeral tributaries.

Results of Storm Event Monitoring

During the observation period, seven storm events above 3 m³/s were identified as major storms (Table 1.). Stream discharges monitored in Carnation Creek for these seven events were: 13.1, 8.3, 10.0, 5.3, 3.0, 4.0, and 4.4 m³/s, respectively. Cumulative rainfall was 1490 mm during this period. As a result, a total of 120 water samples (500 mL PT) were collected on 30 different days from the main channel and three tributaries (750, 1600 and C) (Table 1). No quantifiable residues of glyphosate or AMPA were found in any of the water samples. Trace amounts (<1 µg/L) of glyphosate were detected in one sample from the main channel following storm event 7 and in one water sample from tributary 750 following the first storm event. Similarly, transient indications of trace residues were observed in tributary 1600 in five of seven major storm events (i.e. on days 23, 25, 49, 59 and 150 post-application). Glyphosate concentrations observed 23 days after treatment were approximately 1000-fold lower than those found after the rainfall (39 mm) event 27 h post-application. These results are consistent with the observations of other workers (Kimmins 1975; Edwards et al. 1980), that the first rainfall after treatment generates the highest residue concentrations in stream water.

A total of 120 samples of stream bottom sediments were collected in conjunction with storm events. No quantifiable amounts of glyphosate or AMPA were found in the buffered tributary C and main channel during the storm-event monitoring period. In the directly treated Tributaries 750 and 1600, glyphosate and AMPA residues in bottom sediments persisted throughout the storm-event monitoring period (Fig. 4). The highest bottom sediment concentrations of glyphosate (0.44 and 0.58 µg/g dry mass) found in tributary 750 were in conjunction with the third major storm event. 53 and 57 days post-application, respectively. In tributary 1600, peak bottom sediment concentrations (6.80 and 6.34 µg/g dry mass) were observed 24 and 30 days post-application, respectively (Fig. 4).

A total of 29 suspended sediment samples were collected at B weir during 8 storm events that occurred between 23 and 171 days post-treatment (Table 1). Quantifiable glyphosate residues were found in only four of the 29 samples collected. The highest concentrations detected in suspended sediments (0.060 µg/L) occurred in conjunction with the first storm event, 23 days post-application.

Monitoring in conjunction with major storm events indicated that residues of glyphosate and AMPA are associated primarily with bottom sediments, with no quantifiable residues being observed in stream water. Highest concentrations were found in the slow-flowing tributary 1600, which meanders through the floodplain, while the swift-flowing 750 tributary had much lower con-
Figure 4. Residues of glyphosate in bottom sediments of directly oversprayed tributaries at Carnation Creek, British Columbia.
centrations. Levels of glyphosate residue associated with bottom sediments appear to depend largely on stream flow dynamics. In slow-flowing, meandering streams deposition of contaminated sediment may result in transient increases in residue concentrations. In contrast, fast-flowing streams inherently have little sediment deposition and are regularly flushed-out during storm events, resulting in bottom sediment concentrations being somewhat lower.

Results of Long Term Dissipation Study

Biweekly samples of both water and bottom sediments were taken from the main stream and tributaries 750, 1600 and C during the period 196 to 364 days after treatment (Table 2). No detectable residues (detection limit = 0.1 µg/L) were found in any of the 48 scheduled water samples. Analyses of 49 bottom sediment samples taken during this period showed no quantifiable residues in sediments of the Carnation Creek main channel or C-tributary (Fig. 4). Quantifiable residues (1.92 to 0.14 µg/g dry mass) were observed in bottom sediments of directly sprayed tributaries 750 and 1600 during the long term monitoring period (196-364 days post application). The data indicate that residues in bottom sediments were comparatively persistent, with levels variable but generally declining over time. By the end of the long term monitoring period, residue levels were less than 0.2 µg/g dry mass. Results of the long term monitoring program provide no evidence of glyphosate or AMPA accumulation in either bottom sediments or water and no quantifiable residues in stream water resulting from inputs via mass transfer or lateral movement mechanisms.

Relationship of Observed Residue Concentrations to Toxicological Data

Application of glyphosate to the Carnation Creek Watershed approximates a worst-case scenario for the silvicultural use of this herbicide. As would be expected, the highest residue concentrations were observed in water samples taken immediately after direct application to tributaries 750 and 1600. Residues dissipated rapidly from water and tended to be sorbed by bottom sediments. No evidence of accumulation of glyphosate or its metabolite AMPA in sediments was observed.

Although it is beyond the scope of this paper to draw absolute conclusions regarding the potential for aquatic impacts as a result of silvicultural applications of ROUNDUP, it is of interest to compare actual environmental concentrations of glyphosate observed in this study with those concentrations of the active ingredient known to elicit acute toxic response. Servizi et al. (1987) have recently reported on the acute toxicity of ROUNDUP, the active ingredient glyphosate and the surfactant MON0818 to four aquatic organisms including Olenochlorinae sp. fry. The data indicate that all four species show similar sensitivities to these materials. Mitchell and Chapman (1986) reported that environmental concentrations resulting from aerial spraying of ROUNDUP herbicide are 100-fold less than levels found to be acutely toxic to salmonids in 96 h LC50 tests. The highest streamwater concentrations observed in this study (162 µg/L in directly oversprayed tributary 1600) is approximately 80-fold less than the 96 hour LC50 reported for coho salmon (Wan et al. 1988), when corrected for glyphosate equivalence (30% a.e.). Similarly, the highest concentrations observed in our study were well below sub-lethal no-effect levels for coho salmon smolt osmoregulation or growth as reported by Mitchell et al. (1987).

With respect to toxicity of glyphosate to organisms other than fish, direct observation indicated that residue concentrations at B Weir and tributaries 1600 and C induced a minimum response in drift of aquatic invertebrates (Kreutzweiser and Kingsbury 1989).
Thus, the results of this study generally indicate a large safety margin between stream water concentrations of glyphosate resulting from forest applications and known acute and sub-acute toxicological endpoints.

CONCLUSIONS

In relation to the objectives of the study, the following conclusions may be drawn:

a) Results of the off-target deposit collector experiment indicate that the herbicide application was reasonably accurate in that the empirical value for application rate was within 6% of the nominal rate for target area. The data also showed that use of the MICROFOIL BOOM under operational spraying conditions results in very little off-target deposit. Estimated deposit at distances greater than 8 m off-target were less than 0.1% of full application rates in this study. Results of the off-target deposit study conducted at Carnation Creek suggest that under the specific application and meteorological conditions of this study, a 10-m wide vegetation buffer zone of either salmonberry or alder, effectively protected streams from herbicide contamination following application of the herbicide ROUNDUP with a MICROFOIL BOOM.

b) Initial residue levels in stream water were correlated with a variety of factors including; stream flow rate and volume, occlusion of water surface by overhanging vegetation, and degree of input from intentional direct treatment. Directly treated tributaries contained the highest concentrations of the active ingredient, these levels were well below concentrations known to be acutely toxic to sensitive aquatic organisms. Residues in stream water dissipated rapidly, so that chemical concentrations were below detection limits (0.1 ppb) within 96 h of the application. Dissipation was more rapid in a fast flowing tributary than in a slow-flowing, meandering tributary in the floodplain.

c) Storm-event monitoring showed that no quantifiable residues of glyphosate occurred in stream water in conjunction with storm events. Bottom sediments appeared to be the major sink for glyphosate residues with high concentrations correlated to storm events. Residues associated with bottom sediments persisted throughout the monitoring period. The degree of contamination appears to be related to stream dynamics and location.

d) Results of the long-term dissipation monitoring study indicated no potential for persistence of residues of either glyphosate or AMPA in stream water. Long-term residues were associated predominantly with bottom sediments, indicating that this substrate attenuated residues from stream water by sorption processes. In contrast with the rapid dissipation of residues in stream water, sediment residues were relatively persistent. The slow rate of glyphosate degradation in bottom sediments, coupled with the known chemical behavior of glyphosate on organic substrates indicates that these residues are strongly sorbed to this substrate and thus unlikely to be biologically available.

The residue data resulting from this study support the conclusion of Tooby (1985) who stated that "...it is unlikely that glyphosate will affect aquatic organisms at the concentrations found in the environment after use at the recommended rates." Given the rapid dissipation of this chemical in forest stream ecosystems, its susceptibility to biodegradation and its tendency to sorb strongly to organic substrates, significant biological impact to aquatic organisms as the result of silvicultural applications at recommended rates would be highly unlikely.
ACKNOWLEDGEMENTS

This research, supported under the British Columbia Forest Resource and Development Agreement (FRDA), was conducted by members of the Forest Pest Management Institute (FPMI), of the Canadian Forestry Service. Cooperation of the British Columbia Ministry of Forests, the Pacific Forestry Centre (PFC), Fisheries and Oceans Canada, MacMillan Bloedel Ltd., and Monsanto Canada Inc. were integral to the success of this project. Herbicide application was contracted to Rotor Vegetation Control (R. Rowe) and Alpine Helicopters (D. Gubbels and D. Cholka) both of Calgary Alberta. The authors sincerely appreciate and acknowledge the excellent technical assistance in residue analysis of B. Staznik, T. Buscarini, V. Manniste-Squire, and L. MacDonald (FPMI), and of H. Klassen and D. DeKoven (V.A. Poulin and Assoc. Ltd.) who performed the field sampling.

REFERENCES


PERSISTENCE AND DISSIPATION OF GLYPHOSATE IN FOLIAGE AND SOILS
OF A CANADIAN COASTAL FOREST WATERSHED

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ABSTRACT

The environmental persistence and behavior of glyphosate and its major metabolite - amino methylphosphonic acid (AMPA), were investigated in terrestrial components of a Canadian coastal forest watershed, following aerial application of ROUNDUP herbicide. The uniformity of herbicide deposition resulting from rotary-wing application with a MICROFOIL BOOM was assessed through analyses of deposit collectors and initial soil residues at three sampling sites located in the upper, middle and lower sections of the watershed. Samples of soil from three depth-layers were analyzed to determine the persistence and leaching of glyphosate and AMPA in both seasonally flooded and well-drained soils. In addition, foliage and leaf litter of two brush species, salmonberry (Rubus spectabilis) and red alder (Alnus rubra Bong) were monitored to determine initial foliage residue, residues associated with leaf litter and to estimate the degree of residue input via leaf fall.

Both the deposit collector and soil residue methods provided average estimates of initial deposit rates (2.52 and 1.85 kg/ha, respectively), which were reasonably close to the nominal application rate of 2.0 kg/ha. Both data sets also indicated that deposition rates varied greatly between different sites, ranging from a low of 0.60 kg/ha to a high of 3.42 kg/ha. Time of application, meteorological conditions and individual site characteristics may all have contributed to variable chemical deposit.

Analyses of initial foliage samples also indicated highly variable chemical deposition. Residue levels in both salmonberry and leaf litter collected 15 days post-application were significantly lower (P > 0.05) than initial foliage residues. Subsequently, leaf litter residues of glyphosate and AMPA in both species declined over time and less than 1% remained 29 days post-application. The significant difference between initial foliage residues and the first leaf litter residues was attributed to wash-off resulting from a rainfall event which occurred 1 day post-application. The results indicate that while leaf-litter residues would be an unimportant transient source of chemical contamination, wash-off of unabsorbed foliage residues may provide an important non-point source input. if rainfall occurs shortly after application.

Soil residue determinations showed that both glyphosate and AMPA were retained primarily in the upper, organic-rich soil layer, 0-15 cm. Of 63 determinations of mean glyphosate distribution, only 10 data points indicated greater than 10% of total soil core residue in the 15-30 cm layer. No quantifiable residues were detected in samples taken from the 30-35 cm layer. Residues of glyphosate declined with time at all locations so that only 6-18% of initial levels remained after 360 days. Declining glyphosate residues coupled with transient increases in AMPA residues were indicative of microbial degradation. Insufficient replication, high variability in
soil residues and site location effects on chemical behavior prohibited accurate derivation of persistence endpoints by regression analysis. However, pooling of the data provided an approximate time to 50% dissipation of glyphosate from watershed soils of 45-60 days. The results of this one-year monitoring study indicate that glyphosate and its major metabolite AMPA are non-persistent in terrestrial components (soil and leaf-litter) of a Canadian coastal rainforest watershed. In addition, the data clearly showed that neither glyphosate nor AMPA are susceptible to leaching under the conditions studied. The data provide no evidence of potential for long-term groundwater or surface water contamination as a result of inputs from terrestrial substrates.

INTRODUCTION

The herbicide ROUNDUP\(^1\) (active ingredient - glyphosate), received federal registration for silvicultural use in 1984. Since that time, use of this chemical in Canada has been steadily increasing. The environmental fate and persistence of glyphosate in soils has been extensively investigated by a number of researchers (Rueppel et al. 1977; Edwards et al. 1980; Hance 1976; Sprankle et al. 1975; Muller et al. 1981; Mosher and Penner 1976). However, the majority of this research has been conducted in the United States and pertains primarily to persistence and adsorption in agricultural soils. The environmental behavior of glyphosate in other terrestrial ecosystems has been less thoroughly studied. Newton et al. (1984) and Torstenson and Stark (1981), have both reported on the fate and behavior of glyphosate in forest soils; both studies indicating that glyphosate is relatively non-persistent. Torstenson (1985) indicated that the persistence of glyphosate in soils is affected by a multiplicity of factors that mediate microbial activity, the primary mechanism by which this herbicide is degraded.

In the coastal area of British Columbia, typical climatic conditions include frequent autumn and winter rainstorms with annual rainfall often exceeding 2000 mm annually. The results of such precipitation pattern are: areas of high water table, seasonally saturated soils and frequent surface runoff events following major storms. Typically, soil profiles in the floodplain of coastal forest watersheds are highly stratified into organic-rich (30% or greater organic matter content) upper horizons, underlain by coarse-textured mineral soils, low in organic matter. Thus, from a purely physical standpoint, terrestrial forest ecosystems are vastly different than the more homogeneous agricultural soil systems that are traditionally studied. The potential for vertical leaching, loss through surface runoff and persistence of glyphosate under such soil and climatic conditions is unknown.

A relatively large amount of information is available with respect to the fate and behavior of glyphosate in plants. However, most of these studies have been conducted on agricultural crops or specific weed species, which may have little relevance to typical crop and weed species in forest environments. Newton et al. (1984) monitored the persistence of glyphosate in red alder (Alnus rubra Bong.) and other forest hardwood species. Lund-Hoie (1976) reported on the uptake, distribution and metabolism of this herbicide in spruce (Picea abies) and later in two brush species - ash (Fraxinus excelsior) and birch (Betula verrucosa) (Lund-Hoie 1979). Putnam (1976) studied the translocation and persistence of glyphosate in various deciduous fruit tree species following basal bark applications. During aerial application of herbicides, chemical is intercepted primarily by the broadleaf-target species. The herbicide may persist in or on the leaf tissue until senescence and leaf fall during autumn. In this way, chemical may be transported to the forest floor in the form of leaf-litter residue. The degree to which foliar interception and deposition (via subsequent leaf fall) occurs has not been adequately quantified.

\(^{1}\)Registered trademark of Monsanto Agricultural Products Co., St. Louis, Missouri.
Although an extensive data base exists with respect to the environmental fate and behavior of glyphosate in terrestrial ecosystems, little is pertinent to the conditions typical of the western coastal forest region where glyphosate receives widespread use for conifer release and site preparation. Federal and provincial regulatory agencies require further information on the fate and persistence of glyphosate relevant to its operational use under local geological and climatic conditions.

The research described in the following manuscript was undertaken to provide data relevant to the concerns of federal and regional regulatory agencies in Canada and to address questions that are inadequately dealt with in the current literature.

The specific objectives of the study were:

a) To assess the uniformity of deposition of glyphosate following a rotary-wing, aerial application with a MICROFOIL BOOM, under near-operational conditions in a coastal British Columbia watershed.

b) To monitor the persistence of glyphosate and its major degradation product, AMPA, in both well-drained and seasonally flooded soils over a one year period following aerial application.

c) To determine the leaching potential of glyphosate and AMPA in soil systems typical of a coastal British Columbia watershed.

d) To determine the initial residue levels associated with the major target species and to monitor the degree to which residues are transported to the forest floor as leaf-litter residue.

MATERIALS AND METHODS

Site Description

The experimental study site is located in the Carnation Creek watershed on the west coast of Vancouver Island, British Columbia (48°50'N, 125°2'W), about 200 km west of Victoria (Fig. 1). The 10-km watershed is within a coastal hemlock and cedar ecozone (Krajina 1969). Annual precipitation ranges from 2500 to 3800 mm and occurs primarily from October through March (Hetherington 1982). The study site was clear-cut in 1975 and site-prepared and planted in 1976 (Dryburg 1982). At the time of chemical application (September 1984), thick vegetation dominated by salmonberry (Rubus spectabilis Pursh) and red alder (Alnus rubra Bong.) covered the area, ranging in height from 1.5-2.5 m and 7-10 m respectively. Characteristics of soils within the watershed (Table 1) were determined from samples taken immediately prior to herbicide application.

Site Preparation

Three soil sampling sites were chosen within the watershed as indicated in Figure 1 and Table 2. Soil sites were selected in both the upper (stations 1-3) and lower (stations 7-9) sections of the watershed to monitor persistence and leaching in well-drained soils. The mid-watershed soil site (stations 4-6) was established in a low-lying area known to be seasonally flooded. At each site, three 5 x 5 m areas were cleared by removing above-ground vegetation.

Registered trademark of Union Carbide Inc., Ambler, Pennsylvania.
Table 1. Soil characteristics of the Carnation Creek Watershed study site

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>OM (%)</th>
<th>CEC (%)</th>
<th>N (%)</th>
<th>P (ppm)</th>
<th>K (%)</th>
<th>pH</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stations 1-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>30.39</td>
<td>45.85</td>
<td>0.60</td>
<td>17.05</td>
<td>0.03</td>
<td>4.94</td>
<td>55.85</td>
<td>23.70</td>
<td>20.46</td>
</tr>
<tr>
<td>5-15</td>
<td>19.47</td>
<td>51.33</td>
<td>0.50</td>
<td>15.18</td>
<td>0.02</td>
<td>4.55</td>
<td>55.79</td>
<td>23.73</td>
<td>20.48</td>
</tr>
<tr>
<td>15-35</td>
<td>9.28</td>
<td>26.37</td>
<td>0.21</td>
<td>1.47</td>
<td>0.01</td>
<td>5.28</td>
<td>62.01</td>
<td>17.50</td>
<td>20.49</td>
</tr>
<tr>
<td>Stations 7-9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>30.90</td>
<td>50.47</td>
<td>0.12</td>
<td>54.04</td>
<td>0.03</td>
<td>4.49</td>
<td>62.02</td>
<td>24.99</td>
<td>12.99</td>
</tr>
<tr>
<td>5-15</td>
<td>14.88</td>
<td>48.13</td>
<td>0.84</td>
<td>10.55</td>
<td>0.02</td>
<td>4.20</td>
<td>54.68</td>
<td>24.90</td>
<td>20.42</td>
</tr>
<tr>
<td>15-35</td>
<td>10.21</td>
<td>27.44</td>
<td>0.07</td>
<td>1.03</td>
<td>0.01</td>
<td>4.65</td>
<td>65.80</td>
<td>16.23</td>
<td>17.97</td>
</tr>
</tbody>
</table>

CEE = Cation exchange capacity  
OM = Organic matter  
N = Nitrogen  
P = Phosphorous  
K = Potassium

Table 2. Herbicide application data for the Carnation Creek Watershed study site

<table>
<thead>
<tr>
<th>Application specifics</th>
<th>Sampling stations</th>
<th>Date</th>
<th>Time</th>
<th>Nominal rate kg/ha</th>
<th>Treatment area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil (1,2,3)</td>
<td>06-09-84</td>
<td>1935-2005</td>
<td>2.0</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>Leaf-litter (A-1*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil (4,5,6)</td>
<td>14-09-84</td>
<td>1430-1539</td>
<td>2.1</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>Leaf-litter (S-1*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leaf-litter (A-2,S-2*)</td>
<td>14-09-84</td>
<td>1730-1814</td>
<td>2.1</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>Soil (7,8,9)</td>
<td>06-09-84</td>
<td>1900-1925</td>
<td>2.0</td>
<td>I</td>
</tr>
</tbody>
</table>

* A-1/A-2 = Alder - stations 1 and 2, respectively.  
S-1/S-2 = Salmonberry - stations 1 and 2, respectively  
** Reynolds et al. 1989  
+ Treatment areas as shown in Figure 1.

Large debris and slash, with minimal disturbance to the forest floor. Three replicate sampling stations were created. At each site, a total of eight deposit plates, each with a surface area of 400 cm², were placed around the periphery of the sampling stations. The deposit collectors were used to provide an estimate of the initial residue deposited on the soil surface and to allow assessment of the uniformity of chemical application using the MICROFOIL BOOM.

Duplicate leaf-litter sampling stations were established in each of two separate areas dominated by salmonberry and red alder respectively (Fig. 1 and Table 2). Sampling plots for
Figure 1. Location of the Carnation Creek Study Area and Terrestrial Sampling Stations.
interception estimates were at sites removed from those used to determine leaf-litter residues. A total of 20 m² surface area of nylon mesh was placed under appropriate species to trap leaf-litter, thus providing a sample substrate for leaf-litter residue determinations.

**Herbicide Application**

ROUNDUP (isopropylamine salt of glyphosate) was applied at a nominal rate of 2 kg/ha active ingredient with a Bell-47 helicopter and a MICROFOIL BOOM equipped with 1.5 mm hayrack nozzles (Reynolds et al. 1989). The volume application rate was calibrated to be 258.25 L/ha. Due to inclement weather conditions, chemical applications were made over a 9-day period on 11 spray blocks (Fig. 1 and Table 2). During application to the pertinent areas, meteorological conditions monitored by the weather station established near the mouth of Carnation Creek were as follows: relative humidity - 61%, air temperature - 24°C, windspeed - 11 km/h.

**Sampling Methodology**

Soil samples were obtained from each sampling station with a Campbell soil coring device, as described elsewhere (Feng and Klassen 1986). Soil cores were taken to a depth of 30 cm and each core was sliced into three sections corresponding to soil depths of 0-5 cm, 5-15 cm and 15-30 cm layers respectively. Volume, fresh weight and air dry weight were determined for each layer. These determinations allowed computation of moisture content, bulk density and residue concentration on both an area and dry weight basis. Soil samples were collected before and immediately after chemical application and thereafter on an increased temporal spacing (i.e. 3 day intervals for the first month, weekly during the second month, biweekly for the third month and monthly between the fourth and twelfth months). The exact times of soil sampling are presented in Appendix 1.

Aluminum foil sheets (400 cm²) on corrugated cardboard plates were used to provide initial deposit samples. Deposit sampling sheets were collected immediately following chemical application, packaged, stored and shipped according to procedures as described by Feng and Klassen (1986).

Fresh leaves were collected immediately following treatment by felling a representative tree (red alder) or clipping brush (salmonberry). Individual leaves were then harvested to provide a composite sample for each species at each sampling site. Leaf senescence began in mid-September 1984, and leaf-litter samples were collected from nylon mesh traps between 01 October and 30 November. Samples of leaf-litter were collected biweekly generally and on a weekly schedule during the peak leaf fall period. Details of sampling methodologies for all substrates are reported by Feng and Klassen (1986).

**Residue Analysis**

Formulation analysis

Samples of ROUNDUP formulation (356 g a.i./L) were collected before mixing for application and kept at ambient temperature. Quadruplicate 1 mL aliquots were serially diluted (10⁵ X) with KH₂PO₄ buffer solution as described in Table 3. The diluents were filtered with Millipore filter units (Millex HV, 0.45 µm) and subjected to high performance liquid chromatographic (HPLC) analysis for glyphosate and its major degradation product - aminomethylphosphonic acid (AMPA).
Table 3. Specifications of HPLC instrumentation

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPLC System:</td>
<td>Varian Model 5560 Ternary HPLC, Model 8085 Autosampler</td>
</tr>
<tr>
<td>Detector:</td>
<td>UV-200 variable wavelength detector set at 570 nm</td>
</tr>
<tr>
<td>Derivatization System:</td>
<td>Ninhydrin post column reactor (100°C)</td>
</tr>
<tr>
<td></td>
<td>System V Model 5000 (Varian Inc.)</td>
</tr>
<tr>
<td>Analytical Column:</td>
<td>Bio-Rad Aminex A-9 10 cm X 4.6 mm i.d.</td>
</tr>
<tr>
<td>Guard Column:</td>
<td>Bio-Rad Aminex A-9 (K+ form cartridge)</td>
</tr>
<tr>
<td>Mobile Phase:</td>
<td>0.005 M KH₂PO₄ buffer in 4% methanol pH = 1.9</td>
</tr>
<tr>
<td>Flow Rate:</td>
<td>0.5 mL/min (isocratic)</td>
</tr>
<tr>
<td>Column Temperature:</td>
<td>50°C</td>
</tr>
</tbody>
</table>

Tank mix analysis

Tank-mix samples (400 mL) collected immediately prior to application to Treatment Area III, were stored frozen until analyzed. Duplicate 1 mL aliquots were diluted (10³ X) in buffer solution, filtered and analyzed for both glyphosate and AMPA, as described above.

Deposit collector sample analysis

Residues of glyphosate and AMPA were extracted from the deposit collecting sheet by a multiple rinsing/shaking and sonicating procedure using 0.1 N HCl as the extraction solvent (Feng and Klassen 1986). The extracts were then subjected to cation and anion exchange column cleanup prior to quantification by HPLC analysis. Herbicide quantities (glyphosate plus AMPA as glyphosate equivalent) on the deposit plates, were converted to kg/ha rates using the equation: kg/ha = 2.5 X 10⁻⁴ x R where R = total residue (μg) per deposit collector (400 cm²).

Leaf-litter and foliage sample analysis

Whole samples of foliage and leaf-litter were air-dried and macerated by passage through a Hobart chopper. Finely chopped particles were mixed in large, inflated, plastic bags, to provide a homogeneous sample. From the homogenized samples, two subsamples (5 g) were taken and used for determination of oven-dry weight and for residue content, respectively. The analytical procedures used for leaf litter and foliage sample analyses are detailed in Thompson et al. (1989). Briefly, the method involves triplicate extraction with 0.5 M NH₄OH, pre-concentration on an anion exchange column, cleanup via cation exchange, evaporation, solvation in mobile phase solution and HPLC analysis (Table 3). Results were corrected for recovery efficiency of the analytical method (Table 4) and reported as μg per g of oven-dried leaf tissue.
### Table 4. Validation data for analytical methods

<table>
<thead>
<tr>
<th>Substrate level</th>
<th>Analyte</th>
<th>% Recovery</th>
<th>LOD*</th>
<th>LOQ**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit Collector</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Humus Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1-6.0</td>
<td>GLYH</td>
<td>77.7 ± 8.9 (11.56)</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.025-1.5</td>
<td>AMPA</td>
<td>67.7 ± 10.9 (16.09)</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Mineral Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1-6.0</td>
<td>GLYH</td>
<td>73.5 ± 7.7 (10.53)</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>0.025-1.5</td>
<td>AMPA</td>
<td>58.2 ± 10.9 (12.77)</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Leaf Litter (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5-5.0</td>
<td>GLYH</td>
<td>84.4 ± 5.3 (6.25)</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>0.1-1.0</td>
<td>AMPA</td>
<td>54.7 ± 1.7 (3.21)</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>Leaf Litter (a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5-5.0</td>
<td>GLYH</td>
<td>81.3 ± 7.7 (9.47)</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>0.1-1.0</td>
<td>AMPA</td>
<td>60.9 ± 12.2 (20.03)</td>
<td>0.03</td>
<td>0.08</td>
</tr>
</tbody>
</table>

All values presented in terms of ppm = μg/g dry mass (for solids).

* LOD = limits of detection = detector response equivalent to 2X S:N ratio.
** LOQ = limits of quantification = detector response 6X S:N ratio.

+LOD and LOQ values for deposit collectors equate to 2.5 X 10^-5 and 1.25 X 10^-4 kg/ha respectively.

### Soil sample analysis

Soil samples obtained from the Carnation Creek study site were immediately frozen, shipped and stored under cold (-10°C), dark conditions until analysis. Owing to the large number of samples of various substrates taken during the course of the study and the requirement for priority on aquatic substrates, soil samples were not analyzed until 2 years after the study was initiated.

Subsamples (5 g) of air-dried and homogenized soils were extracted three times with 0.5 M NH₄OH. Extracts were diluted to 1800 mL, concentrated on an anion exchange column and processed as described above for leaf-litter and foliage samples. Aliquots (100 μL) of the final solutions were analyzed by HPLC (Table 3). Results were corrected for recovery efficiency of the analytical method (Table 4) and reported as μg of glyphosate per g of air-dried soil. For samples taken at 0-time, soil residues (glyphosate + AMPA as glyphosate equivalent) were converted from total micrograms found to initial deposit in terms of kg/ha, using the following equation:

\[ \frac{R}{A}/10 = \text{kg/ha} \]

where \( R \) = initial residue (total μg of glyphosate and AMPA)

\( A \) = cross-sectional surface area of soil auger (78.54)
High Performance Liquid Chromatography (HPLC)

Determination of glyphosate residues in environmental substrates continues to be one of the more difficult aspects of herbicide analytical chemistry. A variety of methods are described in the literature, with some validation data also available (Lundgren 1986; Monsanto 1986; Seiber et al. 1984; Glass 1983; Edwards et al. 1980; Moe and St. John 1980; Monsanto 1977). The analytical methods used for determination of AMPA and glyphosate in soil and leaf litter samples were modifications of the Monsanto (1986, personal communication) method, supplied courtesy of Dr. J. Cowell, Monsanto Co. Inc., St. Louis, Missouri. A detailed description of the method is given in Thompson et al. (1989). Briefly, the method employs cation exchange - HPLC, coupled with a post-column ninhydrin derivatization to separate glyphosate and AMPA analytes from co-extractive interferences and provide derivatization products capable of absorbing in the visible portion of the spectrum. Characteristics of the HPLC system are described in Table 3.

Preliminary validation tests of the analytical method indicated that the determination of glyphosate and AMPA in fortified substrates derived from the Carnation Creek study site were relatively accurate and precise, with no co-extractive interferences at the retention times of the two analytes. Throughout the course of analytical determinations a quality control (QC) program was conducted. Results of the QC samples, which were processed and analyzed daily in conjunction with field samples, confirmed that the accuracy and precision of the method (Table 4). While not ideal, these data were similar to reported values in the available literature. The QC data were subsequently used to correct the field sample data for recovery efficiency of the analytical method.

RESULTS AND DISCUSSION

Formulation Analysis

Analysis of the ROUNDPUP formulation utilized for the herbicide application in this study indicated that the amount of active ingredient (glyphosate) was 363 g/L ± 2% cv, approximately 2% in excess of the label concentration (356 g/L). No AMPA was detected in the formulation, which had been stored at ambient temperature for 3 months.

Tank Mix Analysis

Results of the analyses conducted on the tank mix showed concentrations of 7889 and 58 μL/L of glyphosate and AMPA respectively. There was a 6% v/v contamination of the tank-mix from a six-day old mixture used to spray adjacent areas of the watershed. The amount of AMPA detected (0.7% of glyphosate concentration in the tank mix) indicated a 13% degradation of glyphosate in the previous mixture after six days of storage at ambient temperature. The initial concentration of the tank mix was corrected by converting the AMPA concentration to a glyphosate equivalence. The corrected value was 103% of the concentration required to yield an application rate of 2 kg a.i/ha.

Deposit Collector Analysis

Analysis of deposit collectors placed around the periphery of the sampling stations allowed empirical estimation of the initial deposit rate and subsequent comparison with similar estimates based on soil residues. Thus variability of initial chemical deposition both within and among site locations could be determined. The results indicate that the deposit collectors con-
sistantly estimated higher deposition rates with greater precision than estimates from soil residues. Differences in rate estimates derived from deposit collectors and soil residues were significant (P > 0.05) for the upper and middle sampling locations. This discrepancy may be due in part to differences in replication (n = 3 for soil samples per location; n = 8 for deposit collector samples per location) and to interception of chemical by ground vegetation. Analysis of variance (ANOVA) and multiple comparison procedures (LSD and Bonferroni), indicated that mean rate estimates as determined by deposit collectors, were significantly different for each of the three locations (P > 0.05). Mean rate estimates at the three different sites as derived from soil residues were not significantly different due to greater variation in these samples.

The average empirical rate estimates of 2.52 and 1.85 kg/ha, as determined by deposit collector analysis and by soil residue analysis respectively, were reasonably close to the nominal value of 2.0 kg/ha (Table 5). However, significant differences between deposition rates at various sites, as previously noted, indicate extreme variability in chemical deposition to different areas of the watershed (section on Herbicide Application and Table 5). Both methods of empirical estimation indicated that application rates for the lower portion of the watershed were higher than for the upper watershed. The mid-watershed site (Treatment Area III) received the least chemical deposition, probably owing to the gusty wind conditions prevailing during the mid-afternoon application (Table 2). The high mean value in soil residues recorded for the lower sampling location, resulted from one station (station 8) with a reported initial deposit equivalent to 5.67 kg/ha. No explanation could be found for this anomalous result. Initial levels of AMPA were less than 2% of corresponding glyphosate residues for all deposit collector samples, but varied between 4 and 13% for initial deposit as determined from soil sample residues. The higher levels of AMPA in O-time soil samples, when compared with deposit collector samples, may be indicative of minor degradation of glyphosate during the 2-year storage period for soil samples.

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Treat. area</th>
<th>Initial deposition rate estimates (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Deposit collector**</td>
</tr>
<tr>
<td>Stations 1-3 (Upper Watershed)</td>
<td>I</td>
<td>2.0</td>
</tr>
<tr>
<td>Stations 4-6 (Mid Watershed)</td>
<td>III</td>
<td>2.1</td>
</tr>
<tr>
<td>Stations 7-9 (Lower Watershed)</td>
<td>I</td>
<td>2.0</td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

* Nominal rates as reported by Reynolds et al. (1989).
** Values based on total residue (glyphosate plus AMPA) with n=8 for deposit collectors and n=3 for soil residues.
Deposit collector values followed by different letters are significantly different (P >0.05) as determined by LSD and Bonferroni multiple comparison procedures.
Within each sampling location (i.e. amongst replicates), the variability (as denoted by the coefficient of variation) was similar for deposit collectors and soil residue estimates, with the exception of the lower location. The higher variation at this location is also the result of one anomalous data point as described previously.

Results of the quality control program, comprising over 160 samples analyzed in conjunction with field samples throughout the 8-month analysis period, indicated that analytical variability (coefficient of variation) for soil residue determinations was less than 12% for glyphosate and less than 16% for AMPA. These results indicate that significant differences exist in deposition between various locations, however, the average deposition for the entire watershed is reasonably close to the nominal rate. The differences observed may be attributed to variable meteorological and application parameters for different spray blocks. The data also indicate that greater replication in soil residue sampling would be required to achieve precision equivalent to the deposit collector method for estimating initial deposit.

**Leaf-Litter and Foliage Sample Analysis**

Results of the leaf litter and foliage sample analyses are presented in Table 6. In general, the data show that residues decline over time in both salmonberry and alder leaf litter. Statistical analysis (ANOVA) of the results indicated that the decline in glyphosate residues is significant for both alder and salmonberry (P > 0.0589 and P > 0.0001 respectively). This rapid dissipation from foliage may be attributed to wash-off caused by the rainfall event (39 mm) that occurred 23 h post-application. Residues continued to decline throughout the observation period to the extent that less than 0.1% of initial levels remained 75 days post-application.

<table>
<thead>
<tr>
<th>Table 6. Residues of glyphosate and AMPA associated with leaf litter of two target species from the Carnation Creek*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Days (post-spray)</strong></td>
</tr>
<tr>
<td></td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>58</td>
</tr>
<tr>
<td>75</td>
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</tbody>
</table>

*Residue values are means of two replications in μg per gram dry tissue.

Residues of AMPA found on either type of foliage immediately after application were less than 2% of glyphosate residues, a result that is in good agreement with both the tank mix analysis and deposit collector results. No transient increase in AMPA residue was observed for either foliage type after leaf fall.
The results of leaf tissue analyses indicate that both target species intercepted a relatively large amount of chemical and that leaf-litter contained much less residue, which dissipated slowly with time. In general, these results support those of Lund-Hoie (1979), who found that only 20% of the glyphosate initially applied was absorbed in ash and birch foliage and that 35% of the absorbed amount was decomposed within 2 months, little being recovered as AMPA.

The data derived from this experiment suggest that glyphosate residue levels in leaf-litter of major brush species would present an insignificant, transient source of chemical input onto forest floor or into streams. One may hypothesize that foliage residues present a major source for ecosystem contamination only through wash-off of unabsorbed chemical, with contamination via leaf-fall being relatively minor. Further research is required on the aspect of binding and subsequent wash-off of glyphosate from treated leaf surfaces.

Soil Sample Analysis

Leaching potential

Residue analyses were conducted on each of three individual layers - 0-5 cm (organic), 5-15 cm (organic), 15-30 cm (organic and mineral) - from each soil core. In addition, at sampling dates beyond 150 days post-application, a fourth layer [30-35 cm (mineral)] was obtained and analyzed. Results of these analyses are presented in terms of means for replicate samples taken throughout the observation period at each of the soil sampling locations (upper, middle and lower watershed). The histograms and tabular data indicate the percent of total residue distributed throughout the various layers (Fig. 3 & Appendices). Quantifiable residues of glyphosate were found in only one of the 30-35 cm layer samples, the residue (0.46 ppm) being equivalent to 11.5% of the total found in the core. This anomalous result was attributed to mislabeling during the air-drying process, however, positive proof of this could not be obtained from available laboratory records. In general terms, virtually all (>90%) of the residue was associated with the 0-5 cm organic layer. Two anomalous values were observed at day 60 for glyphosate in the lower watershed site (30.28% of total glyphosate in layer C) and at day 360 for AMPA in the lower watershed (27.28% of total AMPA in layer C). Although of little practical importance, higher mean residue levels in layer C from stations 7-9 relative to other sites indicated a slightly greater tendency towards leaching in these soils. No differences in leaching potential between the seasonally flooded and well-drained soil sites was apparent.

Results of the vertical distribution determinations indicate that neither glyphosate nor AMPA are susceptible to leaching. The findings are consistent with the general literature (Helling 1971; Sprinkle et al. 1975; Rueppel et al. 1977; Damanakis 1976; and Edwards et al. 1980) and support the conclusion of Torstensson (1985), who stated that glyphosate is practically immobile in soil.

The majority of research conducted on the adsorption of glyphosate to soils or soil fractions (i.e. mineral components), suggests that glyphosate is bound to soils through the phosphonic acid moiety and that sorption is positively correlated with clay content, cation exchange capacity and unoccupied phosphate sorption capacity (Sprinkle et al. 1975; Hance 1976; Glass 1987). Since Carnation Creek soils are characterized by a relatively high cation-exchange capacity and organic matter content, especially in the upper 15 cm layers (Table 1), we suggest that the lack of vertical mobility exhibited by glyphosate in these soils is due to strong adsorption to cation saturated clays and/or organic matter in the upper soil horizons. An essentially identical leaching pattern was exhibited by AMPA in this study.
Figure 2. Persistence and distribution of glyphosate and AMPA in Carnation Creek Watershed Study soils.
Persistence

Computation of mean soil residues of glyphosate and AMPA in the 0-30 cm soil layer was done at each sampling time to allow determination of persistence in each sampling location - upper, middle and lower watershed. (Figure 2 and Appendices).

Although the data clearly show that residues decline over time (Fig. 2), variability within replicates resulted in poor regression coefficients for both linear and log transformed data (.17 < r < .46), which prohibited the use of regression equations for estimation of time to 50% and 90% dissipation (DT50 and DT90, respectively). In addition, no statistically valid comparisons could be made with respect to persistence of glyphosate or AMPA in seasonally flooded soils or in well-drained soils. Quantifiable residues of both glyphosate and AMPA did remain after 360 days. In terms of percent of initial residues, these values ranged from 6-18% and 16-27% for glyphosate and AMPA, respectively. AMPA residues, which were initially very low (4-13% of glyphosate residues), followed a pattern of transient increase and subsequent decline at all sampling locations (Appendices 2.1-2.3). Peak residue means were less than 40% of mean initial glyphosate residues for the respective sites.

The general decline in glyphosate residues over time at all three sampling locations, coupled with transient increase in AMPA residues is indicative of microbial degradation of glyphosate in the soils studied. Although accurate estimates of DT50 and DT90 could not be made from regression analysis, averaging glyphosate residues for all sample locations indicated that glyphosate residues were consistently less than 50% of initial residues after 45-60 days post-application. At the end of the observation period, both glyphosate and AMPA residues were lowest in the middle watershed site. Due to the nature of this site (low-lying and seasonally flooded), it is probable that reduced residue levels could be attributed to movement of chemical away from the sampling with surface water present at time of application.

Laboratory experiments conducted by Torstensson and Stark (1981), showed that the time to 50% degradation of glyphosate in a number of different forest soils was quite variable, ranging from 6 days in an iron podsol to 200 days in a podsol with ashes. Torstensson (1985) noted that the variable rate of degradation of glyphosate cannot be correlated to a single soil factor, but reflects the general microbial activity of the soils being investigated, which in turn is affected by a multiplicity of environmental factors. Since the influencing factors may vary from soil to soil and/or from year to year, prediction or comparison of glyphosate persistence, based on either laboratory studies or field studies, should be avoided unless most of the important influencing variables are quantified or controlled. Newton et al. (1984) estimated time to 50% dissipation of glyphosate as 40.2 days based on the results of a study conducted in a semi-arid Oregon forest watershed. However, owing to the differences between the two studies, especially with respect to the method by which the persistence estimates were derived, no valid conclusion can be drawn regarding glyphosate persistence estimates (similarity or lack thereof). In general terms, however, the results of Oregon study and the Carnation Creek study are in agreement. In short, the Carnation Creek study provides no evidence of extraordinary soil persistence of either glyphosate or AMPA.

ACKNOWLEDGEMENTS

This research, supported under the British Columbia Forest Resource and Development Agreement (FRDA), was conducted by members of the Forest Pest Management Institute (FPMI), of the Canadian Forestry Service. Cooperation of the British Columbia Ministry of Forests, the Pacific Forestry Centre (PFC), Fisheries and Oceans Canada, MacMillan Bloedel Ltd., and Monsanto Canada
Inc. were integral to the success of this project. Herbicide application was contracted to Rotor Vegetation Control (R. Rowe) and Alpine Helicopters (D. Gubbels and D. Cholka) both of Calgary Alberta, was coordinated by Dr. P. Reynolds (FPMI). The authors sincerely appreciate and acknowledge the excellent technical assistance in residue analysis of B. Staznik, T. Buscarini, V. Manniste-Squire, and L. MacDonald (FPMI), and of H. Klassen and D. DeKoven (V.A. Poulin and Assoc. Ltd.) who performed the field sampling.

REFERENCES


### APPENDIX 1.1  CARNATION CREEK SOIL RESIDUE DATA - GLYPHOSATE

**SAMPLING LOCATION - LOWER WATERSHED (STATIONS 7, 8, 9)**

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Total residue (μg/s) (0-30 cm core)</th>
<th>Distribution of residues (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2469.11 ± 1763.37 (71.4)</td>
<td>98.33 1.67 0.00</td>
</tr>
<tr>
<td>3</td>
<td>1413.61 ± 749.08 (52.9)</td>
<td>72.30 8.46 19.23</td>
</tr>
<tr>
<td>6</td>
<td>1889.74 ± 1061.57 (56.1)</td>
<td>99.63 0.37 0.00</td>
</tr>
<tr>
<td>9</td>
<td>2391.87 ± 760.40 (31.7)</td>
<td>86.64 7.85 5.51</td>
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<tr>
<td>12</td>
<td>2408.22 ± 1488.79 (61.8)</td>
<td>95.82 4.18 0.00</td>
</tr>
<tr>
<td>15</td>
<td>1491.85 ± 838.63 (56.2)</td>
<td>90.62 6.92 2.46</td>
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<tr>
<td>18</td>
<td>1156.54 ± 575.29 (49.7)</td>
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</tr>
<tr>
<td>21</td>
<td>1586.90 ± 196.94 (12.4)</td>
<td>81.68 5.87 12.45</td>
</tr>
<tr>
<td>24</td>
<td>1197.29 ± 840.91 (70.2)</td>
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</tr>
<tr>
<td>27</td>
<td>1430.13 ± 552.84 (38.6)</td>
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</tr>
<tr>
<td>30</td>
<td>1456.88 ± 574.10 (39.4)</td>
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</tr>
<tr>
<td>37</td>
<td>989.57 ± 376.70 (38.0)</td>
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</tr>
<tr>
<td>45</td>
<td>1414.60 ± 2096.59 (148.2)</td>
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<tr>
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<td>1248.91 ± 1478.50 (118.3)</td>
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<tr>
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<td>1129.65 ± 687.63 (60.8)</td>
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<td>90</td>
<td>814.29 ± 532.17 (65.3)</td>
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<td>752.69 ± 518.08 (68.8)</td>
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<td>467.88 ± 425.77 (91.0)</td>
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<tr>
<td>270</td>
<td>260.19 ± 154.83 (59.5)</td>
<td>74.15 10.58 15.27</td>
</tr>
<tr>
<td>360</td>
<td>436.75 ± 177.72 (40.6)</td>
<td>68.32 6.14 25.54</td>
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</tbody>
</table>
### Appendix 1.2 Carnation Creek Soil Residue Data - Glyphosate

**Sampling Location - Middle Watershed (Stations 4, 6)**

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Total Residue (µg) (0-30 cm core)</th>
<th>Distribution of Residues (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>484.00</td>
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<td>6</td>
<td>172.18 ± 217.39 (126.2)</td>
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<tr>
<td>9</td>
<td>369.65 ± 370.68 (100.2)</td>
<td>94.65 5.35 0.00</td>
</tr>
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<td>147.01 ± 96.94 (65.9)</td>
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<tr>
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<td>125.97 ± 2.45 (1.9)</td>
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<td>113.93 ± 73.58 (64.5)</td>
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</tr>
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<td>92.40 ± 60.28 (65.2)</td>
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<td>56.79 ± 6.57 (11.5)</td>
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<td>70.25 ± 4.94 (7.0)</td>
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<td>82.71 ± 44.68 (54.0)</td>
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</tr>
<tr>
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<tr>
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<td>54.70 ± 59.69 (109.1)</td>
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<tr>
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<td>34.08 ± 14.40 (42.2)</td>
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<td>35.10 ± 2.84 (8.1)</td>
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<td>8.29 ± 11.73 (141.4)</td>
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<tr>
<td>360</td>
<td>28.98 ± 4.22 (14.5)</td>
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</tr>
<tr>
<td>Time (days)</td>
<td>Total residue (µg) (0-30 cm core)</td>
<td>Distribution of residues (%)</td>
</tr>
<tr>
<td>------------</td>
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</tr>
<tr>
<td></td>
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<td>0-5 cm</td>
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<td>1476.96 ± 376.25 (25.5)</td>
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<td>1410.93 ± 1238.64 (87.7)</td>
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<td>926.39 ± 983.53 (106.1)</td>
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<td>992.08 ± 1552.66 (156.5)</td>
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<td>809.63 ± 882.92 (109.0)</td>
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<td>1140.02 ± 1048.37 (91.9)</td>
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<td>1313.89 ± 1048.25 (79.7)</td>
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<td>669.76 ± 560.39 (83.6)</td>
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<td>668.25 ± 226.16 (33.8)</td>
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<td>1004.85 ± 1182.40 (117.6)</td>
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<tr>
<td>60</td>
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<tr>
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<td>522.29 ± 130.66 (25.0)</td>
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<td>533.29 ± 486.51 (91.2)</td>
<td>83.45</td>
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<td>150</td>
<td>782.87 ± 523.55 (66.8)</td>
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<td>180</td>
<td>157.71 ± 82.23 (52.1)</td>
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<td>270</td>
<td>394.36 ± 332.45 (84.3)</td>
<td>80.95</td>
</tr>
<tr>
<td>360</td>
<td>198.07 ± 116.21 (58.6)</td>
<td>100.00</td>
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</tbody>
</table>
### Appendix 2.1 Carnation Creek Soil Residue Data - AMPA

**Sampling Location**: Lower Watershed (Stations 7, 8, 9)

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Total residue (µgs)</th>
<th>Distribution of residues (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0-30 cm core)</td>
<td>0-5 cm</td>
</tr>
<tr>
<td>0</td>
<td>101.24 ± 68.52 (67.68)</td>
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<td>163.56 ± 70.24 (42.95)</td>
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</tr>
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<td>9</td>
<td>238.59 ± 20.68 (8.67)</td>
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</tr>
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<td>342.58 ± 213.01 (62.18)</td>
<td>92.76</td>
</tr>
<tr>
<td>15</td>
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<tr>
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<td>334.51 ± 197.41 (59.02)</td>
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<tr>
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<td>299.13 ± 119.41 (39.92)</td>
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<tr>
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<td>391.22 ± 66.67 (17.04)</td>
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<td>389.49 ± 199.36 (51.19)</td>
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<td>474.77 ± 370.03 (77.94)</td>
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<td>342.28 ± 106.88 (31.23)</td>
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<td>470.50 ± 308.24 (65.51)</td>
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<td>270</td>
<td>614.96 ± 304.59 (49.53)</td>
<td>81.02</td>
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<tr>
<td>360</td>
<td>583.37 ± 372.03 (63.77)</td>
<td>66.99</td>
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</table>
**APPENDIX 2.2 CARNATION CREEK SOIL RESIDUE DATA - AMPA**

**SAMPLING LOCATION - MIDDLE WATERSHED (STATIONS 4, 6)**

<table>
<thead>
<tr>
<th>TIME (DAYS)</th>
<th>TOTAL RESIDUE (UGS)</th>
<th>DISTRIBUTION OF RESIDUES (%)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>(0 - 30 CM CORE)</td>
<td>0-5 CM</td>
</tr>
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<td>121.07</td>
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<td>95.59</td>
<td>16.28 (17.03)</td>
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<td>21.71 (12.96)</td>
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<tr>
<td>120</td>
<td>64.93</td>
<td>63.11 (97.20)</td>
</tr>
<tr>
<td>150</td>
<td>113.09</td>
<td>40.87 (36.14)</td>
</tr>
<tr>
<td>180</td>
<td>107.52</td>
<td>66.24 (61.60)</td>
</tr>
<tr>
<td>270</td>
<td>38.86</td>
<td>32.07 (82.53)</td>
</tr>
<tr>
<td>360</td>
<td>144.84</td>
<td>204.84 (141.42)</td>
</tr>
</tbody>
</table>
### APPENDIX 2.3 CARNATION CREEK SOIL RESIDUE DATA - AMBA

**SAMPLING LOCATION - UPPER WATERSHED (STATIONS 1, 2, 3)**

<table>
<thead>
<tr>
<th>TIME (DAYS)</th>
<th>TOTAL RESIDUE (G/6)</th>
<th>DISTRIBUTION OF RESIDUES (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0 - 30 CM CORE)</td>
<td>0-5 CM 5-15 CM 15-30 CM</td>
</tr>
<tr>
<td>0</td>
<td>64.98 ± 59.49 (91.55)</td>
<td>87.16 12.84 0.00</td>
</tr>
<tr>
<td>3</td>
<td>148.03 ± 99.96 (67.53)</td>
<td>90.60 9.40 0.00</td>
</tr>
<tr>
<td>6</td>
<td>239.82 ± 23.98 (10.00)</td>
<td>96.97 3.03 0.00</td>
</tr>
<tr>
<td>9</td>
<td>236.97 ± 214.26 (90.42)</td>
<td>85.99 14.01 0.00</td>
</tr>
<tr>
<td>12</td>
<td>145.99 ± 153.54 (105.18)</td>
<td>56.58 43.42 0.00</td>
</tr>
<tr>
<td>15</td>
<td>320.34 ± 123.41 (38.52)</td>
<td>93.27 6.73 0.00</td>
</tr>
<tr>
<td>18</td>
<td>369.90 ± 176.29 (47.66)</td>
<td>85.80 14.20 0.00</td>
</tr>
<tr>
<td>21</td>
<td>448.62 ± 270.28 (60.25)</td>
<td>82.08 12.51 5.40</td>
</tr>
<tr>
<td>24</td>
<td>391.57 ± 187.21 (47.81)</td>
<td>87.74 11.01 1.26</td>
</tr>
<tr>
<td>27</td>
<td>363.23 ± 252.93 (69.63)</td>
<td>90.59 9.41 0.00</td>
</tr>
<tr>
<td>30</td>
<td>307.27 ± 128.93 (41.96)</td>
<td>98.73 1.27 0.00</td>
</tr>
<tr>
<td>37</td>
<td>426.39 ± 136.46 (32.00)</td>
<td>88.64 11.36 0.00</td>
</tr>
<tr>
<td>45</td>
<td>255.44 ± 42.02 (16.45)</td>
<td>94.12 5.88 0.00</td>
</tr>
<tr>
<td>60</td>
<td>240.43 ± 40.75 (16.95)</td>
<td>92.69 7.31 0.00</td>
</tr>
<tr>
<td>75</td>
<td>359.93 ± 233.64 (64.91)</td>
<td>96.55 3.45 0.00</td>
</tr>
<tr>
<td>90</td>
<td>320.98 ± 80.12 (24.96)</td>
<td>92.71 7.29 0.00</td>
</tr>
<tr>
<td>120</td>
<td>347.99 ± 38.65 (11.11)</td>
<td>61.66 38.34 0.00</td>
</tr>
<tr>
<td>150</td>
<td>588.14 ± 230.23 (39.15)</td>
<td>76.28 17.02 6.70</td>
</tr>
<tr>
<td>180</td>
<td>359.84 ± 140.37 (39.01)</td>
<td>77.87 22.13 0.00</td>
</tr>
<tr>
<td>270</td>
<td>284.75 ± 221.38 (77.75)</td>
<td>68.71 18.05 13.24</td>
</tr>
<tr>
<td>360</td>
<td>248.96 ± 100.47 (40.36)</td>
<td>98.03 1.97 0.00</td>
</tr>
</tbody>
</table>
OFF-TARGET DEPOSIT MEASUREMENTS AND BUFFER ZONES REQUIRED
AROUND WATER FOR VARIOUS AERIAL APPLICATIONS OF Glyphosate

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P6A 5M7

ABSTRACT

An investigation was conducted to quantify off-target deposit from three types of aerial glyphosate use-strategies for forestry use, and to estimate the width of buffer zones required around water to protect fish and their food supply from direct toxicological effects. To overcome the difficulty of estimating different buffer widths to meet the various conditions encountered, e.g., windspeed, boundary layer stability, active ingredient application rate, etc., a realistic worst case scenario was chosen, and data were collected accordingly. Glyphosate applications were made by helicopter, using three types of dispersal system, a MICROFOIL BOOM, a Thru Valve Boom and a D8-46 hydraulic nozzle. Airborne glyphosate and off-target deposits on water and foliar surfaces were measured at various downwind distances up to 200 m from multiple swaths overlaid on a crosswind track. Using these measurements, calculations were made to predict glyphosate deposits on water surfaces downwind of multiple swath applications with the use-strategies tested. Based on published measurements of the toxicity of ROUNDUP to salmon, rainbow trout and various aquatic invertebrates, an estimate was then made of buffer widths required around water bodies to keep mortality at an acceptable level. In general, measured airborne glyphosate and off-target deposit was highest from the D8-46 application, and lowest from the MICROFOIL BOOM application. In all applications off-target deposit on water decreased rapidly with downwind distance. A buffer width of 25 m around water bodies is adequate to protect salmon, rainbow trout and aquatic invertebrates from significant direct effects resulting from off-target ROUNDUP deposits from the MICROFOIL and Thru Valve Boom use-strategies: for the D8-46 use-strategy, a 30 m buffer width is required.

INTRODUCTION

Glyphosate (N-(phosphonomethyl) glycine) is a broad spectrum herbicide that is effective in controlling deep-rooted perennial species, and also annual and biennial broad-leaf, grass and sedge species (WSSA 1983). The isopropylamine salt of glyphosate forms the active ingredient (a.i.) of the herbicide ROUNDUP (Monsanto, St. Louis, MO), which is registered in Canada for forestry use. The toxicity of ROUNDUP (now Vision®) to fish and aquatic arthropods (Folmar et al. 1979) has led the federal Department of Fisheries and Oceans and the Environmental Protection Service of Environment Canada to raise objections to its use near water bodies because of the possibility of fish mortality caused by an overspray, or the drifted cloud.
The need to minimize the hazard posed by ROUNDUP to fish and aquatic arthropods is particularly acute in the coastal region of British Columbia, where fertile alluvial sites are adjacent to salmon-bearing rivers. By maintaining a minimum distance of approach, or buffer zone, between a pesticide application and water body, the unwanted side-effects from a herbicide application can be reduced. The present investigation was conducted to quantify off-target deposit from aerial ROUNDUP use-strategies suitable for use in the mountainous B.C. terrain and to estimate the buffer width required to prevent significant mortality in populations of salmon and trout. This investigation addresses the problem of protecting fish and aquatic species from direct toxicological effects: the problem of assessing the buffer width required to protect riparian vegetation remains. To estimate the buffer width required to protect riparian and other vegetation requires measurements of the phytotoxicity of sub-lethal glyphosate deposits, as yet unknown, but the subject of an investigation in progress. Because of the phytotoxic nature of glyphosate, the buffer width required to protect vegetation may be larger than that required to protect fish and aquatic species from direct effects.

PROBLEM ANALYSIS

The use of buffer zones enable environmental impact to be controlled, however, they should not be unnecessarily wide, because this impedes efficient forest management. The buffer width required to protect a sensitive area varies according to many factors, including the state of the atmospheric boundary layer (Pasquill 1974), structure of the plant canopy (Thom 1975), dropsize spectrum of the spray cloud and its release height (Pasquill 1974), volume and active ingredient application rates, and the number and spacing of swaths applied. The physical and biological characteristics of the buffered water body, e.g. still or flowing water, water depth, fish species present, also affect buffer width. In this investigation buffer width estimation was based on the assumption that, where possible, worst case conditions should be used. The use of a worst case scenario resolves the problem of defining and regulating buffer zones with many different widths, because conditions are chosen to give the widest buffer needed to limit the unwanted effects of the herbicide to an acceptable level.

To estimate the widths of buffer zones required around water bodies to protect fish and aquatic invertebrates during operational ROUNDUP applications, it is necessary to know how much a.i. is deposited on the water surfaces and its biological effect. Because a.i. deposit and biological effect diminish with distance from the spray application, at a certain distance from the application the environmental impact becomes negligible, i.e., comparable with natural influences. A buffer can be estimated from this distance. This technique for buffer estimation was devised and first used in estimating buffers required during applications of the insecticide permethrin (Payne et al. 1986; 1988). The problem of estimating the buffer width required around water was split into four parts. First, measurements were made of the amount of glyphosate deposited on water surfaces at various downwind distances from a single crosswind swath. Second, using the experimental data obtained for a single swath, glyphosate deposit from a multiple swath application was calculated. Third, calculated glyphosate deposits were converted into corresponding ROUNDUP concentrations, assuming uniform a.i. mixing in various water depths. Finally, buffer widths were estimated, using published measurements of the toxicity of ROUNDUP to fish and aquatic invertebrates.

Pesticide applications may require upwind, crosswind and downwind buffers. However, drops can be transported over greater distances by advection than by atmospheric diffusion or aircraft vortices (Payne et al. 1986). The largest buffer width is therefore required in the downwind direction, and this can safely be used for an upwind or crosswind buffer. This investigation addresses the problem of setting downwind buffer widths.
The dropsize spectrum of the spray cloud affects the proportion of spray deposited off-target during a pesticide application. In considering the effect of dropsize on the dispersal and deposition of a spray cloud, the spectrum can be viewed as comprising two dropsize ranges, large and small. These two size ranges are distinguished by comparing the magnitude of the drop sedimentation velocities with the standard deviation of vertical windspeeds in the atmospheric boundary layer. The physical significance of this classification is that small drop dispersal and deposition can be considered, to a first approximation, to be independent of sedimentation velocity and dependent only on meteorological variables, e.g. atmospheric stability or windspeed; plant canopy variables, e.g. canopy height, or plant density; and spray application variables, e.g. cloud release height, or tank mix volatility. For large drops the effect of the sedimentation velocity on dispersal and deposition may not be ignored, but allows large drop behavior to be viewed in terms of ballistics, with some spreading of the cloud about its centre of mass, caused by atmospheric diffusion (Pasquill 1974). The magnitude of the standard deviation of vertical windspeed in the atmospheric boundary layer varies according to atmospheric stability, geostrophic windspeed, and height above ground. Typical values are ¼-½ m/s, which provides an upper size limit of 100 to 150 μm for small drops. ULV insecticide applications generally use small drops, whereas herbicide applications generate both large and small drops (Matthews 1979). Because small drops may be transported further by the atmosphere than large drops, drift of small drops is often considered to be of greater importance in causing off-target deposit.

Worst Case Analysis

The worst case described below applies to off-target deposit on water bodies resulting from small drop drift. The variables considered in choosing a worst case were those affecting the amount of a.i. deposited on water downwind of the herbicide application.

Spray cloud dispersal experiment

For the experimental part of the study these variables fall into three categories, those related to meteorology, plant canopy, and spray application variables. However for reasons of data utility, a number of the plant canopy and spray application variables were set in accordance with operational conditions rather than the worst case.

The meteorological variables that affect spray cloud dispersal are atmospheric boundary layer stability, windspeed, relative humidity and air temperature. The influence of atmospheric stability lies in its effect on windspeed and turbulence, through its enhancement or damping of vertical mixing (Thom 1975). Atmospheric boundary layer stabilities are categorized as stable, unstable and neutral (Neiburger et al. 1973), according to the gradient of the vertical air temperature profile. Stable conditions are normally found at night and around dawn and dusk, unstable conditions are found during daylight hours when significant insolation occurs. Neutral conditions are usually found in overcast conditions or with high windspeeds, and for short periods near dawn and dusk (Sutton 1953). Stable conditions have been, and in regulatory circles still are, favored for minimizing drift of both large and small drops. However, Crabbe and his co-workers (Crabbe et al. 1983; Crabbe and McCooeeye 1985) have shown that neutral or unstable conditions minimize small drop drift, whereas stable conditions cause increased drift beyond the treatment area.

Windspeed is another important meteorological variable affecting off-target deposit. Drop deposition on a water surface occurs at a rate proportional to the drop concentration in the air above (Pasquill 1974). Increased windspeed reduces drop concentration near the ground (Crabbe and McCooeeye 1985; Joyce et al. 1981); this is partly because drop impaction efficiency increases with
windspeed (May and Clifford 1967). The worst case for drop deposition on a water surface is, therefore, to spray in light winds, but not calm conditions.

Relative humidity (r.h.) is also influential if water-based sprays are used (Green and Lane 1964). Drop impaction efficiency increases with drop diameter (May and Clifford 1967), thus drift will increase if dropsizes are reduced because the spray cloud will be deposited more slowly. Because r.h. is inversely related to drop evaporation rate (Rogers 1979), the worst case is to use low r.h. values in the range normally encountered while spraying. Increased air temperature increases drop evaporation rate (Green and Lane 1964; Rogers 1979), and thus reduces dropsizes and impaction efficiencies, causing increased drift. The worst case is, therefore, to use a high air temperature in the range encountered while spraying. In summary the worst case meteorological conditions for small drop drift include a stable boundary layer, light wind, low r.h. and high air temperature.

Plant canopy variables also have an effect on off-target deposit by modifying the atmospheric boundary layer and filtering the spray cloud. The significant variables include canopy height, density (plants/m²) and plant type, i.e. deciduous or coniferous. The effects of plant canopy variables are discussed further by Payne et al. (1986). The canopy selected in this investigation was typical of those requiring herbicide treatment in the coastal regions of British Columbia, and was therefore of operational relevance, but being aerodynamically rough did not provide a worst case.

The spray application variables influencing dispersal include the dropsizes spectrum and release height of the spray cloud, the volume and a.i. application rate, the tank mix volatility and the number and spacing of swaths. Dropsizes spectra are determined by the choice of atomizer and settings, the air-speed past the atomizer and the physical characteristics of the tank mix. All of these variables were set according to the use-strategies tested. Spray cloud release height was low, in accordance with operational practice. However this release height also provides a worst case for spray deposited on water surfaces, because mixing and dilution of the spray cloud increases with release height, and spray deposit on water is proportional to drop concentration in the air above. Volume application rates ranged between 90 and 230 L/ha, also in accordance with operational practice for a canopy of the height and density treated. The tank mix diluent was water, which provides a worst case for tank mix volatility because of its relatively high vapor pressure compared to other diluents used in operational spray applications (Matthews 1979; Riddick and Bunger 1970). A high volatility tank mix causes fast drop evaporation, which in turn decreases dropsizes and impaction efficiency, resulting in greater drift than from low volatility tank mixes. Swath width was also set in accordance with operational practice.

Modeling glyphosate deposit from multiple swath applications

A worst case was also chosen for modeling deposit from multiple swath applications. Off-target deposit downwind of a multiple swath application increases with the total amount of a.i. sprayed, which depends on the a.i. application rate and the size of treatment area. The glyphosate application rate was 2.1 kg acid equivalent (a.e.)/ha, the maximum recommended rate in Canadian forestry. The swath number was also worst case, based on a 100 ha (1 x 1 km) area, which is at or near the upper limit for size of treatment area for glyphosate applications in Canadian forestry.
EXPERIMENTAL METHODS

Site and Canopy

The experiment was conducted on a nearly flat area in the Skeena River Valley, near grid reference 129°23'W, 54°19'N (Fig. 1). With the wind direction chosen for the spray trials, i.e. up-valley and approximately SW, there was an upwind fetch of nearly flat terrain about 1 km long, bearing a largely deciduous forest with a canopy 10-30 m in height. Upwind of this was a fetch of about 3 km comprising wooded floodplain and open water. Over this distance the valley floor was at least 2.5 km wide. Wind directions suitable for the trials were restricted to up and down the valley because of the lee eddies caused by air flow over mountains which results in irregular and atypical spray cloud dispersal (Atkinson 1981; Scorer 1978).

![Map of experimental site location (A) in Skeena river valley (1:50,000 map 103-I/6, Salvus).](image)

Figure 1. Experimental site location (A) in Skeena river valley (1:50,000 map 103-I/6, Salvus).

The spray site was a 1968-69 cutover, which bore a largely deciduous canopy. Canopy composition and tree heights were measured at five locations, 100 m apart, along a transect across the site. At each location all trees within a circular area with radius 10 m were counted, and the heights of ten randomly selected trees were measured. The results are given in Table 1.

Meteorological Measurements

On-site meteorological measurements were used to select suitable spraying conditions and to characterize conditions during the spray application and dispersal. Windspeed was measured at 13 and 22 m above ground level (agl), with cup anemometers (threshold speed 0.34 m/s, Heathkit digital weather computer Model ID-4001. Heath Co., Benton Harbour, MI). At 13 m agl the lower
### Table 1. Plant canopy composition

<table>
<thead>
<tr>
<th>Tree species</th>
<th>Plant density (Avg stems/ha)</th>
<th>Plant height (m, Avg ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Alder</td>
<td>1318</td>
<td>17.3 ± 4.3</td>
</tr>
<tr>
<td><em>Alnus rubra Bong</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Cottonwood</td>
<td>146</td>
<td>27.3 ± 2.1</td>
</tr>
<tr>
<td><em>Populus trichocarpa</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torr. &amp; Gray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bebb's willow</td>
<td>1236</td>
<td>9.7 ± 2.2</td>
</tr>
<tr>
<td><em>Salix bebbiana Sarg.</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Anemometer was just above the canopy. Measured windspeeds were corrected to provide true windspeeds, using calibration curves. Wind direction was measured at 22 m agl (wind vane, Heathkit digital weather computer ID-4001). Air temperatures were measured at 13 and 22 m agl with diode type sensors (Heathkit digital weather computer) shaded to prevent direct heating by solar or terrestrial radiation. Relative humidity was measured at 2 m agl (capacitance type hygrometer, Heath Co.) during the spray application and dispersal. Meteorological measurements were manually recorded at half minute intervals during the spray application and dispersal, a period of up to 20 min. Meteorological conditions during the trials (Table 2) provided the worst case conditions required to maximize glyphosate deposit on downwind water bodies from small drop drift.

### Table 2. Meteorological measurements during spray applications and dispersal

<table>
<thead>
<tr>
<th>Trial number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of trial</td>
<td>19/9/84</td>
<td>30/9/84</td>
<td>30/9/84</td>
</tr>
<tr>
<td>Time spraying commenced</td>
<td>1915</td>
<td>1630</td>
<td>1920</td>
</tr>
<tr>
<td>Time of Sunset (PST)</td>
<td>2046</td>
<td>2022</td>
<td>2022</td>
</tr>
<tr>
<td>Windspeed @ 13m agl (avg ± SD m/s)</td>
<td>0.4 ± -</td>
<td>0.5 ± 0.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>Windspeed @ 22m agl (m/s)</td>
<td>0.8 ± 0.3</td>
<td>0.9 ± 0.3</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Air temperature @ 13m agl (avg., °C)</td>
<td>8</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Air temperature @ 22m agl (°C)</td>
<td>10</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Stability of lowest 20m of atmosphere</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>Relative humidity (avg. %)</td>
<td>80</td>
<td>76</td>
<td>88</td>
</tr>
</tbody>
</table>
Spray Applications

Three use-strategies were tested, including two designed during this investigation to provide low off-target deposits (Microfoil and Thru Valve Boom) and another widely used by the USDA Forest Service (D8-46). A helicopter was chosen for all applications because of its maneuverability, and hence its suitability for applying pesticide in mountainous terrain, such as that in the B.C. coastal region. Different dispersal systems were used in each trial, but spray cloud release heights, and meteorological conditions were similar in all.

The application in trial 1 was made with a MICROFOIL BOOM (Rhone Poulenc, Lansdale, PA). This dispersal system was designed to provide good drift control by minimizing the proportion of small drops generated. The glyphosate and volume application rates were 3.4 kg a.e./ha and 230 L/ha per swath. The chosen a.i. application rate provided detectable residues at the sampling stations furthest downwind, however the results presented were adjusted to the maximum recommended rate in Canadian forestry. The volume application rate is representative of operational herbicide applications in which a dense multi-storey plant canopy is treated. The MICROFOIL BOOM was 7.9 m long, and carried 52 hayrake nozzles at 0.15 m intervals. The hayrake nozzles were fitted with 2.4 mm restricting orifices and comprised 10 jets (I.D. 1.5 mm), oriented backwards to minimize relative fluid velocities. The dispersal system was forward-mounted on a Bell 47-T helicopter, and flown at 11 m/s at about 3 m above canopy height, using a boom pressure of 137 kPa, giving a total flow rate of 200 L/min. The planned swath width was 13 m, and the tank mix sprayed was a 4.2% v/v mixture of ROUNDP and water. The chosen flying speed and boom pressure fall within the recommended range for minimum drift. From a previous study (van Vliet et al. 1988) the dropsize spectrum in trial 1 was estimated to have volume and number median diameters of about 3000 and 2700 microns at release, with 4% of drops having diameters less than 1600 microns, representing 0.63% of the spray volume.

Swath-length and number were an important consideration in the design of the spray trials. Measurements of average spray deposit from a single swath were required for modelling. In each trial several swaths were overlaid along a crosswind track to reduce deposit variability and provide sufficient a.i. for detection at the sampling stations furthest downwind. Swath lengths were sufficient to make the application representative of an infinite line source at the downwind distances where deposits were sampled (Payne 1983), and thus provide worst case deposits. In trial 1 three swaths 300 m in length were applied. The volume application rate used in trial 1 is relatively high and consequently the work rate is low, making this type of application expensive for operational use.

The application in trial 2 was made with a Thru Valve Boom (TVB, Waldrum Specialties, Ambler, PA). The TVB is also designed to provide good drift control by minimizing the proportion of small drops generated. A.i. and volume application rates were 2.2 kg a.e./ha and 91 L/ha per swath. The TVB was 9.1 m long and carried 62 burr nozzles at 0.15 m intervals. The burr nozzles were fitted with 2.03 mm restricting orifices and comprised 15 jets (I.D. 1.1 mm) oriented backwards to reduce relative fluid velocity. The TVB was forward-mounted on a Bell 47-T helicopter and flown at about 20 m/s at about 3 m above the canopy height, using a boom pressure of 171 kPa, giving a total flow rate of 165 L/min. The planned swath width was 15 m, and the tank mix sprayed was a 6.7% v/v mixture of ROUNDP and water. From a previous study (van Vliet et al. 1988) the dropsize spectrum in trial 2 was estimated to have volume and number median diameters of about 1000 and 150 microns at release, with about 30% of drops having diameters less than 100 microns, representing 0.04% of the spray volume at release. In trial 2 five swaths 300 m long were applied. As used in trial 2 the TVB provides lower volume application rates and consequently higher work rates than the MICROFOIL BOOM configuration employed in trial 1. However the volume rate is still relatively high for glyphosate applications in Canadian forestry.
The application in trial 3 was made with a D8-46 hydraulic nozzle, and employed a use-strategy used in USDA Forest Service herbicide applications. A.i. and volume application rates were 2.1 kg a.e./ha and 90 L/ha per swath respectively. The boom was 8.5 m long and carried 32 hollow cone nozzles (disc number 8, 46 whirlplate), evenly spaced along the boom and oriented backwards to reduce relative fluid velocity. The dispersal system was mid-mounted on a Bell 47-T helicopter and flown at about 20 m/s at 3 m above canopy height, using a boom pressure of 171 kPa, giving a total flow rate of 163 L/min. The planned swath width was 15 m, and the tank mix sprayed was a 6.5% v/v mixture of Roundup and water. From a previous study (Yates et al. 1985) the drop-size spectrum was estimated to have volume and number median diameters of about 460 and 70 microns respectively at release, with about 60% of drops having diameters less than 100 microns, representing 1% of the spray volume. In trial 3 four swaths 300 m long were applied.

**Off-target Deposit and Airborne Glyphosate Measurements**

Sampling methods

The layout of the experimental site is shown in Figure 2; swaths were laid along a NW-SE crosswind track (B), and sampling stations (C) were set up at downwind distances of 25, 50, 75, 100 and 200 m.

![Diagram](image)

Figure 2. Experimental layout (to scale), with planned wind direction (A), 300 m crosswind track (B), sampling stations (C) and meteorological station (D).

Because average wind directions during the trials were within 20° of the planned direction, the downwind distances of the sampling stations were within 6% of the planned values, and consequently no corrections were applied. Clearings 8 m in diameter (50% canopy height) were made...
around each sampling station to reduce local interception of the spray cloud by the canopy and expose the collectors to ensure maximum deposition, and provide worst case deposits.

Glyphosate deposit on imitation water and foliar surfaces and airborne glyphosate were measured. Off-target glyphosate deposit was sampled at all stations with collectors comprised of a polyethylene sampling sheet (0.3 x 1 m) placed on a larger polyethylene sheet (2 x 2 m), pegged over an area cleared of vegetation. These collectors were aerodynamically similar to a water surface and thus the airflow over them was similar to that over water. Spray deposits on a water surface and the collector were therefore assumed to be similar. At the 25, 50 and 75 m stations one sheet was exposed and at the remaining stations the sampling area was doubled. To prevent contamination in the second and third trials a backing sheet was placed beneath the sampling sheet. Glyphosate deposits on the sampling sheet were quantified.

Off-target glyphosate deposits at the 50, 100 and 200 m stations were sampled with collectors comprised of a red alder branch on which the upper and lower surfaces of ten randomly chosen leaves were covered with a polyethylene sheet, cut to match the leaf shape. Red alder was chosen as a common weed species in B.C. herbicide applications. At each station an apical branch was mounted vertically at the canopy top, and a dorsal branch was mounted horizontally at 2 m agl, using light-weight sampling masts (Beveridge and Payne 1986). Glyphosate deposits on the polyethylene leaf covers were quantified, and their areas were measured with a polar planimeter (Davis and Kelly 1967).

Measurements of airborne glyphosate were made at the 50, 100 and 200 m sampling stations using Rotorod samplers (Ted Brown Associates, 26338 Esperanza Drive, Los Altos Hills, CA 94022), which collect drops by inertial impaction (Fig. 3). Based on measurements of impaction efficiency (May and Clifford 1967), these devices were assumed to collect all drops in the volume of air sampled. The glyphosate deposit on the Rotorod collecting surface is proportional to the concentration of airborne glyphosate (May et al. 1976). Because glyphosate has a very low vapor pressure (WSSA 1983), airborne a.i. is largely contained within spray drops and vapor sampling is unnecessary. Drops were collected on two teflon cylinders (O.D. 2.6 mm) mounted on 'U' rods. Two samplers were deployed at each station supported on the sampling masts, with one at canopy top and the other at 2 m agl. Glyphosate deposits on the teflon cylinders were quantified.

All collectors were exposed for up to 20 min after the spray application was completed to allow the spray cloud to be advected over all sampling stations, and for drops to penetrate the plant canopy and be deposited. Samples were then collected and stored at about -10°C until deposits were quantified.

Glyphosate quantification

Spray deposits were washed from collecting surfaces with 0.1N hydrochloric acid by sonication and mechanical agitation. The rinsings from the ground sheets were cleaned-up with anion- and cation-exchange columns, according to the method described by Cowell et al. (1986). Samples were then filtered (Milipore SLHV 025 NS filter) and the residues of glyphosate and its principal metabolite aminomethyl-phosphonic acid (AMPA) were quantified by high performance liquid chromatography. Detection and derivatisation were carried out using a methodology developed by Monsanto (1983, unpublished report). The chromatograph was fitted with a variable wavelength UV/vis light detector and a ninhydrin post-column reactor. Glyphosate and AMPA residues were quantified by
measuring peak heights of detector response, which were then interpreted by comparison with analytical standards injected after every second sample. With this method the limit of quantification for glyphosate was about 500 ng, while that for AMPA was about 150 ng. AMPA comprised less than 6% of the glyphosate residue in any sample.

**Estimating Buffer Width**

The technique for estimating buffer widths required around pesticide applications described by Payne et al. (1988) has been applied in the present investigation. The total a.i. deposited on water bodies downwind of a multiple swath application was calculated by adding the contributions from individual swaths using a computer program. The deposit-distance relationships were based on the measurements of average glyphosate deposit from a single swath with an a.i. application rate of 2.1 kg/ha. Interpolation and extrapolation were made by assuming that glyphosate deposit on water surfaces varied according to the equation:

\[ J = A x^B \]  

(1)
where J is glyphosate deposit (µg/m²), x is downwind distance from the swath and A and B are constant for a given use-strategy. Equation (1) is often used to describe deposit-distance relationships beyond the distance of maximum deposit (Pasquill 1974; Sutton 1953).

The calculations required extrapolation of the off-target deposit measurements from a downwind distance of 200 m to about 1 km; this was done using the curve (equation 1) fitted to the measurements at 100 and 200 m downwind. This extrapolation provides worst case spray deposits for two reasons. First, the spray lines are subject to crosswind spreading by atmospheric diffusion. This lateral broadening will dilute the cloud and reduce airborne drop concentrations and hence spray deposit. Second, the cloud is winnowed as it moves downwind because inertial impaction efficiency increases with dropsize, depositing large drops faster than small drops. As a result the average deposition velocity of the cloud is reduced and actual spray deposit will be less than the extrapolated value.

Buffer widths were estimated as follows. Using the mathematical model, glyphosate deposit was calculated at various downwind distances from a 100 ha (1 x 1 km) spray application, assuming operational swath widths. The predicted glyphosate deposit was then converted to a glyphosate concentration in water by assuming complete and even mixing in various water depths, with no further dilution. This assumption is worst case because glyphosate is rapidly adsorbed onto suspended particulate matter, which reduces its availability to aquatic organisms (Tooby 1985); also the salmon and trout populations requiring protection are usually in flowing water, which causes dilution. Buffer widths were estimated from the downwind distance at which the predicted glyphosate concentration fell below an acceptable level.

RESULTS AND DISCUSSION

Airborne Glyphosate and Off-target Deposit Measurements

Table 3 presents measurements of glyphosate deposit (µg/m²) collected by Rotorod samplers at various downwind distances from a single crosswind swath with an a.i. application rate of 2.1 kg a.e./ha. Figures 4 (a) and (b) show measurements of glyphosate deposit (µg/m²) on ground sheets and leaf covers, at various downwind distances from a similar application. The measurements represent the average deposit from a single swath. Actual measurements were adjusted to correspond to this a.i. application rate, in addition, measurements of glyphosate deposit on the leaf covers and teflon collecting surfaces at canopy top and at 2 m agl were averaged. The mean ratio of glyphosate deposit on leaf covers at canopy top to that at 2 m agl was 1.24 (S.D. = 1.00, n = 9), indicating that average deposit increased with height above ground.

The results in Table 3 and Figures 4 (a) and (b) indicate that the lowest airborne glyphosate concentrations and off-target deposits were from the Microfoil application and the highest were from the D8-46 application. These measurements are consistent with the dropsize spectra statistics presented above, which indicate that the spray volume in drops with diameters less than 100 microns was greatest in the D8-46 application, and least in the Microfoil application. Glyphosate residues collected by Rotorods at 50 m in trial 1 were lower than those in trials 2 and 3 by factors of 5 and 35 respectively, and that collected at 200 m from the swath was unquantifiable (<200 ng) in trials 2 and 3. The measured glyphosate deposit on teflon collectors at 200 m in trial 1 is anomalous. In trials 1 and 2 glyphosate deposits on ground sheets were higher than those on leaf covers, but this was not the case in trial 3. This difference is caused by differences in dropsize spectra, in particular the smaller proportion of large drops in trial 3.
Table 3. Glyphosate deposits on teflon collectors at various downwind distances from a single crosswind swath at 2.1 kg a.i./ha

<table>
<thead>
<tr>
<th>Downwind distance (m)</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>380</td>
<td>1960</td>
<td>13400</td>
</tr>
<tr>
<td>100</td>
<td>103</td>
<td>195</td>
<td>536</td>
</tr>
<tr>
<td>200</td>
<td>130</td>
<td>&lt; 71</td>
<td>&lt; 71</td>
</tr>
</tbody>
</table>

Glyphosate deposits on ground sheets in trial 1 (Microfoil) were 10 to 100 fold lower than in trials 2 (TVB) and 3 (D8-46), at distances of 75 m and less from the track. However, by 200 m downwind the glyphosate deposits on ground sheets in trials 1 and 2 were similar and approximately half the amount found in trial 3. Glyphosate deposits on leaf covers 50 m downwind of the Microfoil application were 10 to 50 fold lower than that measured from the other two applications. In contrast to the glyphosate deposits on ground sheets, large differences in foliar glyphosate deposit were found at 200 m downwind. The foliar deposit at 200 m in trial 1 is anomalously large.

Off-target Deposit from Multiple Swath Applications

Calculated glyphosate deposits on water surfaces downwind of multiple swath ROUNDUP applications at 2.1 kg a.e./ha are presented in Figure 5. For the TVB and D8-46 results extrapolation beyond 200 m was made using exponent (B) obtained from the Microfoil extrapolation, because the exponents derived for the TVB and D8-46 trials would have given quicker attenuation of deposit than for the Microfoil trial. In view of the proportions of spray volume in drops with diameters less than 100 microns, this was thought to be an unrealistic assumption. No extrapolation was made upward of the 25 m sampling station because of swath displacement (see below). Table 4 shows the downwind distances from the closest swath by which calculated glyphosate deposit on water surfaces from a 100 ha application falls to 0.1, 1, or 5% of the maximum recommended a.i. application rate, i.e. 210, 2100 and 10,500 μg/m².

Effect of Off-target on Fish and Aquatic Invertebrates

The effect on fish and aquatic invertebrates of glyphosate deposits from a 100 ha application was assessed using toxicological data from several published studies. ROUNDUP toxicity to fish has been measured by EVS Consultants in static tests for Monsanto (1985a-d), using coho and chinook salmon smolt (Oncorhynchus kisutch & O. tshawytscha) and rainbow trout fry (Salmo gairdneri). The tests showed that following a 10 d exposure to ROUNDUP in fresh water at concentrations up to 3.2 mg/L, coho salmon smolts were capable of survival and adapting to seawater. Static tests gave measured 96 h ROUNDUP LC₅₀s of 22.4, 20 and 26 mg/L respectively for coho and chinook salmon and rainbow trout. Fish mortalities of less than 10% were reported for ROUNDUP concentrations up to 6.6 mg/L.
Figure 4. (a). Glyphosate deposit on ground sheets downwind of a single crosswind swath at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.
Figure 4. (b). Glyphosate deposit on leaf covers downwind of a single crosswind swath at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.
Figure 5. Calculated glyphosate deposit on water surface downwind of 100 ha application at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.
Table 4. Distances from 100 ha application by which calculated glyphosate deposit on water surfaces falls to various percentages of maximum recommended a.i. application rate

<table>
<thead>
<tr>
<th>Glyphosate deposit as percentage of 2.1 kg/ha (%)</th>
<th>Downwind distance from closest swath (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Microfoil</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>1</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>0.1</td>
<td>&lt; 25</td>
</tr>
</tbody>
</table>

Hildebrand et al. (1982) studied the effects of ROUNDUP on fingerling rainbow trout populations, and reported 96 h LC$_{50}$ s of 52 and 54.8 mg/L respectively from field and laboratory bioassays. ROUNDUP was also applied manually to shallow forest streams in which pens containing fingerling rainbow trout (2.3 g) had been placed in water depths between 15 and 29 cm. Glyphosate application rates of 2.2, 22 and 220 kg a.e./ha were used in direct oversprays. No rainbow trout mortality occurred and no symptoms of stress or physical discomfort were observed. Glyphosate concentrations in stream water were not reported.

A study by Folmar et al. (1979) reported acute ROUNDUP toxicities from static tests on various fish and aquatic invertebrates. The 96 h ROUNDUP LC$_{50}$ s for adult rainbow trout and fathead minnow (Pimephales promelas) were 8.3 and 23 mg/L respectively. The rainbow trout life stage most sensitive to ROUNDUP was the fingerling (1.0 g), having a 96 h ROUNDUP LC$_{50}$ of 1.3 mg/L. No changes in fecundity were observed in adult rainbow trout exposed for 12 h to 2.0 mg/L. The 48 h EC$_{50}$ s (immobilizing concentration) measured for first-instar daphnids (Daphnia magna) and fourth-instar midge larvae (Chironomus plumosus) were 3.0 and 18 mg/L respectively.

Hildebrand et al. (1980) also studied the effect of ROUNDUP on daphnid (D. magna) populations. This abundant aquatic invertebrate forms a significant part of the diet of fish (Crosby and Tucker 1966). A manual application of ROUNDUP was made to forest ponds containing pens into which adult D. magna had been placed. The pens restricted the organisms to a surface layer 30 cm in depth. Glyphosate application rates of 2.2, 22 and 220 kg a.e./ha were used in a direct overspray. Survival rates exceeded 90% in all trials, and the control survival rate was similar to that obtained at 220 kg a.e./ha. Glyphosate concentrations in pond water were not reported.

Based on the EVS laboratory study cited above, a ROUNDUP concentration of 1.0 mg/L, equivalent to 0.3 mg glyphosate a.e./L, will limit mortality to less than 10% in populations of salmon smolt and rainbow trout fry. In contrast, the laboratory study by Folmar et al. (1979) indicates that a ROUNDUP concentrations of 1.0 mg/L, if maintained for 96 h, could result in about 50% mortality in the most sensitive life stage of rainbow trout. However, the studies by Hildebrand et al. (1980 & 1982) showed no rainbow trout mortality with theoretical ROUNDUP concentrations from oversprays of 249-480 mg/L, and greater than 90% survival of adult D. magna at theoretical ROUNDUP concentrations of 250 mg/L. For the purposes of buffer setting, a ROUNDUP concentration of 1 mg/L was chosen as the maximum tolerable level, however a more conservative limit may be argued considering Folmar’s (1979) results.
Buffer Widths

Table 5 shows the predicted ROUNDFUP concentrations (µg/L) in water bodies at various downwind distances from 100 ha applications at 2.1 kg/ha with the three use strategies tested. The buffer widths required around water to limit ROUNDFUP concentrations to 1 mg/L (1000 µg/L) were estimated for water depths of 0.1, 0.25 and 0.5 m. For each combination of use-strategy and water depth, the downwind distances from the final swath at which ROUNDFUP concentrations fell to 1 mg/L were less than 25 m. A buffer width of 25 m is therefore adequate to limit off-target deposit from small drop drift to the chosen level for all three use-strategies tried. Extrapolation of the spray deposit data to distances less than 25 m in order to estimate a more exact buffer width is inadvisable because of swath displacement, a discussion of which follows.

<table>
<thead>
<tr>
<th>Downwind distance (m)</th>
<th>Trial number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>25</td>
<td>1.77</td>
</tr>
<tr>
<td>50</td>
<td>0.85</td>
</tr>
<tr>
<td>75</td>
<td>0.79</td>
</tr>
</tbody>
</table>

The model and data from this investigation can be used to estimate buffer widths for use-strategies similar to those tested, but with different a.i. application rates and areas. However, the data from this investigation are not generally applicable for use-strategies employing different dispersal systems, emission rates or airspeeds, due to differences in droplet size spectra. When measurements of the phytotoxicity of sub-lethal glyphosate deposits become available, the off-target deposit measurements from this investigation can be used to estimate buffer widths required to protect riparian and other vegetation with these use-strategies.

Swath Displacement

It is apparent from the above discussion that buffer widths required around water bodies to protect fish and aquatic invertebrates from small drop drift are relatively small (<25 m). In light of this, the significance of large drop drift, or swath displacement must also be assessed. Swath displacement or large drop drift has been estimated for the three use-strategies tried in this investigation for worst case meteorological conditions for small and large drop drift. Wind-speed is the most influential meteorological variable causing large drop drift, with higher wind-speeds causing greater swath displacement. Atmospheric stability also affects swath displacement through its effect on the horizontal wind-speed profile. However for the low release heights in these trials differences caused by stability are small and were ignored in estimating swath dis-
placement. Large drop evaporation during flight was slight for the present trials, because their
lifetimes are much larger than flight times, e.g. a 200 micron diameter water drop has a lifetime
of about 200s in air at 20°C with a relative humidity of 80% (Matthews 1979), compared to large
drop flight times of 1-10s.

Swath displacement was estimated using ballistics (Pasquill 1974). The following simpli-
ifying assumptions were made. The large drop component of the spray cloud was represented by the
volume median drop size, and the fallspeed was chosen accordingly. Initial drop velocities were
assumed to be negligible. The spray cloud was advected through the 3 m release height (above
canopy), and the top third of the canopy height (1/3 x 18 m = 6 m). Windspeed inside a forest
canopy increases with height, however, the lower two thirds of the canopy windspeeds are low
(Oliver 1971, 1975), and therefore advection is slight. The average horizontal windspeed at
canopy top was used to calculate displacement. In fact, the average horizontal windspeeds above
and below this height are greater and smaller respectively than the value at canopy top, making
this approximation a good one. The effect of the two counter-rotating aircraft vortices on swath
displacement or large drop drift was assumed to be small due to the magnitude of drop fallspeeds,
with the vortices acting to spread the cloud about its centre of mass rather than causing advec-
tion of the total cloud. Swaths were crosswind. In the microfoil application the volume median
diameter (VMD) was about 3000 µm. A water drop of this size has a fallspeed of about 8.1 m/s
(Rogers 1979). In the TVB and D8-46 applications the VMDs were about 1000 and 460 µm. The falls-
speeds of water drops with these diameters are about 3.9 and 1.9 m/s (Hinds 1982).

At the windspeeds used for the present trials, about 1 m/s at canopy top, the swath dis-
placements i.e. the distance from the centre of the spray deposition pattern or effective swath to
the release line for microfoil, TVB and D8-46 were estimated to be 1, 2 and 4 m respectively.
Under worst case conditions for large drop drift, with an average horizontal windspeed of 4 m/s
at canopy top (about 16 km/h), swath displacements were estimated to be 5, 9 and 18 m respec-
tively. It should be noted that these swath displacements refer to the large drop component of
the spray cloud, and predict the average drop displacement for a release height 3 m above canopy
top.

This estimate of swath displacement allows small and large drop drift to be compared.
Figure 6 shows estimated swath position in relation to the release line for the three types of
application used, in average horizontal windspeeds of 1 and 4 m/s. Swath widths were those
described above. For the use-strategies tested a buffer of 25 m from the closest downwind swath
has been shown to protect fish and aquatic invertebrates from significant direct toxicological
effects of glyphosate small drop drift. However, taking large drop drift into account, it is
apparent that for the D8-46 a slightly larger buffer of 28-30 m is required to prevent the swath
from reaching the water body by displacement, for a release height of 3 m above canopy top.
Greater release heights will result in larger swath displacements.

Effect of Overspray

A calculation was made of the ROUNDUP concentration in water resulting from an overspray.
To provide worst case deposit all a.i. was assumed to be deposited in the swath region. For a
spray over still water 0.1 m deep, assuming complete and even mixing, and no further dilution, the
resulting glyphosate (a.e.) concentration is 2.1 mg/L. In flowing water dilution will occur, re-
ducing the concentration. However, the suggested acceptable value is 0.3 mg/L, indicating that an
overspray with ROUNDUP at 2.1 kg a.e./ha may cause unacceptable mortality in shallow water bodies,
and should be avoided.
Figure 6. Swath position in relation to crosswind release line (A) and line 25 m downwind (B) (to scale). Labels 1, 2 and 3 denote trial numbers, suffixes a and b refer to windspeeds of 1 and 4 m/s.
SUMMARY AND CONCLUSIONS

Drift trials were carried out with three rotary-wing ROUNDUP use-strategies employing the MICROFOIL BOOM, Thru Valve Boom, and D8-46 hydraulic nozzle, under meteorological conditions chosen to maximize small drop drift and off-target deposit on downwind water surfaces. Airborne herbicide and off-target deposits on imitation water and foliar surfaces were measured up to 200 m downwind. In general the least and greatest airborne glyphosate concentrations and off-target deposits resulted from the microfoil and D8-46 applications respectively, in accordance with the volume proportions of the spray cloud represented by drops with diameters less than 100 μm. Estimates were made of the buffer widths required to prevent significant direct toxicological effects on salmon, rainbow trout and aquatic invertebrates from 100 ha applications with the use-strategies tested, using a mathematical model based on the off-target deposit measurements and published toxicological data for fish and aquatic invertebrates. For the MICROFOIL BOOM and Thru Valve Boom use-strategies a buffer width of 25 m from the closest swath will limit ROUNDUP concentrations to less than 1 mg/L, and prevent significant direct toxicological effects from either small or large drop drift. For the D8-46 hydraulic nozzle use-strategy tested a 30 m buffer is needed to prevent swath displacement resulting in the possibility of significant toxicological effects.

ACKNOWLEDGMENTS

The authors thank the British Columbia Ministry of Forests and Monsanto Canada Inc. for their financial support, and Ron Rowe, Brent Birkedal, Wayne Enlow, David Gubbel, Jim Beveridge and Bozena Staznik for technical assistance during the spray cloud dispersal experiment.

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DEVELOPMENT OF NON-COMMERCIAL VEGETATION FOLLOWING CLEARCUTTING AND CLEARCUTTING-PLUS-SLASHBURNING, AND SOME BIOGEOCHEMICAL EFFECTS OF HERBICIDAL CONTROL OF THIS VEGETATION

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Faculty of Forestry
University of British Columbia
Vancouver, B.C.
V6T 1W5

ABSTRACT

The development of aboveground biomass of herbs, shrubs and non-commercial deciduous trees was monitored following clearcutting and clearcutting-plus-slashburning in low elevation coastal forests in British Columbia. After eight years, 21 t ha$^{-1}$ of aboveground non-crop vegetation biomass had accumulated on the clearcut site [2.5 t ha$^{-1}$ of herbs, 3.6 t ha$^{-1}$ of shrubs, and 15.1 t ha$^{-1}$ of deciduous trees (mostly red alder)], in comparison to 3.9 t ha$^{-1}$ on the slashburned site [2.6 t ha$^{-1}$ of herbs, 0.8 t ha$^{-1}$ of shrubs, and 0.5 t ha$^{-1}$ of deciduous trees (mostly willow and cottonwood)]. The unburned clearcut area was then sprayed with glyphosate (nine years after cutting). One year following the spray, live aboveground biomass had been reduced to about 2.6 t ha$^{-1}$. This had increased to about 3.5 t ha$^{-1}$ (2.9 t ha$^{-1}$ of shrubs and 0.5 t ha$^{-1}$ of herbs) by three years post-spray (year 12 of the study). In comparison, the slashburned site had an aboveground non-crop biomass of 4.5 t ha$^{-1}$ in the 12th year (3.0 t ha$^{-1}$ of herbs, 1.5 t ha$^{-1}$ of shrubs). Unfortunately, some of the deciduous trees on the slashburned site were manually removed by mistake ten years after the start of the study. No estimate of what their biomass would have been in year 12 is available.

The herbicide treatment had a significant effect on the nitrogen budget of the site. Nitrate concentrations in soil solution were increased about 2.8 times (to a peak concentration of 7.8 mg L$^{-1}$ of NO$_3^-$), while streamwater concentrations increased 7 times to a peak value of 2 mg L$^{-1}$. A preliminary and incomplete nitrogen budget suggests that somewhere between 80 and 150 kg ha$^{-1}$ of nitrogen (depending upon what assumptions are made) may have been lost in solution in the three years following the herbicide treatment. This compares with an estimated output in logs at the time of harvest of 234 kg ha$^{-1}$ and an estimated input by red alder prior to the herbicide spray of 194 kg ha$^{-1}$. The estimated overall nitrogen balance for 1973-1984 on the herbicide-treated area was -93 to -163 kg ha$^{-1}$ (depending on assumptions). This compares with a nitrogen balance for the slashburned area of -1260 kg ha$^{-1}$ (982 kg ha$^{-1}$ lost in the fire, and 308 kg ha$^{-1}$ lost in harvested materials).

It is concluded that the herbicide treatment caused a significant loss of nitrogen from the ecosystem, but that this was approximately balanced by the symbiotic nitrogen fixation prior to the spray. It is anticipated that the herbicide-related loss would in any case be more than compensated for by precipitation and fixation inputs of nitrogen over a 60-year rotation. The slashburn-related loss of nitrogen was much greater than the herbicide-related loss, and it is doubtful if the loss would be compensated for by natural inputs over a 60-year rotation. It would appear that nitrogen fertilization will be necessary on the slashburned watershed if growth is to be maintained at the same level as that expected on the herbicide-treated area. Where herbicides
are used to kill nitrogen-fixing species, the most dramatic ecological impact of the spray in terms of site biogeochemistry may be the cessation of the nitrogen inputs by symbiotic fixation.

INTRODUCTION

Hydrological and ecological studies of the devegetation of an eastern deciduous hardwood forest watershed at Hubbard Brook, New Hampshire, in the 1960s and 1970s (Bormann et al. 1968; Likens et al. 1970) led to concerns about the effects of herbicides on streamwater chemistry and on the biogeochemical integrity of ecosystems. Several studies since then have confirmed that herbicide treatments can cause significant increases in the leakage of nitrogen and other nutrients from ecosystems (Johnson and Swank 1973; Sollins et al. 1981; Edwards and Ross-Todd 1979; Miller and Newton 1983; Davis 1984, 1987; Dyck et al. 1983; Vitousek and Matson 1985; Neary et al. 1986). Herbicides are not the only site treatments that can result in nutrient loss, however. Slashburning, which can be used as an alternative to herbicidal control of non-commercial plant competition prior to planting tree crops, can also cause substantial losses of site nutrient capital (e.g., Harwood and Jackson 1973; Flinn et al. 1979; Nisley et al. 1980; Feller 1982; Feller and Kimmins 1984). The study reported in this paper was part of a research project initiated in 1971 to quantify the nutrient losses and regrowth of minor vegetation associated with clearcut harvesting, followed after one year by broadcast slashburning or after ten years by herbicidal control of competing vegetation. The paper describes the development of non-crop vegetation following the treatments, and some biogeochemical effects of herbicidal control of this vegetation. The development of crop tree biomass over this time was not studied.

Study Location, Site Description and Experimental Treatments

The study was conducted in two small (less than 30 ha) first order watersheds at 145 to 310 m elevation at the University of B.C. Research Forest at Haney, 60 km east of Vancouver, B.C. The watersheds are located in the dry subzone of the Coastal Western Hemlock biogeochemical zone, (Köppen climate: Cfb) (Krajina 1969) on a gentle southerly slope at an elevation of about 200 m. The soils are generally humo-ferric podzols (Canadian Soil Survey Committee 1978) developed in sandy-loam to loamy-sand with an average soil cation exchange capacity of 31 meq/100 g. The area has a marine, warm-temperate, rainy climate with an annual precipitation of 220–270 cm. Prior to clearcutting, the watersheds carried an approximately 100-year-old coniferous forest dominated by western hemlock [Tsuga heterophylla (Raf.) Sarg.], Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] and western red cedar (Thuja plicata Donn); the stand originated from a wildfire in 1868.

Approximately 15 ha was clearcut and highlead logged in the fall/winter of 1973/74 and spring of 1974 in each of two watersheds equipped with sharp-crested V-notch weirs. Water flow and stream chemistry had been monitored weekly for two years prior to the logging. Following clearcutting, one of the clearcuts (East Creek) was broadcast slashburned in the late summer of 1974. The other clearcut (Marc Creek) was left unburned. Both clearcuts were planted with Douglas-fir seedlings in 1975, although much of the Marc Creek clearcut was not planted because of heavy slash and the rapid development of shrubs [dominated by salmonberry (Rubus spectabilis Pursh.).] A significant amount of natural regeneration of the above three coniferous species developed on the Marc Creek clearcut over the 12 years of study. There was little such invasion on the East Creek clearcut.
The regrowth of minor vegetation was monitored on both clearcuts until 1982, when the Marc Creek clearcut was sprayed (in June) with 3 kg a.i. ha\(^{-1}\) of glyphosate (ROUNDUP). Aboveground biomass of herbs and shrubs was monitored five times between clearcutting (in 1973/74) and the 1982 herbicide treatment by clipping 54 1-m\(^2\) plots distributed in a stratified-random sampling scheme on each clearcut. Deciduous tree growth was also monitored by means of these clip plots until 1981. After 1981, deciduous tree biomass was estimated using biomass regression equations obtained from the literature (Gholz et al. 1979) in conjunction with data on deciduous tree diameters from eighteen 3 m radius circular plots distributed at random along the existing sampling transects. Macronutrient analyses were conducted on all plant samples, and a variety of other biogeochemical studies were conducted (details in Kimmins 1987). Streamflow and streamwater chemistry were analysed throughout most of the 13 years of the study. Lack of funding prevented the monitoring of the growth of the planted Douglas-fir and natural regeneration of conifers on the sites.

**RESULTS**

**Losses of Nutrients by Log Removal and Slashburning**

Losses of nutrients (kg ha\(^{-1}\)) from the two clearcuts in harvested logs, by streamwater export (dissolved nutrients leaving the watershed over the V-notch weirs), and by gassification and flyash during burning from the slashburned East Creek clearcut are shown in Table 1. With the exception of magnesium, stream exports over the weirs were relatively small in comparison to other loss pathways, although the methodology used does not give a reliable measure of losses of nutrients from the watershed. Export of nutrients in particulate matter during storm events was not monitored, dissolved organic nitrogen and organic phosphorus were not measured, and there was no accounting for long-term immobilization of nutrients in stream sediments. Nor was there any quantification of denitrification losses either in the stream or in the clearcuts. Recent evidence (Martin 1985) suggests that denitrification may sometimes be a major post-clearcutting N loss from the forest floor in the humid maritime climates of the British Columbia coast in the absence of slashburning. Denitrification may result in the loss from the stream of much of the nitrogen leached from the land into the stream (M.C. Feller, personal communication). As a result, streamwater analysis may not be an adequate method by which to estimate leaching losses from the land.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>N (kg ha(^{-1}))</th>
<th>P (kg ha(^{-1}))</th>
<th>K (kg ha(^{-1}))</th>
<th>Ca (kg ha(^{-1}))</th>
<th>Mg (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MC</strong></td>
<td>11</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td><strong>EC</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>55</td>
</tr>
<tr>
<td><strong>Mg</strong></td>
<td>9</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.** Estimated nutrient losses (kg ha\(^{-1}\)) from Marc Creek (MC) and East Creek (EC) clearcuts at the Haney Research Forest near Vancouver, B.C. during 1973-75 (from Feller and Kimmins 1984)

**Streamwater exports**

- N: 11 kg ha\(^{-1}\)
- P: 3 kg ha\(^{-1}\)
- K: 0 kg ha\(^{-1}\)
- Ca: 44 kg ha\(^{-1}\)
- Mg: 9 kg ha\(^{-1}\)

**Harvest removals (in logs)**

- N: 234 kg ha\(^{-1}\)
- P: 308 kg ha\(^{-1}\)
- K: 34 kg ha\(^{-1}\)
- Ca: 237 kg ha\(^{-1}\)
- Mg: 260 kg ha\(^{-1}\)
- Atmospheric loss due to slashburning: N: 982 kg ha\(^{-1}\)
- P: 16 kg ha\(^{-1}\)
- K: 37 kg ha\(^{-1}\)
- Ca: 154 kg ha\(^{-1}\)
- Mg: 29 kg ha\(^{-1}\)
Losses of nutrients in harvested materials were somewhat less on the Marc Creek clearcut than on the East Creek clearcut, the observed differences being attributed to differences in tree species composition and the volume of logs removed. Harvest removals constituted a much greater loss than estimated streamwater exports. Although the latter are undoubtedly significant underestimates (as noted above), the true leaching losses from the sites were probably small relative to the harvest removals, with the possible exception of magnesium. Losses of N from the East Creek clearcut during the slashburn were about three times as great as the log exports of N. Losses of the other macronutrients caused by slashburning were much smaller, but they were biologically significant and three or more times greater than the estimated dissolved streamwater losses (but remember that the latter estimates are probably too low).

Post-clearcutting Development of Aboveground Non-commercial Plant Biomass

The development of herb, shrub and deciduous tree biomass on the East Creek and Marc Creek clearcuts between 1975 and 1985 are shown in Figures 1a and 1b. On both clearcuts, herbs developed a biomass of about 2.5 t ha\(^{-1}\) by 1979 (six years after logging on the Marc Creek clearcut and five years after slashburning on the East Creek clearcut). Herb biomass continued to increase on the slashburned clearcut, to about 3 t ha\(^{-1}\) by 10 years post-burning. The slower development and lower final aboveground biomass of herbs on the unburned Marc Creek clearcut was the result of the greater development of shrub and deciduous tree biomass on the unburned clearcut than on the burned clearcut. Shrubs achieved an aboveground biomass of about 3.8 t ha\(^{-1}\) on the unburned clearcut four years after clearcutting, compared with 0.7 t ha\(^{-1}\) on the burned clearcut. Similarly, aboveground biomass of deciduous trees had reached an estimated 10.3 t ha\(^{-1}\) by 1979 on the unburned clearcut, in comparison with 0.4 t ha\(^{-1}\) on the burned watershed. These values increased to 15 t ha\(^{-1}\) and 0.5 t ha\(^{-1}\), respectively, by 1981, the year before the Marc Creek clearcut was treated with herbicides. Unfortunately, some of the developing deciduous trees [mostly willows (Salix spp. L.) and cottonwoods (Populus trichocarpa Torr. and Gray)] were manually removed from the burned clearcut by mistake in 1983, so the comparisons are only valid until 1981.

Successional Patterns on the Two Clearcuts

The early succession on the burned clearcut was dominated by Polytrichum juniperinum Hedw., a pioneer moss that commonly forms a dense mat a few years after burning in coastal forest ecosystems. This moss layer appears to inhibit the invasion of vascular plant species other than those that spread vegetatively by rhizomes. As a result of the Polytrichum layer, the vegetation on the burned clearcut was dominated initially by fireweed (Epilobium angustifolium L.), which reached a peak aboveground biomass of about 1.2 t ha\(^{-1}\) by 1984, three years after burning. Thereafter, the herbaceous layer was dominated by bracken fern (Pteridium aquilinum (L.) Kuhn), which increased to an aboveground biomass of 2.7 t ha\(^{-1}\) by 1984, ten years after burning. These two species accounted for the majority of the herb biomass, which remained greater than the shrub biomass until the end of the study in 1985, when shrubs had a total biomass of only 1.5 t ha\(^{-1}\) in comparison to the herb biomass of about 3.0 t ha\(^{-1}\).

The combination of the Polytrichum layer and the dense community of fireweed and bracken fern appeared to effectively prevent or greatly inhibit the invasion of shrubs and deciduous trees, in spite of abundant nearby seed sources. Shrubs that were present prior to clearcutting resprouted from rootstocks after burning, but the aboveground biomass development was much slower.