CMER/RSAG Temperature Workshop – 2001
SUMMARY REPORT

Prepared By EDAW, INC.
&
Mason, Bruce & Girard, Inc.

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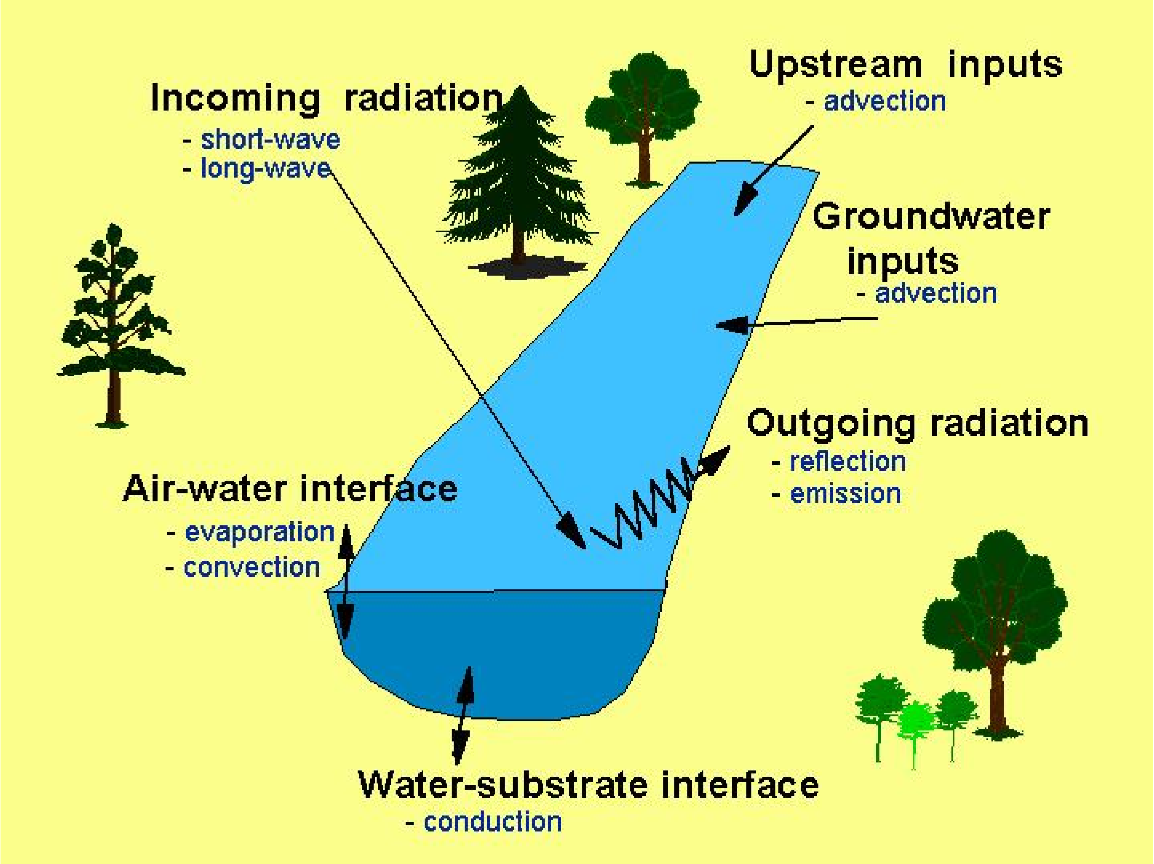
Summary Report

CMER/RSAG Temperature Workshop - 2001



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Prepared for

RSAG – the Riparian Scientific and Advisory Group, and
CMER – the Cooperative Monitoring, Evaluation, and Research Committee
Olympia, Washington

Prepared by:

EDAW, Inc.
Seattle, Washington

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Executive Summary

The purpose of this report is to summarize the proceedings and discussion from two workshops on the subject of heat transfer processes in forested stream environments. The workshops, held in Lacey, WA in February and May of 2001, were organized as part of the Cooperative, Monitoring, Evaluation, and Research (CMER) program, and sponsored by the Riparian Scientific Advisory Group (RSAG).

The goals of the Temperature Workshops were to identify where scientific consensus exists and where it is lacking on **heat transfer processes in forested watersheds**, to provide overviews of past and current research, and to identify future priorities based on stakeholder review of this information. Specific topics addressed included:

- The effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources;
- Currently used **temperature models**, addressing their inputs, strengths, and weaknesses;
- Heat transfer processes via **groundwater**; and
- Heat transfer processes via **microclimate** conditions (both in the riparian zone and over the stream).

Recognized scientific leaders in current research efforts were identified and invited as panelists in the workshops. Invited panelists included Dr. George Ice, NCASI (who addressed solar radiation inputs); Dennis Schult, Western Watershed Analysts (who discussed current temperature modeling efforts); Dr. Patricia Olson, Pacific Watershed Institute (who addressed groundwater inputs); Dr. Sam Chan, PNW Lab/USFS (who addressed microclimate conditions in riparian areas); and Dr. Sherri Johnson, OSU (who addressed microclimate effects on stream systems).

Areas of Consensus Among Panelists

Solar Insolation. The panelists noted that the best science to date has confirmed that solar insolation (i.e., direct solar radiation to the water's surface) is the dominant source of heat energy to surface water. Although other heat sources received considerable attention in recent years, validation of these effects is lacking.

Microclimate. Although older reviews on water temperature frequently refer to microclimate, successful measurement of this effect on surface water temperature has been elusive. In the past four years, a number of careful studies have taken advantage of the availability of reliable low cost submersible data loggers to isolate the microclimate effect. These data loggers should be reliable enough to detect differences in water temperature 0.5 centigrade units or less. These studies (Brosofske et al 2000, Johnson and Jones 2000, James pers. comm.) have not been able to measure a microclimate effect on water temperature where there was a buffer 15 meters (50 feet) wide or greater. Where buffers are narrower or absent, it becomes impossible to separate the microclimate effect from the more significant solar insolation effect.

The microclimate hypothesis suggests water temperatures will always move towards equilibrium with the surrounding air. Panelists noted that this was still a fundamental fact. However, elevated air temperature occurs only during the middle of the day. Air has a significantly lower heat capacity than water, thus it takes significant time for air to bring a body of water into equilibrium. Furthermore, microclimate effects from timber harvest are a combination of three effects; higher mid-day air temperatures, lower mid-day humidity, and higher wind speeds. The latter two effects combine to increase evaporation from the water's surface, which has a cooling effect on water temperature.

Solar Tracking. Several panelists suggested that a better measure of solar insolation would to measure the shade in the path of the summer sun, i.e., solar tracking, rather than measuring the shade from the entire 'view to sky'. The current board manual densiometer method assumes the latter.

Groundwater. More research is needed to determine forest practices induced groundwater effects on surface water temperature. At this time relatively little is known with certainty.

Headwater Temperature Transfers. Panelists agreed that surface water temperature in headwater streams did re-establish temperature equilibrium with air upon re-entering shaded stream reaches. The distance and time that it takes to re-establish equilibrium is a function of many variables.

Areas of Non-Consensus

There were no major areas of non-consensus among the panelists.

Future Research Priorities

Solar Insolation. No future research is needed to validate the fundamental effects of solar insolation.

Solar Insolation Measurement. Research is needed on the most effective measure of solar insolation. Current rules require a densiometer, which is time consuming to use and readings are subjective. In recent years, there have been a number of additional tools available that appear to be more precise and eliminate user subjectivity. Research into the utility of these tools for research measurements and rule implementation would be desirable.

Solar Tracking. Research on this subject as it applies to forest channels is sparse. If solar tracking proves to be a better predictor of water temperature response, this would create flexibility to manage for other riparian functions on the north bank of stream channels. Evaluation of tools for measuring shade along summer solar pathway is needed. This is a moderate priority for research.

Headwater Temperature Transfers. Additional research is needed to validate the distance and/or time needed to achieve equilibrium with surrounding physical conditions. This is a moderate priority for research.

Microclimate. In light of recent findings and current riparian buffer requirements, additional research on the effects of microclimate on water temperature is a low priority. It may be worthwhile reviewing the scientific literature in several years. The data logger technology will likely facilitate additional scientific publications.

Groundwater effects. Research on groundwater is in a very early phase of development. Both the theory and field methodology need development. A workshop discussion group identified that need for a conceptual model of heat transfer to groundwater, and then from groundwater to surface water. The model will be used to identify priority areas for initial research. This is a high priority.

Eastern Washington Nomograph. There was a broad consensus that the eastern Washington nomograph that is currently in the Board Manual should be revised using current datasets. If possible, a model that considers more that elevation should be developed. This is a high priority

Western Washington Nomograph. With the current 50 foot core zone and an additional inner zone, the western Washington nomograph is not likely to see much use, and thus, it is a low priority for research.

Hyporheic Exchange. Initial research by Johnson and Jones 2000 suggests that hyporheic heat exchange in alluvial streambeds and valley floodplains could have a significant effect on surface water temperature. It appeared to be considerably more significant than the microclimate effect. Other studies also suggest this effect may be under-rated. If significant, the restoration of bedrock channels that were historically alluvial channels, and the restoration of incised channels may be legitimate methods for water temperature restoration. Although this in not a Schedule L-1 question, further research on this subject may be worth considering.

Summary Report

CMER/RSAG Temperature Workshop – 2001

CONTENTS

5.0 Appendices

The appendices contain about 100 pages of material distributed during the workshop. These appendices are available upon request from the DNR upon request.

The panelists have requested that these appendices not be cited directly or reproduced in a published document without permission.

Some of this material is unpublished and/or borrowed from professional peers. Inappropriate use may violate professional ethics. Thus, only paper copies will be distributed.

Appendix A – Workshop Attendance

Appendix B – Key Questions Provided to Panelists

Appendix C – Additional Material – Direct Solar Radiation/Temp. Equilibrium
  Answer to Key Questions (4 pp.)
  Paper: "How Direct Solar Radiation and Shade Influences Temperature in Forest Streams and Relaxation of Changes in Stream Temperature" (33 pp.)
  Dr. George Ice's slide presentation (37 pp., 111 slides)

Appendix D – Additional Material – Stream Temperature Modeling
  Mr. Dennis Schult's slide presentation (21 pp., 41 slides)

Appendix E – Additional Material – Groundwater
  Paper by Dr. Patricia Olson on ground temperature. (12 pp.)
  Dr. Patrica Olson's slide presentation (32 pp. 64 slides)

Appendix F – Additional Material – Microclimate and Riparian Conditions
  Dr Samuel Chan's slide presentation (74 pp., 127 slides)

Appendix G – Additional Material – Microclimate and Stream Temperatures
  Outline of presentation by Dr. Sherri Johnson
  Dr. Sherri Johnson's slide presentation (19 pp., 38 slides)

1.0 INTRODUCTION

The purpose of this report is to summarize the proceedings and discussion from two Temperature Workshops held to address the subject of heat transfer processes in forested stream environments. The workshops, held in Lacey, WA in February and May of 2001, were organized as part of the Cooperative Monitoring, Evaluation, and Research (CMER) program, and sponsored by the Riparian Scientific Advisory Group (RSAG). The workshops were organized as part of the larger effort associated with the Forest and Fish Report (FFR), a Washington State legislative bill passed in May 1999 with the goal of bringing Washington State forest practices into compliance with the Endangered Species Act (ESA), the Clean Water Act (CWA), and Indian Treaty Rights.

Earlier drafts of this report were reviewed by RSAG, CMER, a technical editor, and the panelists. The February 2002 version is the final draft of the document.

1.1 Objectives and Goals

The goals of the Temperature Workshops were to identify where scientific consensus exists and where it is lacking on **heat transfer processes in forested watersheds**, to provide overviews of past and current research, and to identify future priorities for funding and research based on stakeholder review of this information. The Workshops served foremost an educational purpose, intending to provide stakeholders a common basis of understanding in order to implement the FFR. Discussion and dialogue that occurred during the Workshops also served as the starting point for additional research associated with CMER and FFR.

The objectives of the workshops were to establish and articulate to stakeholders what is known on significant heat transfer effects that may change surface water temperature in forested basins, with a focus on the inputs of solar radiation, heat loss from surface waters, microclimate effects, and groundwater and hyporheic zone processes. The cumulative effects of forest practices on surface water temperature were also examined.

As noted above, one of the primary purposes of the Temperature Workshops was educational – that is, attempting to establish a common understanding among stakeholders. Discussion was focused on identifying the following:

- Areas of consensus and non-consensus
- Overall priorities for future research

The primary resource topics addressed in the workshop format were organized as follows:

- The effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources;
- Currently used **temperature models**, addressing their inputs, strengths, and weaknesses;

- Heat transfer processes via **groundwater**; and
- Heat transfer processes resulting from changes in microclimate.

Recognized scientists were identified and invited as panelists in the workshops. Invited panelists (and their field of expertise) included Dr. George Ice, National Council for Air and Stream Improvement (solar radiation inputs); Dennis Schult, Western Watershed Analysts (temperature modeling); Dr. Patricia Olson, Pacific Watershed Institute (groundwater inputs); Dr. Samuel Chan, PNW Labs/USFS (microclimate); and Dr. Sherri Johnson, Oregon State University (microclimatic effects on stream temperature).

Prior to the workshops, RSAG presented the panelists a list of key questions that their presentations should address, focusing on current theory, uncertainty/variability, and applications and alternatives. These questions are included in Appendix B of this Summary Report.

1.2 Workshop Format & Participants

The Temperature Workshops were organized by RSAG members Mark Hunter (WDFW), Steve McConnell (NW Indian Fisheries Commission), and Domoni Glass (Watershed Professionals Network). The Workshops were open to the public, and all Forest and Fish Report stakeholders were invited. Attendance was approximately 45 to 55 people for each workshop. Workshop attendees included representatives from federal, state, and tribal agencies; and the forest products industry. Copies of the sign-in sheets for the workshops' three days are presented in Appendix A.

The first Temperature Workshop was held on February 6 and 7, 2001, at the U.S. Fish and Wildlife Service (USFWS) Sawyer Hall in Lacey, Washington. The first Workshop addressed the effects of solar radiation, temperature modeling efforts, and groundwater inputs. The second Workshop was held May 1, in the same location, and addressed microclimatic effects and continued the dialogue on synthesis and cumulative effects. The original intent was to conduct a single workshop, covering all resource topics in a 2-day meeting. However, schedule coordination among panelists necessitated a second scheduled date to address microclimate and continue synthesis dialogue.

For each resource topic, the overall organization and agenda consisted of the following: (1) an approximately 1.5 hour presentation by the panelist, followed by a short break; (2) a ½-hour question and answer period. Following the three presentations at the February workshop (i.e., solar radiation, temperature models, and groundwater), the floor was opened up for discussion, with the goal of synthesizing the information presented. At the February Workshop, these discussions were facilitated by Mike Liquori. Small group discussions were also held to focus and synthesize the material presented. Each group drafted conclusions and these were reported back to the entire Workshop. The May workshop followed a similar format but without a moderator and without small group sessions.

1.3 Purpose of this Document

This document was prepared to summarize the results of the presentations and subsequent dialogue at the Workshops, and to identify priorities for future research. It will be useful as a reminder for people who attended the Workshops, and will serve as a reference document for interested stakeholders who were unable to attend. The document is **not** intended to be a comprehensive account of all discussion that occurred – that is, it is a summary document and not a transcript. Nor is the report intended to resolve all questions or areas of potential disagreement that were raised. As one panelist humorously (but astutely) noted, CMER stakeholders can agree that the earth orbits the sun, but beyond that debate can be assumed. Therefore, the focus of this document is on issues identified by Workshop participants as the most significant and worthy of future efforts.

To meet this purpose, this report is organized as follows:

- Section 2.0 summarizes the key findings of the Workshops, focusing on key issues identified, as well as priority for future funding and research efforts.
- Section 3.0 presents a summary of each of the five presentations. Literature cited in this section is listed at the end of each subsection.
- Section 4.0 lists references mentioned by the panelists during their presentations or in their written materials, but not directly cited in this document.
- Appendix material includes more detailed information related to the individual presentations, such as copies of slides presented, summary analysis prepared by the participants, and bibliographies/reading lists of related topics

The appendices contain about 100 pages of material distributed during the workshop. Paper copies are available upon request from either Heather Rowton at the Washington Forest Protection Association (hrowton@wfpa.org) or Mark Hunter at the Washington Department of Fish and Wildlife (huntemah@dfw.wa.gov).

The panelists have requested that these appendices not be cited directly or reproduced in a published document without permission.

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2.0 KEY FINDINGS – IDENTIFIED PRIORITIES

As the primary "product" of the Temperature Workshops, this Summary Report presents the following: (1) key issues identified by the Workshop participants and stakeholders; and (2) priorities for future research and funding. This section of the summary report presents the key findings of the Workshops, based on the discussion among the participants and stakeholders. It seems appropriate to present these conclusions at the beginning of the Summary Report, as these identified priorities and key issues are essentially the primary outcome of the Workshops.

It is important to note that there was a consensus among Workshop participants about what is important from a management perspective, as well as what research should be considered high priority, when considering heat transfer processes in forested watersheds. On the other hand, consensus was frequently not reached on some of the finer points of the technical and scientific discussions, where individual stakeholders often had differing opinions. However, these disagreements did not extend into what was considered significant from a natural resource management point of view; rather, disagreements belonged more to the realm of theory and research.

As described above, scientific presentations were followed by discussion periods and "break-out" groups to discuss and identify priority items. Prior to the break-out sessions, Mike Liquori prepared summary lists, by topic, of issues that were most discussed or contentious during question & answer/discussion periods. Break-out groups were encouraged to use these summary lists as a starting point for prioritizing issues and for identifying other important issues. Groups then reported back to the full participant body, where further discussion took place to clarify and reach consensus. Based on the Workshop discussions, priority issues and research needs are summarized below, by topic (i.e., Stream Physics, Modeling, Groundwater, and Microclimate).

2.1 Priority Issues Identified

1. Stream Physics Subgroup

The Stream Physics Subgroup identified the following four priority issues:

- **Eastside vs. Westside Streams Conditions** – There was a general consensus that the current models and understanding of stream systems west of the Cascades are adequate for use in making management decisions, with primary physical processes fairly well understood; such consensus, however, is lacking on eastside stream systems, where conditions may differ significantly. Therefore, stakeholders identified developing a better understanding and better models for the eastside as an important need. A better model would (presumably) incorporate site-specific data for attributes such as shade and stream temperature.

Discussion from the larger group on this item noted that a subtask of such an effort would be to better define what attributes currently being used are not suited for the eastside.

Both elevation and shade levels are model inputs, and these attributes frequently differentiate eastside and westside systems.

- **Shade Measurement Standardization** – Based on extensive discussion during the Workshops, participants identified a need to standardize shade measurement protocols, especially when using densiometers. Of particular issue is the relationship between solar angle and its correlation with water temperature. As noted and discussed in several of the presentations, there are numerous ways currently being used to measure shade, each with strengths and weaknesses. We need to develop a standardized methodology for using the densiometer, and determine if it provides an accurate measurement of effective shade.

A question from the larger group asked why we continue to use densiometer measurements if they don't appear to be an effective tool for measuring shade. Subsequent discussion noted that there is no such agreement that densiometers are NOT an effective tool; rather, the goal would be to do additional research on the accuracy of densiometer readings, perhaps comparing measurements with other currently available methods. We need to determine if we need a better tool. In summary, it is important to determine if measurements taken from densiometers are reproducible, and if such data provide an adequate measure of effective shade. [Note that the issue of measuring effective shade came up during several discussions held over the course of the three days of the Workshops – it is a cross-disciplinary issue of primary concern.]

- **North Side Buffers** – Stakeholders would like to pursue the idea of removing or reducing shade target levels on north side buffers, allowing these riparian areas to be managed for other objectives (e.g., LWD, etc.) depending on site-specific conditions. Such a change in policy would provide greater management flexibility by not being tied to a potentially irrelevant shade target; empirical evidence from current scientific research shows that north side buffers do not affect stream temperatures in the Pacific Northwest. In short, the stakeholders would like to explore alternative north side buffer options.

- **Headwater Stream Temperatures** – Stakeholders identified the need to develop a clear protocol for measuring temperatures in headwater channels. Dr. Ice's presentation noted differences among currently used techniques, which may lead to differing results. A single measurement might not accurately reflect average conditions. Stakeholders are therefore concerned with developing a protocol to obtain more accurate and useful measures of headwater temperatures.

2. Temperature Modeling Subgroup

The Temperature Modeling Subgroup identified the following two priority issues:

- **Evaluate How Existing Models Relate Specifically to FFR Applications** – The stakeholders would like to see a project to evaluate the application of the existing models (see section 3.2 for a list of the specific models considered) to a suite of forest and fish management applications (e.g., modeling effective shade;

modeling as a diagnostic tool for sensitive applications such as bull trout; alternative plans for riparian harvest; modeling application to evaluate type N watershed buffer scenarios). The existing models are available and it wouldn't be too difficult a task to conduct such an evaluation. There was general consensus that it would be valuable to examine the various models and evaluate/compare them.

- **Evaluate the Existing Nomograph** – The stakeholders recommended conducting a project to examine the existing model (i.e., the nomograph). It was noted that some further diagnostic work would be valuable to determine why the model doesn't seem to work or fit certain site-specific conditions, such as on some eastside stream systems. Note that this item overlaps with the first priority identified above under Stream Physics, and it also relates to the ongoing discussion on what constitutes effective shade. In short, the stakeholders would like to identify situations where the nomograph isn't working and figure out how to address such situations.

  In the larger group discussion, it was noted that we have a huge data set to work with at present, and it doesn't make sense to throw out this valuable resource and start from scratch. Rather, we need to examine the relative strengths and weaknesses of the current model and adjust as necessary.

An additional issue rose during the larger group discussion focused on developing an adaptive management strategy based on incorporating equilibrium temperature and microclimate conditions, and the potential need to subsequently refine the modeling physics based on such factors. It was generally agreed that this issue wasn't discussed in greater detail as it represented more of a monitoring and/or research opportunity and less of a modeling issue.

3. Groundwater Subgroup

As described in more detail in Section 3.0, the current research efforts addressing the role of groundwater effects on stream temperature conditions in Pacific Northwest systems are in an early stage of academic and scientific development (that is, relative to stream physics and modeling efforts). The Groundwater Subgroup therefore approached the identification of key issues by prioritizing steps necessary to better understand the role of groundwater influences in forested watersheds, with the eventual goal of incorporating such results as appropriate into the management process. Thus, the Groundwater Subgroup identified the following four-step process:

- **(Step 1) Develop a Clear Conceptual Model–** Stakeholders generally agreed that we don't seem to have an understanding of the specific variables and cause-and-effect relationships linking groundwater inputs and stream temperatures in forested environments in the Pacific Northwest. The current research identifies the important inputs and variables but doesn't provide a model or description that we can adequately understand and hence apply. Ideally, the model would focus on linking groundwater temperature and flow to stream temperature, incorporating other inputs as well (such as solar radiation).

- **(Step 2) Fit the Conceptual Model into a Washington Context**– After developing the initial conceptual model, it will be essential to apply it to the site-specific conditions that occur in Washington State (e.g., shallow soils in upland, deeper in lowlands, variations in latitude, etc.) to see if it predicts a valid water temperature response.

- **(Step 3) Identify Areas Where We Need More Data**– During this process, we'll need to identify data gaps and pursue missing information (e.g., from the literature and/or additional field work) so we can better understand how forest management could influence groundwater processes.

During the larger group discussion, it was noted that there are currently very limited site-specific data to work with (particularly for Washington State), so filling in missing information will require significant resources.

- **(Step 4) Find and Investigate Sensitive Sites**– We need to gather site-specific data and determine specific areas and sites to investigate further, most likely with a focus on sensitive sites such as bull trout habitat.

4. Microclimate Effects Subgroup

Unlike the previous topics, which were discussed at the February Workshop, there were no break-out group discussions at the May Workshop addressing microclimate effects. Instead, after the initial scientific presentations and question and answer period, an informal discussion ensued among the participants.. The informal discussion posed the following main question: Recognizing that current scientific understanding demonstrates that microclimate effects on stream temperatures do occur, what priorities should CMER/RSAG consider in terms of future research and funding?

In answer to this question, participants acknowledged that the current riparian buffer requirements on fish-bearing streams appear to provide adequate stream temperature protection relative to microclimate variables such as humidity, wind, and air temperature. Existing research shows that large temperature changes (i.e., more than 1 degree) to stream systems likely do not occur from microclimate effects along streams with riparian buffers. Therefore, it would not necessarily be a high priority for CMER to pursue or fund additional research efforts. Obviously, stakeholders should be aware of ongoing microclimate research, and in the future evaluate the need for microclimate-related studies.

Dr. Chan noted that research regarding microclimate effects in riparian areas is generally concerned with much more than stream temperature effects – such as the role of LWD, litter, etc. Dr. Chan also stressed that the relevance of microclimate research must be considered in the context of physical and ecological functions and processes, such as the requirements of various suites of biological organisms – for example, amphibians. While important, these considerations are outside the scope of this Temperature Workshop, which was tasked specifically with examining microclimate effects on stream temperatures.

2.2 Ranking and Scheduling the Priority Issues

As documented above, Workshop participants identified 10 key issues for CMER/RSAG consideration in prioritization – four key issues for stream physics, two for temperature modeling, four priority steps for groundwater, and no additional key management issues for microclimate. Recognizing the constraints of funding opportunities and scheduling considerations for CMER, it was then necessary to ask three additional questions:

1. Which of these issues are urgent?
2. Which of these issues are important to address at some time in the future?
3. Which of these issues are linked?

In this management context, “urgent” means those projects that we need to implement on the ground at this time. In addition, it would be ideal to focus on items that can be accomplished in a short amount of time and within existing budgetary constraints. Mark Hunter (WDFW) also stressed that in ranking priorities, it was important to consider the effectiveness of current practices – that is, if a technique appears to be effective as currently used, it doesn’t make sense to invest scarce resources to attempt to refine it.

Workshop participants generally agreed that all of the priorities identified above are important to address at some time in the future (that’s why they were identified as priorities). Based on participant and stakeholder dialogue, the following three priority issues were identified as **urgent**:

- **Standardize Shade Measurements**
- **Build a Better Eastside Model**
- **Develop a Clear Conceptual Model of the Role of Groundwater**

Developing an effective shade/densiometer protocol was identified as an immediate action item, as results from this effort will have an influence on other related issues (such as nomograph refinement and developing an eastside model). If densiometer readings are shown to be precise but not necessarily accurate, it might be possible to develop a correction factor. Building a better eastside model was also identified as an extremely urgent item; it would have immediate utility, and stakeholders have been frustrated in the past over what they perceive as a lack of applicability to actual conditions east of the Cascades. Finally, participants agreed that developing a conceptual groundwater model is an urgent item, as we currently lack a basic understanding of groundwater functions and processes, especially in the Pacific Northwest. Groundwater inputs function as the key factor in depressing stream temperatures below air temperature, and we need to develop a better understanding of the physical processes involved.

2.3 Issues Discussed but Dismissed from List of Priorities

The issues listed above were identified as priorities in a larger list of issues developed to capture significant dialogue occurring during the Temperature Workshops. The remaining issues, while not priorities, are still important. These are listed below, by topic. Most of the issues are phrased as questions, which the stakeholders then discussed.

Non-Urgent Issues – Stream Physics

- Do we need to identify the role of air temperature? This issue was deferred until the May Workshop on microclimate.
- Can (should) we better define when shade no longer significantly affects stream temperatures?
- What is the role of substrate (sediment size, sorting, etc.) on hyporheic exchange? This issue was deferred to the Groundwater Subgroup. In addition, it was noted that this is primarily a research question, as management practices have limited influence on streambed texture.
- Do we need to better understand how feedback loops (e.g., convection, evaporation, etc.) act to limit thermal accumulation? Again, this issue was deferred to later discussion on microclimate issues.
- Do we need to better understand winter temperatures?

Non-Urgent Issues – Modeling

- Should we develop a monitoring design to calibrate models?
- Should we seek to develop a better groundwater smoothing/mixing model?
- Can we use process-based models to focus on microclimate effects?
- Should we further examine the relationships between solar vs. air temperatures in driving stream temperature response in process models?
- Should we seek to explain the discrepancy between the use of regional air temperatures vs. local air temperatures in both empirical and process-based models?
- Should we examine the use of process-based models as diagnostic tools?
- How can we use models to address questions related to microclimate?
- Are there specific model assumptions that need to be addressed to build applicability for any specific model?

Non-Urgent Issues– Groundwater

A list of approximately eight research-related questions was developed related to groundwater. These questions focused on the mechanisms and processes by which groundwater temperatures translate to differences in stream temperatures. The questions specifically addressed such elements as depth of groundwater, relevance to forested mountain environments, soil structure, topography, field methods, and recharge. The Groundwater Subgroup recommended that we develop a clear conceptual model addressing groundwater processes as they relate to stream temperatures in the Pacific

Northwest, and presented this recommendation as a stepwise process. The questions identified during discussion of groundwater issues would be incorporated as appropriate during this stepwise process.

3.0 PRESENTATION SUMMARIES

Section 3.0 presents brief summaries of the individual scientific presentations, organized as follows:

- Section 3.1 summarizes the effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources, as presented by Dr. George Ice;
- Section 3.2 summarizes currently used **temperature models**, addressing their inputs, strengths, and weaknesses, as presented by Dennis Schult;
- Section 3.3 summarizes heat transfer processes via **groundwater,** as presented by Dr. Patricia Olson; and
- Sections 3.3 and 3.4 summarize heat transfer processes via **microclimate** conditions, as presented by Dr. Samuel Chan (addressing riparian conditions) and Dr. Sherri Johnson (addressing effects on stream temperatures).

Each of these panelists provided copies of their presentation materials, which are included in this report as Appendices C through G. This report is intended to be a summary – the reader is referred to the appendices for detailed information. Information presented in Sections 3.1 through 3.4 is provided primarily for context in support of the priorities and key issues identified in Section 2.0.

The summary of information presented here is organized by individual panelists' presentations. With the goal of providing the reader the "take home message" first, summary & conclusion information, when available, is presented at the beginning of each section.

3.1 The Effects of Direct Solar Radiation to Surface Waters

Dr. George Ice, National Council for Air and Stream Improvement, Corvallis, OR.

Key Conclusions

- Solar heat flux is the major input that raises the stream temperature above the local air temperature.
- Groundwater inflow is the major input that lowers the stream temperature below the local air temperature.
- All other heat flux terms involve both the air and water temperature, so the water temperature is always near the local air temperature.
- Energy transfer between the stream and its local environment always tends to bring the stream into equilibrium, with a zero net heat flux for the day.
- The rate at which stream temperature approaches equilibrium is strongly influenced by the average stream depth (small streams relax toward equilibrium more rapidly than large streams).
- The slow response of larger streams to changes in the environment make these streams slow to respond to diurnal variations, thus reducing diurnal temperature variations.
- The shade factor, represented by the view-of-the-stream-for-the-sky, Fwsky, is important in determining peak stream temperatures.
- Other shade and cover measures can be used to estimate the role of vegetation in reducing direct solar radiation inputs to a stream.
- Shade from riparian vegetation offers a practical management option to control changes in stream temperature.

Dr. Ice also presented a list of conclusions recently prepared by the Independent Multidisciplinary Science Team (2000), an advisory group to the Oregon State legislature. Some of the most relevant conclusions from the IMST were as follows:

- Solar radiation is the principal energy source that causes stream heating.
- Direct absorption of solar radiation by the stream and the streambed warms water; interception of solar radiation by vegetation reduces potential warming.
- Shading (vegetative and/or topographic cover) reduces direct solar radiation loading and stream heating.
- The factors that human activities can affect to influence stream temperature are vegetation, stream flow (hydrology), channel morphology, and subsurface/surface interactions.
- The influence of vegetation decreases with increasing channel width.
- The type of vegetation and its influence on temperature vary over time.
- Streams tend to heat in the downstream direction.
- Stream temperature tends to move toward equilibrium temperatures based on the energy balance, which is a function of several variables. As these variables change in time and space, the energy balance and equilibrium temperatures also change.

- It is more efficient ecologically to use shade to protect cool water from warming than to attempt to cool water that has already warmed.
- Vegetation is an important influence on microclimate, which may affect stream temperature if it sufficiently changes the stream environment.
- Riparian vegetation influences other aspects of the thermal environment of streams other than simply intercepting solar radiation.
- The change in temperature is a function of energy input, water surface area, and discharge.
- An increase in the surface area/volume ratio (or width/depth ratio) increases the rate of temperature change when there is a constant input of energy.

Presentation Summary[1]

The focus of Dr. Ice's presentation was solar radiation, the effects of shade, and the causes of temperature relaxation, all related to the overall energy balance. The presentation included the following:

- An introduction to heat balance theories
- More detailed information on forest stream heating
- The role of riparian vegetation and shade
- Relaxation of increases in temperature

An Introduction to Heat Balance Theories - Thermodynamics and Earth/Sun Geometry

Thermodynamics examines energy changes accompanying physical and chemical processes. The first law of thermodynamics relates to the conservation of energy: the temperature change in a stream is proportional to the thermal energy added or removed from the stream. The second law of thermodynamics is that all systems tend to approach equilibrium. Definitions of specific heat, calories, BTUs, heat of fusion, and heat of vaporization were presented.

Understanding earth/sun geometry is critical when considering solar radiation inputs in the Pacific Northwest. The farther north we are from the equator, the lower the maximum angle of the sun hitting the stream. For example, Sacramento is located at 38.5^{o}N, Salem at 45^{o}N, and Olympia at 47^{o}N. Because of its location, the maximum solar angle for Olympia is 66.5^o (at summer solstice). The maximum solar angle for Sacramento, in contrast, is 75^o, significantly closer to directly overhead. This geometry has important implications for measuring incoming solar radiation and determining the effectiveness of buffers. For example, the higher angle of the sun near summer solstice

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[1] Note to the reader – In addition to copies of his slide presentation, Dr. Ice prepared an excellent 30+ page summary of issues addressed in his presentation. The reader is encouraged to review this paper, included in Appendix C. Dr. Ice also prepared specific answers to the "Key Questions" prepared by RSAG and included in Appendix B.

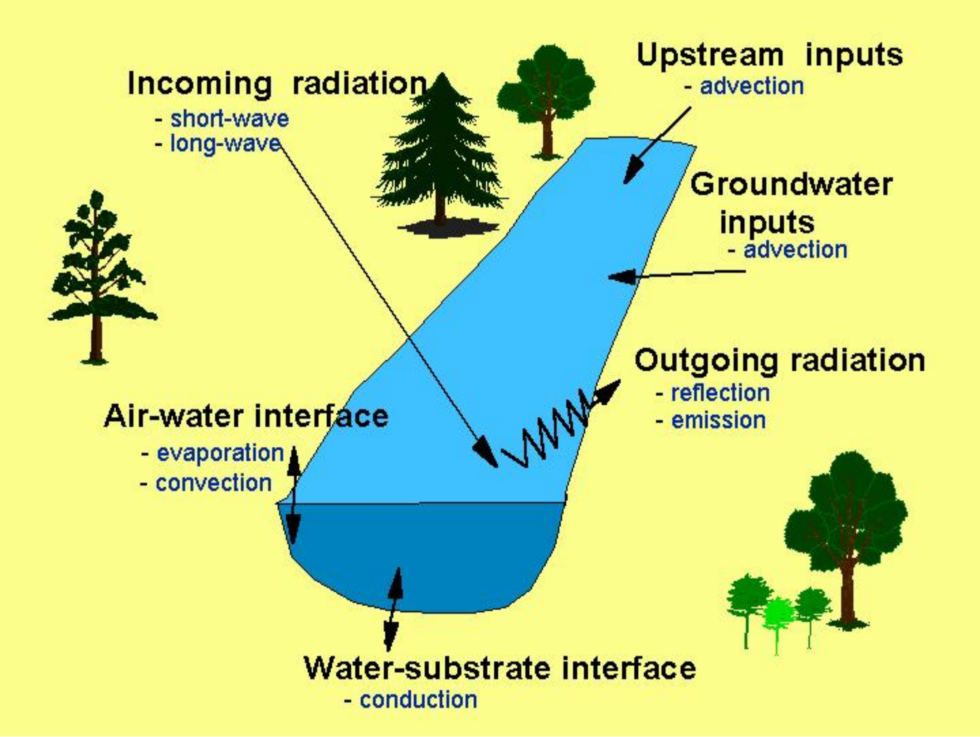
translates directly into more potential solar radiation inputs to the stream system than during the wintertime.

In addition, the short-wave reflectivity coefficient (i.e., albedo) changes with solar angle; at an angle of 60 degrees, for example, 5% is reflected, whereas at 30 degrees, 10% is reflected. The lower the angle, the more solar radiation is reflected.

Forest Stream Heating

Energy inputs and outputs to consider in a stream system include primarily the following: incoming solar radiation (both short-wave and long wave); outgoing radiation (via reflection and emission); stream-sensitive heat inputs and outputs (via advection); groundwater inputs and losses (via advection); the air-water interface (evaporation and convection); and the water-substrate interface (via conduction).

Figure 1. Energy inputs and outputs in a stream system.



A simplified energy balance is captured in Brown's equation (Figure 2), in which the net rate of heat per unit area added to a stream (ΣH) is calculated using the rates of net radiation (N_r) to the stream, and evaporation (E), convection (H), and conduction (C) inputs and outputs. Brown's equation considers maximum potential solar radiation input

Figure 2. Brown's Equation

$$\Sigma H = N_r \pm E \pm H \pm C$$

(based on maximum radiation rate, exposed surface of the stream, and time of travel through the exposed reach) and volume being heated. Using Brown's equation allows us to estimate the average net absorbed solar radiation based on time of day and season.

Brown's equation was tested at the Lewiston Idaho Experimental Streams (Brown 1970), where artificial streams were constructed with both pools and riffles. In this experiment, 100-m stream reaches were fully exposed, had plastic bottoms, and were designed with a 30-minute travel time. Brown's equation was used to estimate the change in temperature from upstream to downstream. Predictions were accurate to within 1°F. Obviously, natural systems are more complex and difficult to quantify, but the basic elements of Brown's equation are still very useful.

Another factor to consider is solar radiation transfer to the stream; water is relatively transparent to shortwave radiation – that is, little radiation is absorbed directly by the stream. However, the streambed can absorb the shortwave energy and transfer it back to the water column via conduction. The effective absorption therefore can be very high (i.e., up to 95%).

Other heat transfer processes to consider include long-wave radiation exchange, heat flux due to convection, and heat flux due to evaporation.

Vegetation, Canopy Cover, and Shade

Riparian vegetation can block direct solar radiation. The shade factor is represented by the view-of-the-stream-for-the-sky, Fwsky, with a value of 1.0 Fwsky representing fully exposed and 0.1 Fwsky indicating heavily shaded. The fraction of maximum solar flux increases proportional to Fwsky; for example, a Fwsky of 0.2 corresponds to a 30% fraction of maximum solar flux, whereas a Fwsky of 0.6 corresponds to approximately 80%. In addition, the shading influence is greater when the solar angle is lower.

Streams flowing east or west are exposed differently than streams oriented north and south. For example, in an east to west flowing stream, riparian vegetation on the north streambank blocks virtually no direct solar radiation.

Dr. Ice presented information on relevant case studies that examined the relationship between stream temperature changes and direct solar radiation. Experiments covered included the Alsea Watershed Study (Moring 1975), and the HJ Andrews Experimental Watershed. In the Alsea Study, Needle Branch was clearcut down to the stream in the winter and spring of 1966. In 1967, the harvest units were broadcast burned and the stream was cleared of woody debris. This resulted in an extremely exposed system. In 1967, the high summer temperature was 26.1°C at the gauging station, and exceeded 30°C in the upper watershed. Temperature changes over time were examined as regrowth occurred in the riparian zone. By 1973, shading from the young riparian alders had returned high summer temperatures almost to pre-harvest levels. Dr. Ice noted that upslope forest regeneration at Needle Branch was proceeding poorly at that time, indicating that microclimate effects from the upslope forest did not appear to be contributing to this temperature recovery.

A similar response was observed in the H.J. Andrews Experimental Forest, where three different treatments were examined (clearcut and burned, no treatment, and 25% clearcut and burned). In these cases, high solar radiation exposure contributed to significantly elevated stream temperatures, with recovery exhibited over time (Johnson and Jones 2000). In summary, increases in stream temperature were directly attributable to increased direct solar radiation.

A recurring point of discussion in the Workshops was the difference between canopy cover and shade. Canopy cover refers to the percent of the sky occupied by vegetation, whereas shade refers to the amount of energy that is obscured or reflected by vegetation or topography. Dr. Ice provided an overview of current measurement tools and techniques, including spherical densiometers, ocular estimates (e.g., computer cards), "moose horn" densiometers, Angular Canopy Density (ACD), solar pathfinder, hemispherical shade photography, and others. The methods have various strengths and weaknesses, biases, correlations, and costs. For information comparing and evaluating these methods (including correlation data), please see Appendix C. In summary, Dr. Ice recommended examining how we quantify canopy cover/shade and determine the effects on stream temperature. Research is needed to determine whether improvements in measurement techniques warrant extra cost and difficulty, and a recurring question throughout the Workshops was "Can we improve on the spherical densiometer"?

Numerous studies have been conducted to examine the role of shade on solar radiation inputs; these case studies have ranged from simplistic and very highly controlled environments to more complex, natural systems. In a recent study, Moore et al (1999) conducted a simplified shade experiment in different water tanks, including shallow vs. deep tanks, and shaded vs. unshaded tanks. Diurnal temperature fluctuations were measured. The unsurprising results were that deep, shaded tanks heated the least, and shallow unshaded tanks heated the most. In a 1998 study, temperature changes in an irrigation ditch were examined, with shading levels of 20, 40, 60, and 80 percent. Similar results were documented, with increased shading contributing to smaller temperature increases.

Another study more closely approximating a natural stream condition on the HJ Andrews Experimental Forest study examined the effect of shading a bedrock stream channel. Over the 200-m reach, maximum stream temperatures decreased with shade, even while air temperatures remained high. Due to rapid travel times within the reach, there was no response for daily mean or minimum temperatures.

In another shading experiment, Jackson (2000) examined the effect on water temperature of blocking solar radiation input with slash (as opposed to live riparian vegetation). Results indicated that slash moderated temperatures, functioning much like live riparian vegetation in preventing temperature increases. A recent study in Maine (Hagan 2000) found that stream temperature responded to various forms of shading, and showed that topographic shading, vegetation shading, and subterranean flow all reduced the effects of solar radiation input into the system.

Temperature Relaxation in Streams

Dr. Ice noted that much of the information presented so far, including results from the various case studies, examined temperatures in a rather conservative, static way; however, temperature is non-conservative in that it is constantly changing and moving toward equilibrium. Larger streams and smaller streams tend to react differently in terms of relaxation, with smaller streams tending to recover more rapidly than larger streams from large temperature increases. Studies have also addressed the temperature-related effects of a clearcut portion of a reach (and hence higher Fwsky), demonstrating that after higher maximum temperatures along those portions of the stream, the temperatures relax toward equilibrium as a function of both time and distance. In short, the temperature moves toward equilibrium after being exposed to higher inputs of solar radiation.

Questions & Answers/Additional Dialogue

- Question/Issue – In Washington's Hoh River, a glacially fed stream system on the Olympic Peninsula, we see a situation where the tributary temperatures average much warmer than the mainstem, in contrast to the "normal" pattern of stream temperatures increasing as they flow downstream. The mainstem average can be 7 degrees, while the tributaries can average up to 17 degrees. What could be the contributing factors? Answer – Site-specific factors would obviously have to be examined.

- Question/Issue – The conclusions presented state that solar radiation is the principal energy source; what about air temperature and the degree to which riparian forest conditions affect air temperature, when shade is held constant? Answer – There is undoubtedly an air temperature influence (which will be addressed in more detail at the Microclimate portion of the Workshop). The ambient air temperature sets the baseline level. However, the data show that the major change above air temperature is driven by solar radiation. For example, the Alsea Study shows that the role of shade is a more significant factor compared to air temperature. The water tank study showed the same results. Tanks respond more to solar radiation, less to air temperature. Air temperature is an energy source, but a muted source of change relative to solar radiation. Related Question– Isn't air temperature the primary factor in that water temperature is striving to reach equilibrium with air temperature? Response - Air temperature is a factor, but not the primary factor. Energy input has a more significant effect than the surrounding air temperature, and air temperatures are also fluctuating in reaction to those same energy inputs.

- Question/Issue – Regarding relaxation, is time or distance a more predictable/relevant measurement? Which is a better predictor of recovery factors - time or distance? Response – This could be approached better from a modeling or research perspective; we could examine both time and distance and develop guidelines as appropriate.

- Question/Issue – What role do channel structure and alluvium have in relaxation? Should we look at in-channel structure restoration for temperature benefits? Response (from an attending stakeholder) – BCC studied this, attempting to create a narrower, deeper channel. Empirical evidence showed that channel structure change can have a significant, measurable effect. However, our ability to influence or modify alluvial texture through management practices is obviously reduced relative to our ability to manage for shade.

- Question/Issue – Also regarding relaxation, what are the physics that would affect temperature changes going from cold to warm, rather than warm to cold? (e.g., a tributary feeding colder water to a warmer mainstem). Response – The same physics are working, but evidence shows that the cooling is slower than warming. The IMST concluded that cooling takes longer unless other processes (e.g., groundwater input) are present. The radiation outputs from the sun exceed those from earth surfaces.

- Question/Issue – In our experience and studies examining eastside vs. westside streams, different streams with similar shading characteristics (and other factors as well) show different temperature responses. What factors could be contributing to these observations? Response – As an example, we can look at recent studies on the fog belt; radiation isn't always at maximum (but we often assume this or analyze for maximum solar radiation input); fog, clouds, etc. can attenuate the effect. There are other factors to consider – "age" of water and its equilibrium state, groundwater inflow, etc. All of these can affect the results.

- Question/Issue – From a temperature perspective, is there any scientific reason to maintain north side buffers (referring only to east to west flowing streams)?. Response – For attenuating temperature effects, only vegetation on the south side prevents significant temperature increases. Convection effects would be worth additional study, but empirical evidence to date shows that evaporation and convection are both relatively minor components. Note, however, that there are other considerations beside stream temperatures when considering north-side buffers (e.g., wood recruitment for channel structure).

- Question/Issue – Regarding the canopy vs. shade issue, the presentation focused on canopy cover adjacent to the stream. What happens to a ray of sunlight as it passes through a vegetation buffer? That is, how important is the degree of solar radiation filtered through the canopy? Answer – Most research has been done on vertical process (direct solar radiation), showing that a full canopy obscures about 80 to 90 percent of solar radiation. Vegetative density, as well as its architecture, are important as well (e.g., consider a mature alder stand with a higher crown and little understory). At a lower angle of the sun, some sunlight does filter through the buffer. Note, however, that this same increased light would tend to contribute to a rapid vegetation response in the understory, which would change the filtering process and amount of solar radiation over time. Also, remember that at lower angles, more energy is reflected from the stream's surface. This issue will be addressed directly in the microclimate portion of the Workshop.

- Question/Issue – Are there any other architectural factors that influence solar radiation inputs, specifically in hardwood vs. conifer stands. Answer – See Dr. Ice's prepared response to Key Question #4; in short, there is scant empirical evidence at present. The westside vs. eastside discrepancies need to be further studied, and other factors such as aspect and stocking levels seem to be relevant.

- Question/Issue- I'm concerned with the statement/assumption that downstream temperatures are independent of upstream temperatures. Cumulative effects from upstream sources are a component of the equilibrium process – downstream temperatures must be dependent to some degree on upstream cumulative sources. Response – This assumption is predicated on that fact that all of these processes are time and spatially dependent. At some point, downstream temperature becomes independent of temperatures at a remote upstream source. The energy balance acts on local conditions, constantly working toward equilibrium.

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3.2 Stream Temperature Modeling

Mr. Dennis Schult, Western Watershed Analysts

Key Conclusions

Acknowledging that models examine heat transfer downstream (as opposed to temperature transfer downstream), Mr. Schult reviewed basic characteristics of equilibrium conditions:

- Heat transfers downstream, but heat transfer processes cause the water temperature to change only until net heat transfer is balanced.
- Energy in equals energy out.
- The temperature where the balance occurs is the equilibrium temperature.
- Downstream temperature is then independent of upstream temperature.

Mr. Schult also reviewed were some basic conclusions regarding the influence of air temperature and stream depth:

- At equilibrium, mean daily air and water temperatures are nearly the same.
- Diurnal water temperature cycle is due to the cycle of solar radiation and air temperature.
- Water temperature variations are smaller for deeper streams, and time to equilibrium is longer.

Presentation Summary

Mr. Schult's presentation addressed four different stream temperature models currently being used at the reach-scale:

- Heat Source[2] (ODEQ 1999), a process-based model which predicts hourly temperatures for one day; it can report both average temperatures as well as maximum temperatures. It is a Visual Basic model with an Excel interface.
- SSTEMP[2] (USFWS; Theurer et al 1984), a process-based model which predicts daily average temperatures. SSTEMP is an executable file and provides a single input/output screen.
- TEMPEST (developed by Adams and Sullivan (1990)).
- TEMP-86 (Beschta and Weatherred 1984).

Temperature models are also used to predict temperature changes at the basin-scale, which in general is a much more challenging process:

- SNTEMP (USFWS), a process-based model. (Editor's note: "SN" stands for stream network; SNTEMP is basically a batch version of SSTEMP, and uses the same algorithms as SSTEMP does.)

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[2] Indicates models that Schult typically uses and hence are addressed in more detail in this presentation.

- QUAL2E (EPA; Brown and Barnwell, 1987), a process-based model which is also used to model nutrients.
- Washington Screen (T/F/W), an empirical model.
- Idaho CWE[2] (IDL 2000), an empirical model.

Mr. Schult's presentation focused on the differences among commonly used process-based models and empirical-based models, as described below. For all models, the assumption is that stream temperature changes are the result of changing physical inputs. The various heat transfer processes – such as solar radiation, atmospheric reflection, evaporation, and convection – constitute the primary inputs.

Process-based Models

Process-based stream temperature models (such as SSTEMP and Heat Source) use several different heat transfer process inputs to account for net energy flux; primary inputs accounted for in the models include solar radiation, stream vegetation and shade, evaporation from the stream, convection between the stream and the air, conduction between the stream and streambed, and groundwater exchange. Specific input parameters fed into the process-based models include stream characteristics (such as aspect, depth, width, and flow); riparian characteristics (such as buffer height, width, overhang); atmospheric conditions (such as air temperature, humidity, and wind); and upstream water temperatures (typically reported hourly throughout the day). Depending on the model used, 25 to 30 input parameters are required for each reach; this can require a substantial amount of time and effort.

Of these input parameters, the process model results tend to be most sensitive to air temperature, humidity, wind speed, stream depth, and – to a lesser extent - shade. Mr. Schult provided specific examples showing sensitivity to inputs such as air temperature, humidity, wind speed, stream depth, buffer height, and reach length; see Appendix D for these graphs.

Based on a limited sampling run prepared specifically for this presentation, Mr. Schult also provided examples of model output sensitivity to variations in model inputs for the SSTEMP and Heat Source process models. In most cases, the two models compared closely, but output temperature variations differed between the two models for certain input parameters. For example, the change in daily average water temperature (i.e., ranges in output in degrees C) resulting from a change in daily average air temperature inputs were identical (2.6^{o}C) for both SSTEMP and Heat Source; however, output temperatures ranged 1.2^{o}C for SSTEMP for changes in average stream depth inputs, whereas Heat Source output ranged 0.6^{o}C for the same changes in average stream depth inputs. In short, the different process based models are more sensitive to certain input parameters, and results therefore vary slightly.

Heat Source has two advantages relative to SSTEMP. First, Heat Source allows both average and maximum temperatures to be predicted, not just the average temperature.

Secondly, as Heat Source is a Visual Basic tool, it allows the source code to be examined to help explain potential anomalies. As SSTEMP is an executable file, the actual code can't be examined to explain individual results. In addition, SSTEMP appears to be a bit weak in examining buffer considerations

To help compensate for such variability, as well as to account for site-specific and local variations, process models require calibration. Input parameters such as air temperature, humidity, wind speed, and groundwater temperature can be adjusted to more accurately reflect site-specific conditions. In particular, air temperature is a key parameter to adjust, as we frequently don't have good site-specific data over individual stream reaches (such data typically come from monitoring stations that can be some distance from the study sites).

In summary, the advantages of process-based models include the following:

- They predict temperatures for any condition
- They are very useful to investigate "what-if" scenarios.

On the other hand, process models have certain drawbacks:

- They require numerous inputs.
- They require calibration, which can be very time consuming.
- SSTEMP in particular is a poor predictor of maximum temperatures.
- Linked processes (such as buffer width and ambient air temperature) are not accounted for in the models – input parameters have to be fed in manually.

Empirical Models

Empirical models (such as Washington T/F/W Screen and Idaho CWE) use observed stream temperatures throughout a region to fit a regression model using selected input parameters such as elevation, shade, stream size, average air temperature, and drought index. Mr. Schult showed several examples of model output changes based on changing input parameters, such as canopy density; he also showed examples comparing results from different empirical models (Washington T/F/W Screen and IDL 2000). See Appendix D for these comparisons.

Mr. Schult noted that for the Washington Screen model, the key input parameters tend to be canopy density and elevation; these inputs provide the best predictors for stream temperatures. Results can be reported as maximum weekly temperatures, as well as by rolling averages. For the Idaho CWE model, canopy density and elevation are key variables; in addition, the drought index improves the predictions.

In summary, the advantages of empirical models include the following:

- They require few input parameters and no calibration
- They can be executed rapidly.

- Current models are already developed for many Pacific Northwest regions.

On the other hand, empirical models have certain drawbacks:

- They require substantial data input up front, and such data are not always available.
- The regressions are fit to only specific temperature parameters (such as maximum summer temperatures).

Mr. Schult compared output from two process models (SSTEMP and Heat Source) and one empirical model (IDL 2000); the case study was Cold Springs Creek (ID). Based on one run, predicted temperature ranges among the three models varied by up to 7°C for site-specific locations along certain reaches of the stream, but at other points along the stream were nearly identical. In addition, actual temperature measurements taken along two stream locations indicated that all models tended to overpredict temperature in this specific run (in this case, by up to 4°C). On average, SSTEMP tended to overpredict temperature by about 1 to 2 ° C. Heat Source overpredicted by 1°C. Idaho CWE overpredicted by 0.5 to 1°C. Schult noted that this was just one model run using specific conditions on a specific day, and that parameters could be adjusted/calibrated as appropriate in the process models to obtain more accurate predictions. SNTEMP would also have been an appropriate tool to use, but he did not prepare such output for this Workshop because the algorithms used are identical to SSTEMP. He noted that the level of effort required to obtain model output varies widely among models, which raises the classical “diminishing returns” question – Is it worthwhile to triple your level of effort for a 0.5°C change in the resulting prediction?

Mr. Schult also presented numerous sample output graphs demonstrating various “what-if” scenarios for such inputs as buffer width and effective shade. For example, Heat Source was used on the Upper Grande Ronde to help determine TMDLs – eight separate reaches were considered, and five different buffer configurations were examined. The reader is referred to Appendix D to see these sample outputs.

In conclusion, Mr. Schult identified some potential future research directions that might be appropriate for evaluating temperature modeling:

- The potential use of microclimate effects as input parameters.
- The potential use of groundwater measures as input parameters
- Evaluation of the balance between simplicity and accuracy. (i.e., do large data input requirements improve accuracy?).
- Examination of the role of stratification and mixing of groundwater input over the range of the reach.
- Examination of sensitivity differences between models.

Questions & Answers/Additional Dialogue

- Question – In modeling, what is the definition of effective shade? Response – Mathematically, effective shade can be defined as

$$[1 - (^{\text{Radiation hitting the stream}}/_{\text{Radiation hitting the canopy}})]$$

- Question/Issue – Do you have any recommendations for the design/protocol for monitoring canopy density to be used as model inputs? What does the model call for? Response –For SSTEMP, spherical densiometer measurements were used. Related Question-Would hemispheric photography be better to use and, if so, where should you take measurements? Response – I'm not sure which method would be more appropriate. Where to measure is situation-dependent. For example, for a mile long reach, you should use the stream's edge.

- Question/Issue – How do you deal with groundwater input, as it varies over the range of the reach? Response – This applies especially to Heat Source, which assumes complete mixing. Due to the model configuration, that's the best we can do, which is why stratification is listed above as an appropriate research direction.

- Question/Issue – How do the models incorporate microclimate conditions? Do microclimate effects have any bearing on empirical models? Response – You don't have to worry about microclimate effects/inputs when working with empirical models. But microclimate effects are indeed input parameters for process models and can be adjusted as the user sees fit.

- Question/Issue – Is there a possible contradiction between the Solar Radiation presentation and the Temperature Modeling presentations? Specifically, Dr. Ice concluded that shade is a significant contributor to buffering stream temperature changes. But the model output does not show shade as such a key input; rather, air temperature is shown as the driving factor. Is this a disagreement? Response – No, this isn't a contradiction or disagreement; we are reporting different, but related, results. Solar radiation is the key driver that influences maximum temperatures; air temperature tends to drive average temperatures. Dr. Ice also clarified that solar radiation is the key input in driving stream temperatures above air temperatures; groundwater is the driving factor in cooling water below air temperature. Shade and direct solar radiation both influence these changes, and air temperature is the base/foundation for which the changes take place. Mr. Schult reiterated that these models do not take into account the interactions among the various inputs which exist in nature (e.g., air temperature/humidity); these need to be input manually into the models.

- Question/Issue – Can process models be used for diagnostic purposes, such as evaluating the results of empirical models? Response – Mr. Schult noted that he hasn't specifically used process models for this purpose.

- Question/Issue – Is canopy density/closure a reasonable proxy for effective shade measurements? Response – Not necessarily. Canopy density does not account for enough geometric variables (such as aspect, latitude). Effective shade does account for these factors. For example, you can get relatively high shading levels without a high canopy density.

- Question/Issue –Regarding microclimate, are there ways to predict local air temperatures under the canopy for different riparian conditions/configurations. Response – According to Dr. Ice, there is a thesis in preparation at Berkeley examining this situation along the Sacramento River. In addition, Dr. Sam Chan is working on this issue, specifically examining buffer widths. This a missing link for this (i.e., February) Workshop, and the issues will be examined at the May Workshop addressing microclimate. Schult also noted that air temperatures derived from local weather stations – which are often fed into empirical models – do not necessarily reflect air temperatures over the water column. Stakeholders agreed that the discrepancies in regional vs. local (i.e., over the stream) temperatures, and how these relate to both empirical and process models, are topics worthy of additional examination.

- Question/Issue – In the example comparing output from various models, the results indicated that output tended to be more conservative for all models examined, when compared to actual stream measurements. Is this typical? That is, does model output tend to be more conservative than actual temperatures? Response – Because of the ability to calibrate process-based models, these results can vary. This sample output was worked up specifically for the Workshop and just represents one modeling scenario.

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3.3 Groundwater and Heat Transport in Forested Ecosystems: Where Are We?

Dr. Patricia Olson, Pacific Watershed Institute

Key Conclusions

- Very little research has been conducted on this specific topic, especially in the Pacific Northwest; historically, groundwater research has focused on resource extraction and contaminant transport. There is a body of research addressing heat transfer by subsurface flow, but these studies have not addressed the effects of vegetation removal.
- Groundwater systems and heat transport mechanisms are highly variable and extremely complex.
- The primary elements of subsurface flow that influence heat transport include flux, storage, and recharge-discharge. These processes are influenced by hydraulic conductivity and porosity.
- In the unsaturated zone, heat transport depends on water content, hydraulic and thermal conductivity, heat and storage capacity, porosity, runoff processes, and travel time.
- In the saturated zone, heat transport depends on hydraulic and thermal conductivity, porosity, heat and storage capacity, travel time, and recharge-discharge dynamics.
- As porosity increases, hydraulic and thermal conductivity, and dampening depth generally decrease.
- Water storage capacity and retention and heat capacity generally increase as porosity increases.
- Theoretical equations for dampening depth and time lag with depth apparently do not predict thermal regimes in forested areas.

Presentation Summary

Dr. Olson prepared a separate paper summarizing her presentation's key points; this paper is included in Appendix E.

Dr. Olson noted that we don't have very much research on the specific topic of groundwater and heat transport. Historically, groundwater was viewed and studied primarily as being an extractable resource. Later, groundwater research focused on contaminant transport processes. Neither of these research designs are particularly relevant to the management of forested areas. Current research is being conducted on hyporheic processes, but these data tend to focus specifically on the interaction zone, not the entire groundwater system. Also, very few of the existing studies were performed in the Pacific Northwest, so their results might not be particularly relevant to our local conditions.

When modeling groundwater systems, we often have to make numerous assumptions regarding such factors as temperature, flow, and volume throughout the entire system. But groundwater systems are highly variable and dynamic, much like stream systems. This variability isn't always captured in current modeling efforts. Obviously, they are difficult systems to model and study.

Given these difficulties and the current state of research, today's presentation does not address volume or modeling specifically; rather, the presentation focuses on basic concepts of the groundwater systems, addressing the following:

- Subsurface flow systems
- Groundwater flow in forested areas
- Heat transport in the subsurface domain
- Factors influencing heat transport
- Examples in forest systems
- Hypotheses

Subsurface Flow Systems and Groundwater Flow in Forested Systems

The groundwater domain is defined as the subsurface zone of permeable material through which water moves. This includes both the unsaturated zone (or vadose zone), as well as the saturated zone. Important processes that occur in this domain include redistribution of soil water, percolation, capillary rise, plant uptake, exfiltration, matrix flow, and thermal energy exchange. When examining the groundwater domain, it is also important to consider the hyporheic zone (the transitional zone between the stream aquatic ecosystem and other groundwater systems). Some of the most important physical and chemical fluctuations occur here. The interactions between streams and groundwater systems are complex processes. In some cases, groundwater functions to recharge streams; under other conditions, the streams recharge the groundwater system; both effluent and influent processes occur.

The key elements of subsurface flow that influence heat transport include **flux, storage,** and **recharge-discharge**. These processes are influenced by hydraulic conductivity, permeability, and porosity.

Flux – the movement of subsurface flow – is governed by Darcy's Law (equations are provided in Appendix D). Important characteristics of subsurface flow include the following:

- Water moves where there is a gradient.

- For a given hydraulic gradient, discharge will be greater as permeability increases.
- Groundwater velocity increases as hydraulic head, grain size, and pore size increase.
- Hydraulic conductivity decreases as porosity increases in unconsolidated sediments.
- Hydraulic conductivity increases with temperature.
- In the unsaturated zone, hydraulic conductivity decreases as moisture content decreases.

Storage characteristics in groundwater systems play a significant role in affecting heat transfer. In general, the greater the storage capacity, the more opportunity for attenuating heat.

Groundwater recharge areas occur where percolating water moves from the unsaturated zone (or surface water) to the saturated zone; discharge areas occur where saturated flow moves to the surface via springs, seeps, or surface water bodies. Factors that influence recharge/discharge areas include climate, lithology, and physiography. In recharge areas, small differences in local conditions can cause large differences in recharge capacity.

Groundwater flow systems can be examined at a variety of spatial scales, including local flow systems, intermediate flow systems, and regional flow systems. Within these scales, flow rates are extremely variable, with numerous interactions occurring. In general, flow systems tend to discharge at low elevation points in a basin, or at faults/fissures that are present.

Heat Transport in the Subsurface Domain

The primary processes governing heat transfer within a porous medium include conduction (especially by gradient), radiation (emitted because of a body's temperature), and convection. Other factors to consider include soil composition, evaporation, infiltration, recharge characteristics, hillslope topography, and seasonality.

Soil factors, such as mineralogical composition, significantly influence heat transport in groundwater systems. There is a dampening effect of heat transport for soil radiation, and dampening depths can be theoretically calculated for different soil types. However, there are very few data on actual measured temperatures, and these are mostly for agricultural soils.

Another factor to consider is the process of evaporation and its effects on heat transfer. For evaporation to occur, there must be a continual supply of water through the soil matrix. Higher evaporation rates will occur in warmer, wetter soils. In a recent study in Minnesota (Bridgham et al. 1999), a summer decline in subsurface temperatures measured at 15 cm was caused by higher evapotranspiration rates. In general, heat losses by evapotranspiration are more than offset by heat gains from increased solar radiation.

Infiltration is an additional factor influencing heat transfer. In general, high water content tends to increase thermal conductivity, while low water content decreases conductivity.

Few studies have been conducted examining recharge and its relationship to heat transport. Taniguchi and Sharma (1993) used soil temperature differences to predict recharge. Their findings indicated that the higher the annual recharge, the greater change in soil temperature from initial surface temperatures. In addition, the seasonal change in soil temperature was greater in a sparser pine area than a dense pine area.

Hillslope and topography influence heat transport processes, as well as recharge-discharge processes. In steep topography, a large part of the available water moves downslope to areas where it can percolate deeper. These processes are complex and site-specific, with flow often regulated by topographic factors. On hillslopes, macropore flow is a potentially significant water and heat transport mechanism.

Seasonal variations are also important to consider in heat transport. In the wet season, recharge filtering through the cool soil matrix moved through the saturated zone, mixing and warming as it transported, resulting in warmer discharges than the initial recharge temperature. In the dry season, the opposite occurred, with discharge being cooler than the infiltrate.

Examples of Forested Systems and Influence on Stream Temperature

Only a few studies have examined groundwater systems in forested areas. Temperature profiles have been developed in forested systems (e.g., Olson 1995, Taniguchi et al. 1997), as well as in comparison with harvested sites. In Taniguchi's study, removal of forest vegetation and the establishment of agricultural lands resulted in temperature increases to a depth of 40 m.

Another local study (Carnation Creek) examined the role of summer storms and groundwater and streams' response to these storms. Fannin et al. (2000) found that rainfall in May through September caused a groundwater temperature response on hillslopes. Heat that accumulated at the surface is transported into the deep soil by convection.

Site-specific studies have also examined the role of groundwater influences on stream temperatures. In a study of 3rd and 4th order streams in Minnesota, Sinokrot et al. (1995) found that groundwater discharge exhibited an influence on stream temperatures 48 km downstream. In another study, Webb and Zhang (1997) concluded that groundwater has a significant impact on the heat budget, although results were variable by season, and patchy over short distances.

Questions to Examine

When examining groundwater influences in a specific watershed, it is important to consider the following questions:

- Where in a watershed does groundwater contribute to surface water, and what role does it play?
- What is the source of subsurface flow to surface water (i.e., local, intermediate, or regional flow system)?
- Where is the groundwater system recharged and discharged?

Very few studies have specifically addressed groundwater systems and related temperature effects in Pacific Northwest forested areas. Future research should focus on the following key questions:

- Do clearcut conditions significantly alter groundwater discharge temperatures when groundwater levels are deeper than 1 meter?
- Do buffer widths influence groundwater discharge temperatures when groundwater levels are deeper than 1 meter?
- How are stream temperatures related to soil temperatures?

Questions & Answers/Additional Dialogue

- Question/Issue – Based on the presentation, it's obvious that there is a substantial amount of research needed to answer our more specific questions. Specifically related to western Washington conditions, how can groundwater transport affect summer stream temperatures? This is the primary issue we'll need to focus our efforts on. Also, the CMER process is concerned specifically with how forest management practices provide adequate protection. We have to start looking at potential problems, which might initially best be examined at local recharge areas closer to streams. Given the complexity of the issue, how do we narrow down what needs to be looked at? Response – Recharge areas close to streams would be a logical initial step in examining the processes.

- Question/Issue – Eventually, we'll need to define mechanisms by which harvest practices translate to groundwater changes that could influence stream temperatures. For example, we should consider the effects of vegetation conditions on soil temperatures.

- Question/Issue – Some of the material presented showed thermal penetration to depths up to 40 m. What types of sites are these, and are they similar to our mountainous areas? Response – Those 40 m sites were in hilly areas, not flatland. Some were in stream valley bottoms.

- Question/Issue- How much does organic matter (vs. mineral content) affect temperature changes? Response – Organic matter can significantly influence temperature changes in soil and groundwater systems.

- Question/Issue – Have there been any studies examining the relationship between vegetative cover and groundwater recharge dynamics? Response – There are some recent studies in Australia examining this issue.

- Question/Issue – As you move downstream, does groundwater temperature contribution and influence decrease? Response – Yes, but it's a matter of scale. The amount primarily depends on the contribution of groundwater-fed streams

- Question/Issue – Is there a field method for evaluating groundwater temperatures on a site scale in a forested habitat? Response – There are different methods; in areas with a shallow water table, steel probes are appropriate. For deeper groundwater systems, sinking a well is required.

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3.4 Upland/Riparian Microclimate Processes[3]

Presented by Dr. Samuel Chan, Pacific NW Laboratories, USFS, Corvallis, OR

Key Conclusions

- Our knowledge of the interactions between the drivers of microclimate (macroclimate, vegetation, geomorphology, topography) with microclimate is still limited.
- Our understanding of interactions that arise from different patterns of microclimate, such as evaporation and convection, is limited.
- Concepts of "interior forest conditions" must be defined on spatial and temporal scales in the context of functions and process.
- When considering riparian microclimates, the complexity of gradients, patterns, and distribution of edges is of great importance.
- The relevance of microclimates must be considered in the context of physical and ecological functions and processes. For example, what are the effects on target organisms such as amphibians?
- Microclimates are often described and often "managed" at a stand or small stream reach scale.
- The mosaic of microclimates associated with patterns in the landscape (drainage, watershed) should first be considered.
- Empirical evidence from recent scientific studies indicates that processes and factors such as relative humidity, soil temperature and characteristics, evaporation, convection, wind speed, air temperature, topography, and solar radiation, can have significant influences on riparian forest conditions at the microclimate scale; however, of particular relevance to this Stream Temperature Workshop, microclimate effects within managed buffer zones DO NOT appear to significantly affect stream temperatures. Microclimate effects should be considered important and warrant additional study when examining potential effects (e.g., to lichens, bryophytes, terrestrial mollusks, amphibians, and vascular plants).
- Management practices, such as use of herbicides, mounding, and blading – can and do change microclimate conditions (e.g., affecting vegetation conditions and accumulated growing degree days). However, these changes do not necessarily translate to changes in macroclimate. It is therefore important to examine effects on a watershed scale.

Presentation Summary

Dr. Chan began his presentation by referencing *Forest Influences* (Kittredge 1948), noting that microclimate patterns and influences have been the subject of physical scientific study for over 50 years, and that much of the information presented from that

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[3] This presentation was a portion of a previous presentation developed with Robert Danehy of Boise Cascade Corporation, Boise, Idaho (Chan and Danehy 2000).

era, as documented in the text, is still relevant. For example, Kittredge addresses climate, soils, physiography, forest factors, solar radiation, air temperature, wind, precipitation, stream flow, evaporation/condensation, soil temperate, floods/erosion, and watershed management – all topics of current and relevant concern. Also noted was the fact that microclimate studies tend to exhibit a high degree of variability due to the difficulty in controlling experimental design factors. This variability was a continuing theme in Dr. Chan's presentation, and he frequently stressed that it is essential to examine research design in microclimate studies and associated results before extrapolating broader conclusions. Often, results can be less conclusive than other research dealing with less complex systems and processes.

Dr. Chan also stressed that due to site microclimate variability and diversity, it is often difficult to develop specific recommendations (such as defined buffer widths); an additional complicating factor is that conditions favorable for one variable (e.g., high shade levels to moderate stream temperature) might be unfavorable for another (e.g., sunlight needed to promote understory growth).

According to Daubenmire (1947), microclimate can be defined as "strictly local combinations of atmospheric factors which, owing to uneven topography, plant cover, etc., differ from the macroclimate as measured in locations where these modifying factors have negligible influence. Within each area embraced by one macroclimate, there exists an intricate matrix of microclimates, at least some of which differ sufficiently to be ecologically important." In particular, in riparian zones microclimates can change substantially in just a few feet, as measured by canopy cover, soil conditions, and other factors. Riparian areas are physically diverse, with components and inputs that include but are not limited to light, soil, soil moisture, geomorphology, edge, and disturbance. For example, a conifer-dominated riparian zone on one side of a stream differs substantially from an alder stand on the other side of the stream, especially when considered from a seasonal perspective. Dr. Chan's presentation therefore focused on the key forest microclimate factors – soil radiation, relative humidity, air temperature, and soil temperature; to a lesser extent, he also addressed precipitation, wind, and soil moisture.

Overview of Microclimate Factors

It needs to be stressed that Dr. Chan's research and presentation focused primarily on microclimate drivers and effects within riparian stands, generally with the goal of promoting complex riparian structure. The data and research results he summarized were not specifically designed to observe stream temperature effects. For this Temperature Workshop, his discussion and results need to be evaluated in this context. In these studies, the experimental design generally involves placing multiple sensors along a transect with prescribed distances upslope from the stream (e.g., 5 m, 10 m, 25 m, etc.), and measuring microclimate conditions at sites subject to differing harvest and buffer treatments.

The presentation began with an overview and examples of various microclimate processes and relationships, with the intent of demonstrating their complexity and diversity. For example, riparian areas often exhibit very complex soils; samples along transects taken every 30 feet show large variability, from sandy loam to silty clay, all of which have different water retention patterns.

As another introductory example, Chan's recent study of Callahan Creek was referenced. At Transect 3B, total radiation, soil temperature, air temperature, and relative humidity were examined, contrasting forested and clearcut conditions. Results indicated that large changes were noted in radiation, medium changes were evident for humidity and temperature, and very little change in soil temperature was observed. Data results change significantly, depending on time of day, and Dr. Chan stressed that results and conclusions were therefore relative to the specific factors examined, with generalizations difficult to make.

Solar Radiation and Shade

As noted previously in Dr. Ice's presentation, the effects of solar radiation are well studied and fairly well understood, particularly in relation to other physical processes. Dr. Chan showed multiple hemispherical images to demonstrate variation in canopy closure. He pointed out its effectiveness in measuring shade levels relative to the human eye, which picks up a much more limited portion of the total light input. Light levels were compared and contrasted for areas above the stream, in the riparian buffer, and in thinned stands. Using the Callahan Creek study as an example, light levels were measured at 8 points from the stream center up to 97 m upslope; light levels ranged from 3 and 4% up to 10%, with levels being very similar up to 61 m upslope.

Especially with solar radiation inputs, the greatest changes in microclimate are often due to weather patterns. Also, because of diurnal cycles, it is essential to examine the extremes (high and low values); average values often are not very meaningful. This holds true for other microclimate variables as well.

Another major theme of the presentation was the importance of maintaining a diverse, complex riparian structure. In contrast to managing for higher shade levels to protect stream temperatures, Dr. Chan emphasized the need to thin buffer stands to allow light to reach the understory, thereby promoting regrowth and structural diversity (which also contribute to greater canopy coverage over time). For example, a 35-year old Douglas-fir stand managed primarily for wood production – the classic "tree farm" environment with even age and high density characteristics–lacks structural diversity; despite a 100% canopy cover, the understory is open, and both light and wind pass through the clean boles. Silvicultural practices can be used to increase complexity under the canopy, and there are obvious tradeoffs that need to be examined when making such choices.

Dr. Chan also addressed various ways to examine and quantify total canopy cover. For example, when measured near the ground (at a height of 1 m), it is possible to obtain cumulative canopy coverage up to 400%, as the forb, shrub, and overstory layers are all considered and cumulative totals reported. As a gross generalization, a coverage of 150% (measured in this fashion) reduces the "available sunlight" reaching the forest floor to about 20%.

When considering canopy coverage, it is also important to consider results over time. Much of Dr. Chan's research focuses on examining differences in riparian structure over time when subject to different thinning rates, with the overarching goal of promoting structural diversity. Numerous examples of light-related effects on various thinning rates (e.g., ranging from 40 TPA to 100 TPA) over time were presented, with copies of the hemispherical photos presented in Appendix E. Microclimate effects can vary substantially over different treatments and at different sites. He also noted that about 3 years after thinning, similar canopy closure rates are exhibited between conifer and hardwood stands. Overall, however, it is difficult to make generalizations about percent sky effects from thinning levels – benefits from thinning are not necessarily proportional to the number of stems removed.

Relative Humidity/Temperature

Unlike the more straightforward, consistent results of canopy coverage and shade, the interpretation of results from relative humidity and temperature studies are more variable and controversial. Dr. Chan noted that very recent changes in technology have greatly improved measurements of microclimate; only within the last four years or so have there been affordable, portable instruments/sensors for relative humidity. When examining the current literature regarding temperature and relative humidity, Dr. Chan stressed the importance of considering the experimental design.

Most current studies indicate that in areas with adequate riparian buffer zones, microclimate conditions do not adversely affect stream temperatures. In one recent study, it was demonstrated that a buffer width of between 0.5 and 1 tree height would be effective in maintaining most microclimate variables, including soil moisture, radiation, soil temperature, and air temperature at levels similar to no-cut situations. An exception in this study was relative humidity. Buffer widths of greater than two site potential tree heights were required to maintain relative humidity at levels comparable to no-cut situations. While not a primary driver in influencing stream temperatures, relative humidity is nonetheless crucial for maintaining healthy macrophyte conditions along a streamside. In general, microclimate plays a critical role in plant regeneration, growth, and distribution. A recent study by Brosofske et al. (1997) analyzed the relationship between microclimate variables and stream temperatures, concluding that wind speed, relative humidity, and solar radiation had little or no relationship to stream water temperatures. In addition, buffer width did not appear to affect stream water temperature at the sites examined, except in the case of an almost complete absence of streamside trees. When considering factors other than stream temperatures, however, that study concluded that riparian microclimatic gradients existed for air temperature, soil temperature, and relative humidity, noting that even conservative buffer width recommendations might not be adequate for preserving an unaltered microclimate near some streams.

Other recent studies have yielded less definitive results. For example, Dong et al. (1998) found that 100-m buffers did not seem to provide protection for soil and water temperature conditions; however, it is difficult to interpret these results due to limitations of the experimental design.

Other recent studies included Chen et al. (1999) and Cajun James' Millseat Creek study. Although Dr. Chen noted difficulties in extrapolating conclusions from these, he noted that James' study examining soil and water temperatures at the stream indicated that there were no detectable changes within her instruments' limits; this study design involved clearcutting in stages closer to the stream, with varying buffer widths decreasing over time. This study examined both north and south side sites. In short, no increase in stream temperature was caused by prescribed forest harvest, nor were increases in turbidity or sediment noted.

Similar results have been noted for relative humidity effects. Danehy and Kirpes (2000) examined both eastside and westside streams. They found that the greatest changes in relative humidity occurred close to the stream (within 5 m), after which the differences become very small. In these studies, macroclimate (local weather) often accounted for the majority of the observed variation in microclimate.

Dr. Chan also referred to several studies examining thinning treatments and their effects on air temperature, soil temperature, and relative humidity. Results for these studies (which included the Green Peak Adaptive Management Project and the Keel Mountain Soil Temperature Study) were highly variable and exhibited substantial uncertainties, although both soil and temperature variations appeared to be surprisingly narrow.

Questions & Answers/Additional Dialogue

Due to the interconnections between riparian microclimate and conditions over the stream, questions and additional dialogue for riparian microclimate are included in Section 3.5.

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3.5 Microclimate Effects on Stream Temperatures

Dr. Sherri Johnson, Oregon State University

Key Conclusions

- Solar radiation is a dominant factor influencing stream temperature dynamics. Numerous other factors also contribute to stream temperatures (see the illustration on the cover of this report).
- Mechanistic studies are necessary to understand the relative importance of various factors influencing stream temperatures. Because of microclimatic variability, stream heat budgets calculated using climatic information from distant or upslope sites may not be accurate.
- Forest harvest practices such as clearcutting have been shown to dramatically increase maximum and minimum stream temperatures. Recovery occurs over time as riparian areas are revegetated. The effects on stream temperature of current selective harvest practices with riparian buffers have been examined in only a few studies.
- The correlation between diurnal or seasonal temperatures of air, water, and soil do not prove cause-and-effect relationships; correlation is a comparison of similarity of patterns, and all temperatures are responding to incoming solar radiation.
- Stream temperatures within stream networks are just beginning to be studied in a systematic manner. Landscape factors, such as elevation, gradient, width, depth, discharge, and watershed area, are all changing between the headwaters and downstream areas, and stream temperatures generally increase with distance downstream. But, that relationship does not prove that these factors are mechanistic drivers of stream temperature.

Presentation Summary

Numerous factors influence water temperature in a stream system; these include incoming radiation, upstream inputs (advection), groundwater inputs, the air-water interface (evaporation and convection), outgoing radiation (via reflection and emission), and the water-substrate interface. The processes influencing stream temperature dynamics are very complex and interrelated, making it difficult to identify the primary controls on stream temperature. Factors other than microclimate, such as climate, landforms, and biosphere, influence temperature and subsequent stream ecology.

Existing theories of temperature influences on stream systems examine effects evident at both the reach scale (generally applying an energy budget approach), and at the network scale (incorporating such factors as landscape patterns and theories about longitudinal patterns). In addition, variability of stream temperatures can be examined at the temporal scale (e.g., annual, seasonal, diurnal), and at the spatial scale (e.g., upstream vs. downstream).

Dr. Johnson noted that microclimate effects have also been studied in lakes, which tend to be easier to understand due to the longer water retention time, as well as more stable inputs and outputs. Streams are by nature more dynamic systems, with changing influences along their length.

Air Water Interface (Evaporation and Convection)

Dr. Johnson described her recent research using heat balance/budget models. In Watershed 3 of the Andrews Experimental Forest, she examined the magnitude of influences of solar radiation versus air water interactions. In this example, a 4°C increase in temperature was observed in a 200-m reach scoured to bedrock. Initial calculations of heat budget for this reach showed inputs of solar energy (at 600 W/m^2) and convection (100 W/m^2), and outputs of evaporation (200 W/m^2) and conduction (50 W/m^2). The resulting 4°C temperature increase equated to +450 W/m^2, showing solar radiation inputs to be the driving factor behind water temperature increase in this reach, and the air-water interchange a lesser factor. Studies from other regions (Sinokrot and Stefan 1993; Webb and Zhang 1997) also show that convection, or flux of heat to the stream from warmer air, is generally less of a factor in heat budgets than evaporation, where heat is lost to the atmosphere.

A portion of the bedrock reach in Watershed 3 was shaded to examine the effects of reducing solar radiation, with temperatures recorded both above and downstream. Results showed that maximum stream temperatures decreased (by 1°C) despite the presence of high air temperatures still in this reach, indicating that stream temperatures were less influenced by air temperature than by solar inputs.

Effects of Forest Harvest on Stream Temperatures

Dr. Johnson presented numerous examples of studies examining microclimate effects on stream temperatures in the context of different forest management practices (referenced studies included the Alsea Basin, the HJ Andrews Experimental Station, and the Beschta and Taylor (1988) study). Forest harvest practices, such as clearcutting and leaving no riparian buffer, led to increased maximum and minimum stream temperatures during summers (Johnson and Jones 2000; Brown and Krygier 1970). The timing of summer maximums also shifted to earlier in the summer, which coincided with seasonal solar maxima. Removal of forest cover results in increased surface soil temperatures and may increase stream substrata temperatures. Studies have documented recovery of stream temperatures following clearcutting to pre-treatment summer maximum temperatures. The recovery times are influenced by the rate of riparian revegetation, which occurs over approximately 15 years in the Cascade and Coast ranges of Oregon.

Present harvest practices (featuring retention of riparian buffers) have been less studied. Riparian buffers can shade small streams and prevent increased amounts of solar radiation from reaching the stream. Questions remain over: (1) the density of riparian buffer needed to prevent harvest effects on stream temperatures, and (2) the recovery of stream temperatures downstream of harvested areas where increased temperatures occur.

Conduction at the water-substrate interface can be an important microclimatic variable, depending on the type of substrates. Streams with high hyporheic exchange can have reduced diurnal temperature fluctuations compared to streams that have been channelized or those flowing over bedrock.

Questions & Answers/Additional Dialogue[4]

- Question/Issue – The energy balance equations that were cited seem to relate to smaller streams; would larger streams react differently? Answer – Small streams respond more quickly to surrounding conditions than larger streams. Input factors change rapidly in the smaller headwater streams relative to the downstream areas; farther downstream, shade by riparian vegetation is less of a factor but wind and evaporation may have more importance. Related Question – Is the air temperature driving this? Answer – It's a factor, but not the main driver.

- Question – One of the initial heat budget equations showed solar radiation levels to be approximately six times the energy of other factors. Does that indicate that solar input is six times more important in terms of influencing temperature than air temperature? Answer —Energy balances are a function of all of the physical processes occurring at that particular stream segment. Tying this into management implications, it seems we can focus on solar inputs – it's the driver and we can also influence it by managing shade levels. On the other hand, air temperature is less of a factor, and we can't necessarily manage for air temperatures effectively. Related Question – What role might narrow riparian buffers have in terms of contributing to elevated air temperatures and related impacts on elevated stream temperatures? Answer – It depends on the amount of solar inputs reaching the stream as well as additional microclimatic factors. One factor that we have very little data on is wind in managed riparian buffers, and evaporation can be a significant factor. The interrelationships indeed are very complicated; you can't necessarily isolate or manage for a single factor as they are interrelated.

- Question – Given these varying results, where should we focus our research priorities? Is microclimate something we need to put our limited resources into, relative to other issues, especially given current buffer zone requirements? Answer – There's a lot we don't know and a good deal of uncertainty; these issues will obviously require additional research. But focusing on what CMER is specifically tasked with, we're not sure what the return would be from a management perspective on microclimatic research. Riparian buffers are important for much more than just stream temperatures and provide benefits such as wood inputs, litter, bank stability, etc. When examining amphibians and plants, riparian microclimate effects are crucial and additional research is needed to address unanswered questions. But from strictly a stream temperature perspective, CMER resources would likely be better focused elsewhere. We'd recommend that CMER do a more thorough review of the existing literature

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[4] Note that these Questions and Answers include responses by both Dr. Chan and Dr. Johnson.

before considering any additional field research efforts examining microclimate effects on stream temperatures.

- Question – Eastside buffer requirements are different than westside requirements, with eastside requirements as little as 65 feet in some cases. Should we consider funding additional microclimate research specifically for eastside scenarios? Answer – Danehy's research shows that a 10-m buffer will provide effective protection in terms of stream temperatures related to microclimate factors.

- Question - For microclimate, would stream temperatures be better protected by a wider but thinned buffer stand, or a narrower but packed (unthinned) stand? Also, what thinning levels are appropriate? Answer – Regarding stream temperature, those studies have not been conducted yet. And the responses would change over time since harvest. Within buffers, it's important to consider changes to plant structure over time related to thinning (e.g., thinning lets in more sunlight that promotes plant growth in the understory, and the canopy coverage and structure thus change over time); it's often critical to thin a buffer to maintain complexity and promote a multiple layered canopy. For bank stability reasons, we tend not to thin directly adjacent to the stream, and these streamside trees provide effective shade directly over the channel. Regarding appropriate thinning levels, historical conditions in Western Washington and Western Oregon exhibited relatively low density, ranging from 20 to 50 trees per acre (TPA). Thinning to 80 TPA translates to approximately 65 percent effective shade, but again this will change over time. Although you may want higher levels of shade for stream temperature reasons, you do want some solar energy to promote understory growth. A related issue is the appropriate target for down wood; this is currently a controversial issue and requires additional research. But it appears that the region is lacking adequate down wood in decay classes 1 and 2, and we should be promoting recruitment. Again, though, this is for healthy riparian conditions and isn't directly related to stream temperatures.

- Question/Issue – In the Watershed 3 example (i.e., scoured to bedrock reach), how were values for evaporation and convection specifically derived? Answer – Formulas were used from atmospheric sciences books for evaporation and convection, because they are very difficult to measure directly. However, these were an initial first approximation, using microclimatic values from a climate station approximately 500 m away. This summer, Dr. Johnson will be measuring those microclimatic factors on site in order to be able to construct as accurate a heat budget as possible. Wind velocity is certainly an important factor to consider, but overall it's a very difficult pattern to predict.

- Question/Issue – As a recurring theme, why are similar streams warmer on the eastside and how might this relate to microclimate? When other factors tend to be the same – elevation, canopy cover, etc. – we see warmer streams on the eastside. Could warmer air temperatures be a factor? Answer – It could be that initial temperatures of groundwater are warmer on the eastside, that there is increased solar inputs due to riparian vegetation densities and high grazing densities, and that the length of time of exposure to surface environmental factors is longer in the eastside streams.

- Question – In one of the studies cited, shading at 1 m above the ground was identified as providing coverage greater than 100 percent; what field method was used? Answer – In our studies, we stratify our canopy coverage measurements, accounting for the herbaceous/forb layer, the understory, and the canopy. Cumulative coverage totals can therefore be larger than 100 percent. Also, in the canopy, overlapping limbs increase the coverage. For example, to achieve (i.e., reduce to) a 40 percent shade level in an alder stand, you'd have to remove 90 percent of the stems.

- Recommendation – Echoing concerns rose in the February Workshops, CMER should consider evaluating the correlation between effective shade and densiometer measurements. Densiometers measure cover, not effective shade, and the correlation might not be very good, especially at the high and low ends of the readings. A microclimate-related study should be considered to further address this uncertainty.

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Appendix A
Workshop Attendance

Attendance - Microclimate Workshop

May 1, 2001

Name	Affiliation	Email
Mark A Hunter	WDFW	huntemah@dfw.wa.gov
L.N. 'Pete' Peterson	Upper Columbia United Tribes	lpet2@aimcomm.com
Sherri Johnson	OSU	johnsons@fsl.orst.ed
Bob Danehy	BCC	bdanehy@bc.com
MAURICE Williamson	WFFA	general@williamsonconsulting.n
Joe Weeks	WADNR	joe weeks @ wadnr. gov
Andrew Kolosseus	Dept. of Ecology	akol461@ecy.wa.gov
Chris Peredney	Dept. of Ecology	chpe461@ecy.wa.gov
Warren Scarlett	DNR	wscc490@WADNR.GO
John Summers	DOE	Josu461 e ECY. WA. GOV
David Roberts	DOE	DROB461@ ECY. WA. GOV
Jim Matthews	Yakama Nation	jmatthews@yakama.com
Martha Jensen	USFWS	martha_L_jensen@fws.gov
Jim Muck	USFWS	jim_muck@fws.gov
Joe Polos	USFWS	joe_polos@fws.gov
Bill Ehinger	D of Ecology	wehi461@ecy.wa.gov
Millard S. Deusen	WDFW	deusemsd@dfw.wa.gov
Mike Mraki	NRC-ITT Ltd	agrofor1@home.com
LAURA VAUGEOIS	DNR	laura.vaugeois @ wadnr.gov
Heather Shelan	DNR	heather.shelan @ wadnr.gov
Ted Thomas	USFWS	ted_thomas@fws.gov
Shelley Spalding	USFWS	shelley_spalding@fws.gov
Dawn Pucci	Suquamish Tribe	dpucci@suquamish.nsn.us
Terry Jackson	WDFW	jackstbj@dfw.wa.gov
Ken Risenhoover	Port Blakely	KRisenhoover@Portblakely.co
Paul Bakke	USFWS	paul_bakke@fws.gov
Chris Mendoza	USFWS	chris_mendoza@fws.gov
VENICE GOETZ	WA DNR	venice.goetz@wadnr.gov

Attendance - Microclimate Workshop
February 2001

Name	Affiliation	e-mail
Jim Ryan	DNR	jrllu490@WADNR.GOV
MAURICE Williamson	WFFA	williamson consulting.Net
Bob Barnard	WDFW	barnarjb@dfw.wa.g
LN 'Pete' Peterson	Upper Columbia United tribes	lpetz@aimcomm.com
Kari Odden	WWU	oddenk@cc.wwu.edu
JAMIE GLASGOW	WA TROUT	jamie@washingtontrout.org
Ted Thomas	USFWS	ted_thomas@fws.gov
Domoni Glass	GECI	dglass@centurytelne
Shelley Spalding	FWS	shelley_spalding@fws.gov
Steve Toth	consultant	thomtoth@nwlink.com
Jill Silver	Hoh Tribe	jsilver@waypt.com
Dave Schuett-Hames	NWIFC	dschuett@nwifc.wa.g
Jim McCracken	Longview	jmac@longfibre.com
Judy DeLaVergne	US FWS-Wen. Sub [illegible]	judy_delavergne@fws.gov
Maryanne Reiter	Weyco	maryanne.reiter@weyerhaeuser.com
VAUGEOIS	DNR	Laura.Vaugeois@WADNR.g
Terry Jackson	WDFW	jackstbj@dfw.wa.gov
KATE Benkert	FWS	Kate_benkert@fws.g
John Gross	Kalispel Tribe	jgross@knrd.org
Chris Peredney	ECY-HQ	chpe461@ECY.wa.gov
Betsy Dickes	ECY-HQ	bedi461@ecy.wa.gov
Mark Mobbs	QIN	mmobbs@quinault.org
Ash Roorbach	NWIFL	aroorbach@nwifc.wa.gov
Craig Graber	ECY-SWRO	CGRA461@ecy.wa.gov
Mark Hunter	WDFW	~~mah~~ huntemah@dfw.wa.g
GEORGE ICE	NCASI	GICE@wcrc-ncasi.org
Heather Shelan	DNR	heather.shelan@wadnr.gov
Venice Goetz	DNR	venice.goetz@wadnr.gov

Name	Affiliation	E-mail
Steve McConnell	NWIFC	smcconnell@nwifc.wa.gov
MARY RAINES	NWIFC	MRAINES@NWIFC.WA.GOV
Todd Baldwin	Kalispel Tribe	tbaldwin@knrd.org
Dave Schuett-Hame	NWIFC	DSCHUETT@NWIFC.WA.GOV
Pete Heide	WFPA	pheide@wfpa.org
VIRGINIA WAEF	Lummi Wat. Res.	virginian@lummi-nation.bia.edu
Steve Toth	Consultant	thomtoth@nwlink.com
Eric Beach	SEATTLE PUBLIC UTILITY	eric.beach@ci.SEATTLE.WA.US
Jason Walter	Weyerhaeuser	jason.walter@weyerhaeuser.com
John Heffner	Weyerhaeuser	John.heffner@weyerhaeuser.com
Maryanne Reiter	Weyerhaeuser	maryanne.reiter@weyerhaeuser
Brian Fransen	"	brian.fransen@weyerhaeuser.com
Domoni Glass	GECI	dglass@centurytel.net
Blake Rowe	Longview Fibre Co	bsrowe@longfibre.com
Anita Stohr	Ecology	asto461@ecy.wa.com
Stephanie Brock	Ecology	steb461@ecy.wa.gov
Trevor Swanson	Ecology	trsw461@ecy.wa.gov
Dustin Bilhimer	Ecology	dbil461@ecy.wa.gov

Name	Affiliation	e-mail
Steve McConnell	NWIFC	smcconnell@nwifc.wa.gov
Jim Matthews	Yakama Nation	jmatthews@yakama.com
Todd Baldwin	Kalispel Tribe	tbaldwin@knrd.org
Laura Pucci	Suquamish Tribe	lpucci@suquamish.nsn.us
DENNIS SCHULT	WESTERN WATERSHED ANALYSTS	des@clarkston.co
Peter Carr	EDAW	carrp@edaw.com
JASON CROSS	UW / RTI	crossco@u.washington edu
Jean Parodi	WDOE	jpar461@ecy.wa.gov
Blake Murden	Port Blakely Tree Farms	bmurden@portblakely.com
Ken Risenhoover	Port Blakely Tree Farms	krisenhoover@portblakely.c
Andy Ross	Lummi Natural Resources	andyr@lummi-nation.bia
Greg Pelletier	Dept. of Ecology	gpel461@ecy.wa.g
Stephanie Brock	Dept. of Ecology	steb461@ecy.wa.gov
Anita Stohr	Dept. Ecology	asto461@ecy.wa.gov
Dustin Bilhimer	Dept. of Ecology	dbil461@ "
Michelle Stevie	Squaxin IS Tribe	mstevie@squaxin.nsn.u
Marty Ereth	Skokomish Tribe	marty@skokomish.org
David Roberts	Ecology	drob461@ecy.wa.gov
Dave Volsen	WDFW	volsedpv@dfw.wa.gc
Paul Bakke	USFWS	paul_bakke@fws.gov
Joe Hiss	"	joe_hiss@fws.gov
MIKE LIQUORI	IP	Mike.Liquori@ipaper.com
Patricia Olson	Pac. Wat. Institute	ardito1@aol.com
Brian SUGDEN	Plum Creek	bsugden@plumcreek.com
Bill Ehinger	Dept Ecology	wehi461@ecy.wa.gov
Marganne Allen	Or. Dept. Forestry	mallen@odf.state.or.us
Jeffrey Clark	Weyerhaeuser	jeffrey.clark@weyerhaeuser.com
Venice Goetz	DNR	venice.goetz@wadnr.gov
SCOTT Craig	USFWS	Scott_Craig@fws.gov
Jeff Light	Plum Creek	jlight@plumcreek.com
Heather Shelan	DNR	heather.shelan@dnr.wadnr.
Carol Langston	USFWS	carol_langston@fws.gov
charleschesnev	WDNR, FPD	alnusrubra@aol.com

Appendix B
Additional Material – Stream Physics

DIRECT SOLAR RADIATION/TEMPERATURE EQUILIBRIUM
ANSWERS TO KEY QUESTIONS

Dr. George Ice, NCASI

Nine specific questions dealing with direct solar radiation and temperature equilibrium were identified as part of the preparation for the temperature workshop. Answers to those nine questions follow below.

(1) Briefly describe the basic details of the transfer of direct solar energy to flowing surface water and subsequent export of energy via radiation, convection, conduction and flow.

A simple energy balance for the increase in temperature expected for a forest stream accounts for the rates of net radiation (N_r) to the stream, and evaporation (E), convection (H), and conduction (C) inputs and outputs (Brown 1980). The net rate of heat per unit area added to a stream ($\sum H$) is calculated as:

$$\sum H = N_r \pm E \pm H \pm C$$

Note that net radiation can be either positive (input to the stream) or negative (output from the stream) and that all the other terms can also be positive or negative. The total heat added to a stream segment can be calculated as the rate of heat input ($\sum H$) multiplied by the time of exposure (t) and areas of exposure (A).

$$\text{Total Heat} = \sum H * A * t$$

This energy is being transferred to a volume of water (V) that can be calculated from the discharge (Q) and time of exposure (t). The greater the volume of water the less the change in temperature for a given amount of energy input.

$$V = Q * t$$

Finally, these can be combined to determine the change in temperature. Details about transfer of energy from short-wave radiation to thermal energy are provided in the answer to question 2 below. Water elements are also subject to advective (flow) transport and exchange. There is flow downstream and into areas of solar exposure and there may be significant exchange between the channel and hyporheic zone. These relationships will be discussed in greater detail in the presentation.

(2) How does solar angle influence the absorption of energy at the water's surface?

While long-wave radiation is rapidly absorbed at the surface of water, water is relatively "transparent" to short-wave radiation. Larson and Larson (1996) note that about 95% of visible light will penetrate water to a depth of 3 feet and 75% will penetrate to 30 feet. However, Adams (NCASI 2001) shows that most of this energy is absorbed by the channel bottom. Because of the water's much large convective transfer coefficient, most of the solar energy goes from the streambed to the stream water. This makes the effective absorptivity of the stream to short-wave radiation very high. However, angle can greatly influence the short-wave reflectivity coefficient (albedo) changes with angle of the sun in the horizon. So for a solar angle of 60°, such as would occur at solar noon close to the Summer Solstice, only 5% of short-wave radiation is reflected off the water. For a moderate solar angle, such as 30°, still only 10% of short-wave solar radiation is reflected. At a low solar angle of 5°, there is a 60% reflectance of short-wave radiation.

Note: The next five questions deal with direct solar radiation and the role of vegetation in buffers. Many of these questions are addressed, if not completely answered, by a shade study underway by the Oregon Department of Forestry (ODF). ODF is using hemisphere photography to measure shade in buffers across Oregon (Liz Dent, Oregon Department of Forestry, personal communication).

(3) Do asymetrical buffers (e.g.., riparian buffers stacked on the south side of the stream) or one-sided buffers provide water temperature protection? What recent research has occurred on the subject? Is there any ongoing research on the subject?

From a theoretical perspective, an east to west or west to east flowing stream will receive all of its shade from the south bank. While reflected short-wave solar radiation and long-wave radiation inputs may be attenuated by vegetation on the north side of the stream, the reduced inputs tend to be balanced by the reduced outputs. There is scant empirical evidence to support this theoretical perspective. Zwieniecki and Newton (1999) measured stream temperature through three units with 12 m screens of shrubs or trees left only between 120 to 270° or within the arc of the sun between 9 A.M. and 6 P.M.. Zwieniecki and Newton reported that "...to the north of each stretch of open water, there was no cover except where trees or shrubs along the south exposure of another reach provided cover because of the meandering of the stream." The average maximum temperatures of these streams did not change appreciably across three 800 m clearcuts where buffers were only left on the south side of the stream. The ODF shade study has been assessing whether one-sided buffers are effective. For coastal Oregon preliminary data suggests that the north-side shade variables are not significant as far a providing shade. Preliminary data from another region finds north side vegetation does contribute to shade but less than south side vegetation. Stream size and overhanging vegetation may be confounding factors where vegetation on the north side of a stream actually contributes to the canopy on the south side of the stream.

(4) Do conifer-dominated riparian stands provide better protection of surface water temperatures than alder stands of a comparable age? How significant is the difference? Is there field research on this issue?

Again, as with all of these questions, there is scant empirical information. Which stand type provides greater shade at a comparable age depends on whether one is looking at younger or older stands. Alder is a very vigorous pioneer species. In the Alsea Watershed Study, riparian alder had grown 16 to 20 ft after three years, providing increasingly abundant shade. Older alder stands (40 to 80 yrs) began to breakup, creating more openings in the canopy. The ODF shade study is comparing hardwood, conifer, and mixed stand types and preliminary analysis shows little difference in shade between these stand types. However, there appears to be some evidence that there is more of a difference in shade between older unharvested conifer stands and younger conifer stands than is seen for older hardwood stands and younger, managed hardwood stands. Sam Chan with the USDA Forest Service reports that a Coastal Oregon Productivity Enhancement Project did look at leaf area index (LAI) and available radiation through riparian canopies. Data from the study is not yet fully analyzed. Conifer stands of about 40 yrs may have slightly higher LAI (6) than a 50 yr old alder stand (5). More important than LAI in this case was the difference in canopy architecture, with the alder stands having fewer lower branches. This translates into approximately 5% of available energy passing through the conifer stand compared to as much as 16% for the alder stand. Chan speculated that younger alder stands might have greater LAI and more lower branches.

(5) Does multiple layered shading resulting from a tree canopy and understory brush provide better shade protection than a single layer of shade? Are there any field studies that document a difference in the surface water temperature response?

Again, the ODF shade study is attempting to address this question by taking pictures with the hemisphere camera at 3 ft (brush contribution to shade included) and 10 ft heights above the stream (above brush shade contribution). However, there is some concern that the data at 10 ft does not completely eliminate the contribution of brush/understory to shade. Shade-producing understory plants, such as salmonberry and vine maple, can exceed the 10 ft height, especially when they are on steep slopes. Conceptually, understory brush can contribute to shade. The differences between the 3 and 10 ft measurements do not appear to be large.

(6) Does reflected solar radiation (i.e., radiation reflected through the riparian understory from an upslope clearcut) result in a measurable increase in solar radiation and/or water temperature?

It is unlikely that significant solar radiation can be reflected from an adjacent clearcut unit off riparian vegetation and into the stream. Reflection of solar radiation will be greatest when the radiation angle is shallow. This is also when energy is low. Only a small portion of the clearcut unit is likely to even have the potential to contribute at any time. Reflected radiation hitting the riparian vegetation can be adsorbed or reflected. Because leaf architecture is relatively random, only a portion of the re-reflected energy has the potential to impact the stream, and if it is at a shallow angle it may be reflected once again.

(7) Current Washington State forest practices requires the use of a hand-held convex spherical densiometer to measure shade from all points of the compass. Is there better equipment or field methods to measure the temperature effects of solar radiation to the water's surface?

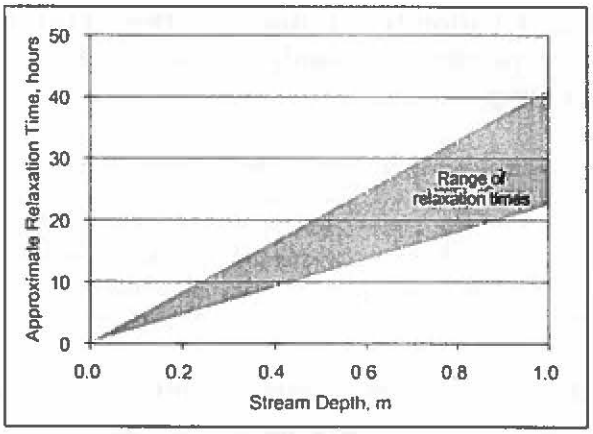
Hemispherical photography methods are becoming an increasingly popular research approach, with a presumption that they provide more realistic estimates of energy attenuation. Although there have been some limited comparisons between different canopy/shade/energy monitoring methods, there remains uncertainty about whether gains going from easy spherical densiometer methods to more costly hemispherical photography can be justified. Angular canopy density measures record the shade at the most critical times for stream heating and might be better developed. We would propose that a study be undertaken to compare the results of these methods to integrated direct radiation measures.

(8) Explain the physical processes by which flowing surface water reaches equilibrium with the surrounding air temperature. Does flowing surface water ever completely recover from an upstream heat source? If so, over what stream channel distances do we normally see this recovery to equilibrium conditions?

If a stream reach is exposed to direct solar radiation through an open reach and experiences an increase in temperature and then re-enters a shaded reach will it come back to equilibrium with the environment it is experiencing? The answer, of course, is yes; but there are different mechanisms and rates involved for different stream systems. Adams (NCASI 2001) uses the term relaxation to indicate that this is an elastic response back toward the characteristic stream temperature profile. All the energy processes identified in the energy balance are at work during both cooling and warming. There is consensus that these processes are slower for cooling than warming. While evaporative cooling, conductance with the streambed, long-wave re-radiation, and sensible heat exchange with the atmosphere can all be operating, very rapid temperature recovery, especially for small streams, occurs as a result of subsurface water exchange.

(9) How do flow volume, water velocity, channel shape/depth, substrate characteristics, and other variables influence the channel distance it takes to return water to equilibrium conditions?

If any stream continues under the same conditions long enough it will come into (near) equilibrium with the surrounding environment. Theoretically, it may not completely come back but the difference will be too small for our methods of detection and certainly not biologically significant. This equilibrium occurs rapidly for a shallow stream and takes longer for a deeper stream. The following figure is an example of a simulation of relaxation from elevated temperature as a function of stream depth. Substrate characteristics can dramatically influence rate of temperature recovery. In the H. J. Andrew Experimental Forest example, we find that complete recovery is occurring in a 300 m reach, largely due to exchange of hyporheic water and extended travel times.


Approximate Relaxation Time, hours
50
40
30
20
10
0
0.0
0.2
0.4
0 6
0 8
1.0
Stream Depth, m
Range of relaxation times

HOW DIRECT SOLAR RADIATION AND SHADE INFLUENCES TEMPERATURE IN FOREST STREAMS AND RELAXATION OF CHANGES IN STREAM TEMPERATURE[1]

Dr. George Ice[2]

Abstract: Temperature is an important property of matter and that changes in response to energy inputs and outputs. In streams, increased direct short-wave solar radiation is the primary energy input that causes elevated stream temperatures in the summer following removal of shading vegetation. Riparian vegetation overhanging the stream or near enough and high enough to cast a shadow on the stream represents an important tool for maintaining stream temperatures. Most measures of canopy cover are only approximations of shade since the effect of obstructing vegetation changes with position of the sun in the sky. Crude estimates of maximum potential increases in temperature are possible by considering only changes in direct short-wave radiation. Artificial shading experiments and watershed studies can be used to interpret the role of direct solar radiation. However, streams are subject to other energy fluxes, and these account for sometimes very rapid cooling of streams or relaxation from increased temperatures. Other things being equal, shallow streams, exposed to full sunlight, will experience greater increases in temperature than deeper streams. But, relaxation from increased water temperatures will occur more rapidly for shallow streams than for deep streams. Results from Timber/Fish/Wildlife-sponsored monitoring of stream temperature response are interpreted based on our understanding of stream heating and cooling processes.

1.0 INTRODUCTION

The water temperature of a stream fluctuates with changing energy inputs and outputs to the stream. One of the most important energy sources for streams is direct solar radiation. In this paper we cover four main topics. First, we review the basic energy balance for streams and discuss the geometry that influences direct solar radiation inputs to streams. This involves both the basic astronomical relationship between the earth and sun and a review of elementary thermodynamics. Second, we provide a more detailed discussion of forest streams and the role of vegetation in attenuating direct solar radiation. This will include a discussion of mechanisms for energy or heat transfer from direct solar radiation to water. A few examples of experiments that test the influence of shade at the watershed scale will be used to demonstrate the importance of shade in influencing stream temperature. Third, we will describe in more detail how riparian vegetation influences direct solar radiation. This will include a discussion of methods used to measure shade from riparian forest vegetation. Some artificial shading experiments will be reviewed. Finally, we will describe how local increases in temperature are attenuated or relaxed as they move downstream. This will again involve both a theoretical discussion and field examples. Our summary will answer some paradoxes about stream temperature as well as

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[1] Cooperative Monitoring, Evaluation and Research (CMER) Workshop: Heat Transfer Processes in Forested Watersheds and Their Effects on Surface Water Temperature, Lacy, Washington, February 2000

[2] Principal Scientist, National Council for Air and Stream Improvement, Inc. PO Box 458, Corvallis, OR 97339

interpret the results of Timber/Fish/Wildfire-sponsored monitoring. A detailed discuss of the energy balance and stream heating in Washington is provided by Sullivan et al. 1990.

2.0 STREAM HEAT BALANCE AND THE ROLE OF DIRECT SOLAR RADIATION

Here we describe input of direct solar radiation to forest streams and review the astronomical geometry and thermodynamics that can be used to explain stream temperature fluxes.

A Quick Introduction to Thermodynamics

Thermodynamics is the study of energy changes accompanying physical and chemical processes (Sawyer and McCarty 1967). The focus of our discussion is on stream water temperature so what is the molecular or thermodynamic explanation for different temperatures? **Temperature** is related to molecular "translational energy." A material at a higher temperature has more molecular motion or vibration than a material at lower temperature. **Heat** "...is that form of energy which passes from one body to another solely as a result of a difference in temperature" but it is not the only form of energy transfer (Sawyer and McCarty 1967). There is also **radiant energy** or **radiation**.

All materials at temperatures greater than absolute zero radiate energy. The amount of energy radiated is in direct proportion to the fourth power of the temperature of the object. Therefore, radiated energy increases greatly with increasing temperature. The peak wavelength emitted by a body is inversely proportional to the temperature of the emitting body. The sun, at tremendous temperatures (≅6,000 K), emits enormous amounts of energy and most of it is at shorter wavelengths. Radiation less than 4.0 μm is classified as **short-wave solar radiation**. Objects on earth are emitting at much lower temperatures and therefore, longer wave lengths. Radiation greater than 4.0 μm is often called **long-wave terrestrial radiation** (Black 1991).

Different forms of energy can be converted back and forth, so short-wave radiation can heat a cooler body and be re-radiated back into space as long-wave radiation. Heat resulting from input of radiation can also be transferred to another object. For example, we can calculate the change in energy in water (ΔE) using the equation:

$$\Delta E = q - w$$

where q is heat or energy flowing into or out of the system and w is work (expansion) done by the system. But there will always be a balance in the total energy, despite changes in forms. The widely recognized **first law of thermodynamics** is that **energy can neither be created or destroyed**. This means that inputs and outputs of energy (and work) to a stream must be balanced by the ΔE of the water or the change in temperature.

The **second law of thermodynamics** is that **all systems tend to approach a state of equilibrium**. This equilibrium is achieved through energy transfer. Energy or heat can be transferred by three general processes:

- **conduction**, which involves the transfer of molecular kinetic energy through contact between objects.

- **convection**, which is the physical movement of more energetic molecules in a liquid or gas (best represented by the rising of hot water from the bottom of a pan on a stove).
- **radiation**, which involves transfer of energy across a space, and is simultaneously described as a particle or quantum of energy and also an energy wave.

The magnitude of difference between the states of objects in a system is the driving factor in the rate at which this equilibrium is approached. So, other things being equal, the greater the difference in temperature between two objects, the more rapid the change in each object as they move toward equilibrium.

We can also consider **advective** heat inputs and outputs. This is transport of water at an existing temperature in or out of a system. So cool groundwater can move into a stream while water that has been exposed to radiation and warmed can move downstream or into the connected subsurface water or **hyporheic zone**.

Different materials have different characteristics that influence energy uptake and their temperature response. **Albedo** is the amount of radiation reflected compared to the incident input, and is usually expressed as a percent. **Specific heat** is the heat required to raise one gram of a material one degree centigrade. The **calorie** is one unit of measure for energy. It is the energy needed to raise the temperature of one gram of water one degree centigrade. Therefore, by definition, the specific heat of water is 1 calorie. The British Thermal Unit (**BTU**), is the heat needed to raise one pound of water one degree Fahrenheit, which is equivalent to 252 calories.

Net changes in energy to water can be partitioned into either **sensible heat** (change in temperature of water) or **latent heat**. Latent heat is the energy that goes into the increased kinetic energy to change the phase of a material (e.g. the energy required to melt ice (solid to liquid) or evaporate liquid water (liquid to gas)). **Heat of fusion** is the energy required to melt ice to water, about 80 calories per gram. **Heat of vaporization** is the energy required to evaporate water at its boiling point, or about 540 calories per gram.

We use the second law of thermodynamics to measure the temperature of water. Because objects in contact will move toward equilibrium, a small, highly conductive device, placed in water will rapidly reach the temperature of the water. Temperature can be measured using a physical response to changing temperature, like expansion of mercury, or increased electrical conductance. There are three principle scales for measuring temperature (Lynds 2001). The most commonly used scale in the United States is the Fahrenheit scale, developed by Gabriel Fahrenheit for mercury thermometers in 1724. The set points for this scale were 0°F for the temperature of a sea salt, ice, and water bath and 96°F for a healthy man. With some slight modifications, this makes the freezing point for water 32°F and the boiling point 212°F. The centigrade temperature scale was designed to have one hundred steps between the freezing point for water (0) and the boiling point for water (100). The centigrade scale was slightly modified to create the nearly equivalent (for our purposes) Celsius scale (°C). Another scale used by physicists is the Kelvin scale. "Absolute zero" is set in this scale as the thermodynamic temperature at which molecular motion essentially stops as does release of radiant energy. Conversions between scales are:

$$K = {}^{\circ}C + 273$$

$$°F = 9/5(°C) + 32$$

Some Simple Astronomy About the Earth and Sun

There is general agreement, even between the stakeholder groups in Washington, that the Earth orbits the sun. This path is an ellipse with the Earth slightly closer to the sun at certain times. Many people assume that proximity to the sun determines the seasons. However, the change in seasons is mainly a result of the tilt of the Earth related to the sun (Figure 1). The Earth's axis tilts away from the sun in the winter and toward the sun in the summer (Northern Hemisphere perspective) (Black 1991). Because the sun is so far away from the earth, short-wave solar radiation rays are essentially parallel. In the winter, with the Earth's axis pointing away from the sun, the sun appears for a shorter time and at a lower angle on the horizon.. The effect on short-wave radiation is to make the rays less perpendicular to the surface thus reducing their energy per unit area (intensity of radiation varies with the cosine of the angle above the horizon). The tilt away from the sun also causes the rays to travel farther through the atmosphere, resulting in more reflection. At summer solstice (June 21) the tilt is 23.5° toward the sun and at winter solstice (December 22) it is 23.5° away from the sun. The sun is directly over the equator at the equinoxes (March 21 and September 22).

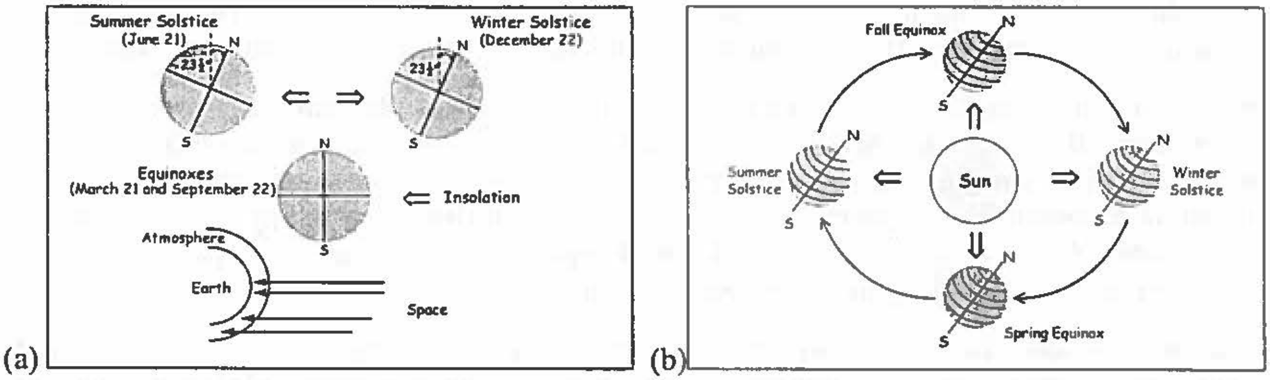

Figure 1. Geometry of Radiation Relationships (Based on Black 1991)
(a) Earthcentric, (b) Suncentric

Latitudes represent the angular declination away from the equator measured on the meridian (Figure 2), so at solar noon on the summer solstice, the sun is directly overhead forests at latitude 23.5° N. At Olympia, 47° N, the sun will never be directly overhead. The highest it can ever get above the horizon is 66.5° (90° - 47° + 23.5°). Can you calculate the lowest angle of the year for the sun at solar noon for Olympia? Aspect and slope angle can also influence solar radiation. South-facing slopes and streams in the Northern Hemisphere above 23.5° N will receive greater energy than north facing slopes and streams. For steep slope angles the difference between north- and south-facing slopes can be important. However, most stream gradients are slight and therefore, this effect generally can be disregarded. Generally more important than the slope of the stream is the steepness of the adjacent topography and the flow direction in relation to shade. We will discuss these later in this paper.

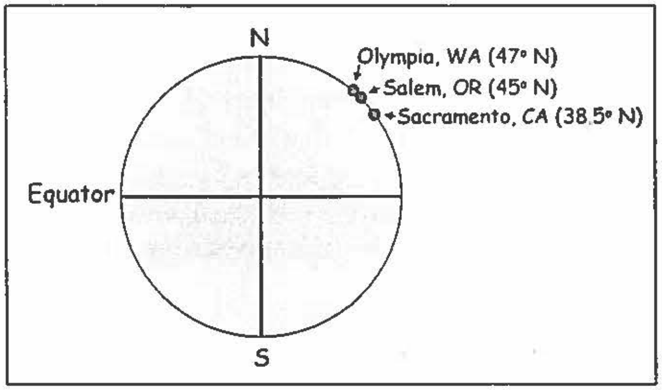

Figure 2. Angular Declination Away from the Equator

A Simple Energy Balance and the Logic of the Brown Equation

A simple energy balance for the increase in temperature expected for a forest stream accounts for the rates of net radiation (N_r) to the stream, and evaporation (E), convection (H), and conduction (C) inputs and outputs (Brown 1980). The net rate of heat per unit area added to a stream (ΣH) is calculated as:

$$\Sigma H = (N_r) \pm (E) \pm (H) \pm (C)$$

Note that net radiation can be either positive (input to the stream) or negative (output from the stream) and that all the other terms can also be positive or negative. The total heat added to a stream segment can be calculated as the rate of heat input (ΣH) multiplied by the time of exposure (t) and areas of exposure (A).

$$\text{Total Heat} = (\Sigma H) * A * t$$

This energy is being transferred to a volume of water (V) that can be calculated from the discharge (Q) and time of exposure (t). The greater the volume of water the less the change in temperature for a given amount of energy input.

$$V = Q * t$$

Finally, these can be combined to determine the change in temperature:

$$\Delta T = (\Sigma H * A)/Q$$

Brown (1969) used this relationship to develop the Brown Equation to predict the maximum heating of a stream through a clearcut unit. If discharge (Q) is in units of cubic feet per second (cfs), stream surface area exposed (A) in units of square feet (ft^2), and energy input rate (ΣH) in units of $BTU/ft^2 min$, then the temperature change (ΔT) can be calculated in degrees Fahrenheit by converting cfs to pounds per minute (lbs/min). This results in the BTUs of heat added per pound of water. Remember that the definition of BTU is the energy needed to raise one pound of water one degree Fahrenheit. The conversion factor from cfs to lbs/min is 0.000267, resulting in the equation:

$$\Delta T = ((\sum H * A)/Q) * 0.000267$$

Brown further simplified the calculation of the maximum change in temperature. He assumed all the energy input was from direct solar radiation, that cloud cover or shade did not attenuate the maximum solar radiation, and that potentially important heat loss processes, such as evaporation or sensible heat exchange, do not occur. Figure 3 (Brown 1980) provides the direct short-wave solar radiation for different midday solar angles and travel times through an exposed reach.

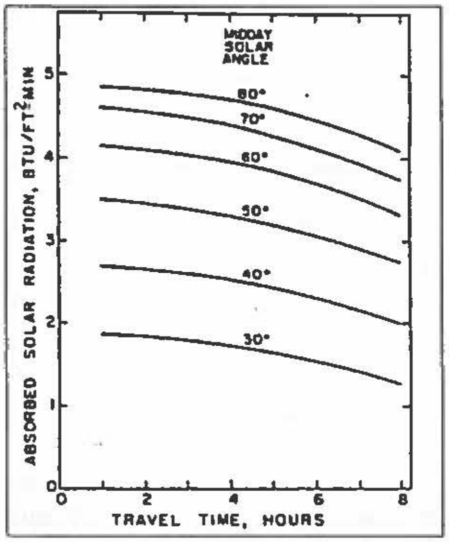

Figure 3. Average Net Absorbed Solar Radiation

3.0 A CLOSER LOOK AT FOREST STREAMS AND DIRECT SOLAR RADIATION

The Brown Equation was designed to provide an envelope on the maximum increase in temperature possible when a stream goes from completely shaded (no energy input) to fully exposed (maximum direct short-wave radiation). It is now appropriate to look more closely at forest streams and how direct solar radiation heats streams. Much of the following material is excepted from the *Primer on the Physics of Forest Stream Temperature* prepared by Dr. Terry Adams for NCASI (2001).

Solar Radiation

In the Brown Equation it is assumed that short-wave solar radiation is direct and unimpeded. In reality, there are a number of potential pathways (Figure 4). Short-wave solar radiation can be direct or it can be partially obscured by clouds and it can be scattered by the atmosphere. Shading can occur from riparian forest vegetation, live and dead material across the stream, and topography. The actual flux of direct and indirect solar radiation will depend on the orientation of the stream, the degree of shading, and the weather. The riparian canopy will be most effective for smaller, narrower streams, and less so for broader streams. Perhaps this is one of the reasons some have argued for narrower buffers on wider streams (Kahl 1996).

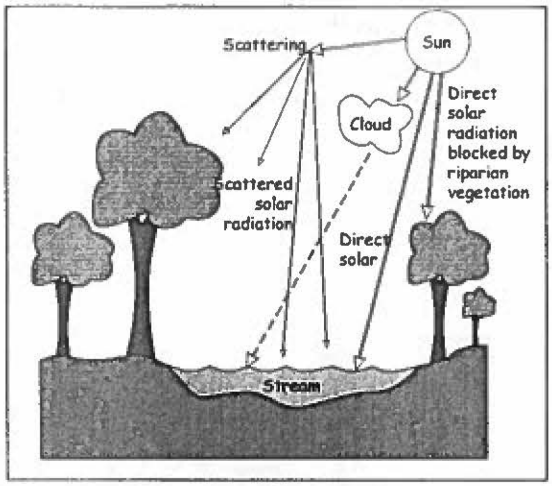

Figure 4. Solar Radiation Pathways

The degree to which a stream is exposed to the sun can be measured and expressed in a variety of ways. These include canopy cover measures such as those collected using spherical densiometers and visual estimates of shade. We will discuss these in more detail later. Because streams tend to be mostly in direct sun or in deep shade, rather than in dappled sunlight, Adams (NCASI 2001) suggests that a parameter that allows the sun to be either "on" or "off" can be used. In this paper we use a parameter of the view factor of the stream for the sky or more commonly called the view-to-sky (Fwsky). Fwsky can be thought of as the average view of the sky from the water for the entire stream surface (Figure 5). When Fwsky is equal to 1 (or 100%) then the stream is exposed to the sun all day without any attenuation of direct solar radiation.

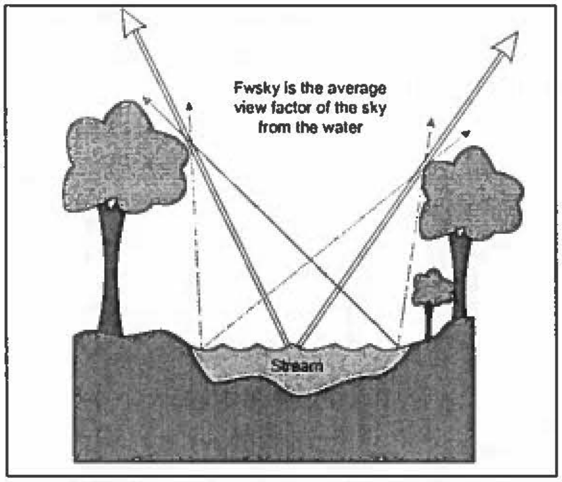

Figure 5. View Factor of the Stream for the Sky

For a north-south flowing stream, the stream sees the sky through a half angle that is equal to Fwsky times 90°, and the stream is only exposed when the sun is in this half angle (Figure 6). The sun angle and the intervening foliage reduces the effectiveness of vegetation away from the stream bank as shade for the stream. As the sun rises each day the stream initially does not see the sun at all, then it is partially exposed to the sun, and finally it is in full sun. The reverse pattern occurs as the sun sets. A reasonable estimate for Fwsky would be the fraction of the day during which the stream fully or partially sees the sun as it is rising and it is setting.

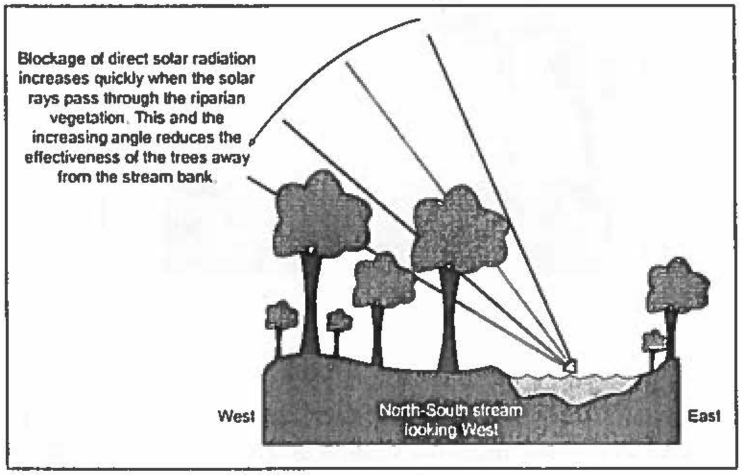

Figure 6. Riparian Shade for a North-South Flowing Stream

Figure 7 shows a simulation of how Fwsky affects direct solar radiation during the day for a north to south flowing stream. When the stream is unshaded (Fwsky = 1.0) the stream is exposed to direct short-wave solar radiation all day. Intensity of radiation varies as the cosine of the sun's angle to the stream surface. As shade is increased, the midday intensity, when the sun is overhead, remains the same, but the solar flux is cut off at some angle due to the riparian vegetation. When the stream is heavily shaded (Fwsky = 0.1) the stream is briefly exposed to the intensity of the midday sun and then is cut off for the rest of the day. Of course this assumes that the vegetation does not overhang the stream. If vegetation does overhang the stream then some attenuation of solar input at midday will also occur.

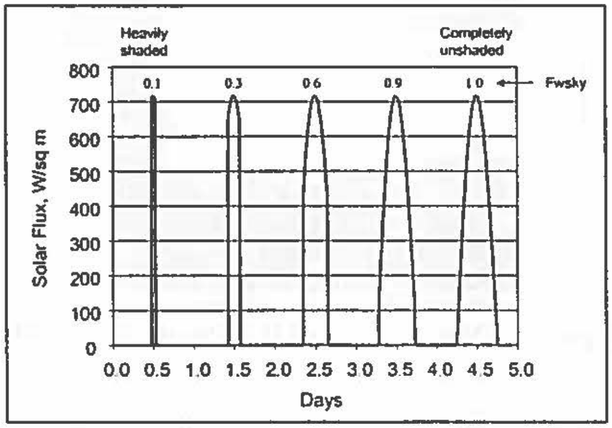

Figure 7. Impact of Fwsky on Solar Radiation Flux

For an east-west flowing stream (Figure 8), the riparian vegetation on the north bank does not block direct short-wave solar radiation. It can reduce energy input from scattered solar radiation, but when it does it reduces heat loss from the stream to the sky. This is nearly a direct trade-off with a net neutral effect. In northern latitudes (above 23.5°N), the riparian vegetation to the south can potentially block the sun nearly all day while the vegetation to the north provides virtually no blocking. Although the sun rises slightly north of east and sets slightly north of west at Summer Solstice, it is only in the north when solar energy inputs are very low.

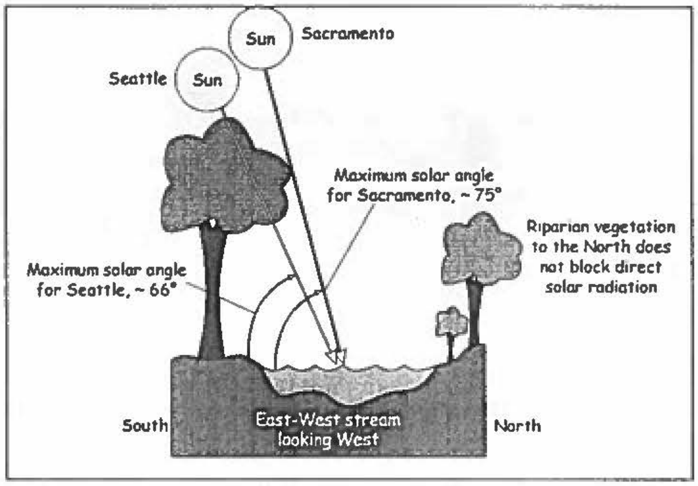

Figure 8. Peak Solar Angle for an East-West Flowing Stream

Figure 9 shows how the total short-wave radiation input varies as the amount of shade decreases (north-south flowing stream). Solar radiation is expected to be zero when the stream is fully shaded at Fwsky = 0. Because small views-to-sky still expose the stream to short-wave radiation at the midday when energy rates are the greatest, there is a disproportionate increase in energy input compared with increasing view-to-sky. At 20% view-to-sky the stream is being exposed to about 30% of the maximum short-wave radiation input. The short-wave radiation input increases to its maximum for the specific location as the shade decreases when Fwsky = 1.0 (full exposure).

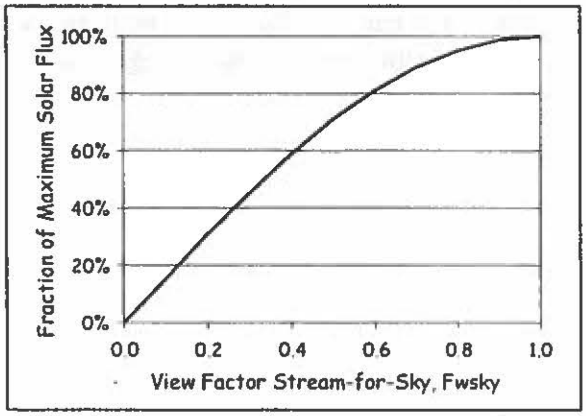

Figure 9. Impact of Fwsky on Solar Radiation Flux

Stream water is not effective in absorbing short-wave radiation, but the streambed surface absorbs it with high efficiency (Figure 10). The energy from short-wave radiation adsorbed by the streambed splits between the water and streambed. Because water has a much larger convective transfer coefficient, most of the solar energy goes to the water. This makes the effective adsorptivity of the stream for short-wave radiation high.

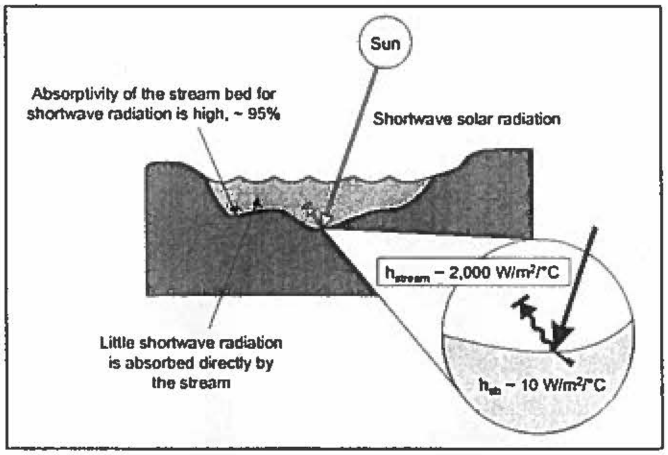

Figure 10. Solar Radiation Transfer to the Stream

Short-wave reflectivity coefficient (albedo) changes with angle of the sun in the sky (Lee 1980). So for a solar angle of 60°, such as would occur at solar noon close to the Summer Solstice, only 5% of short-wave radiation is reflected off the water. For a moderate solar angle, such as 30°, still only 10% of short-wave solar radiation is reflected. At a low solar angle of 5°, there is a 60% reflectance of short-wave radiation.

Some of the other heat processes influencing stream temperature we should also be aware of are long-wave radiation exchange (Figure 11), heat flux due to evaporation (Figure 12), convective heat exchange with the air (Figure 13), and conductive heat exchange with the streambed (Figure 14). These are explained more fully by Adams (NCASI 2001). While direct solar radiation dominates as the process of concern for change in stream temperature, these other stream processes become increasingly important as the stream temperature is elevated and the length of the assessment increases. Mixing and replacement of water with cooler groundwater or tributary inputs is another important process that can rapidly reduce peak temperatures downstream. This will be discussed in the section on maximum temperature relaxation.

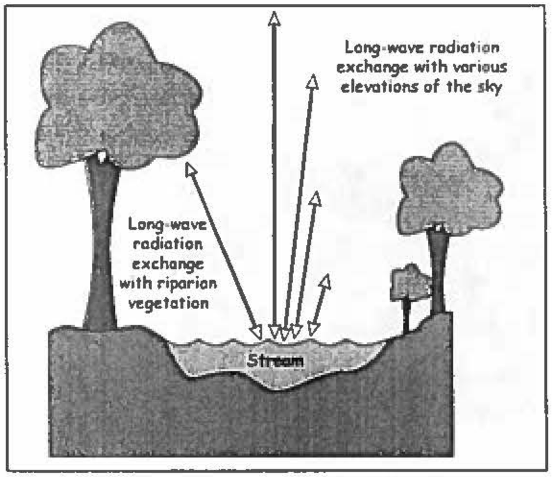

Figure 11. Long-wave Radiation Exchange

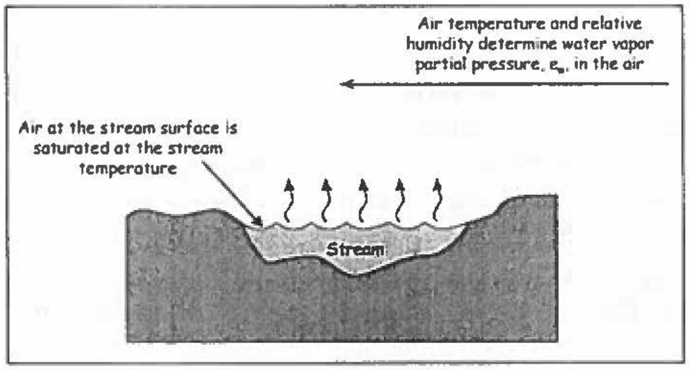

Figure 12. Heat Flux Due to Evaporation

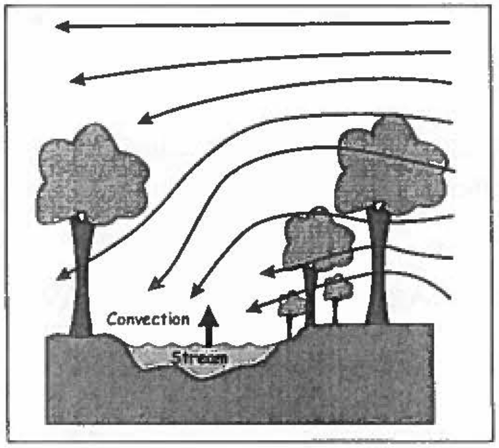

Figure 13. Heat Flux Due to Convection

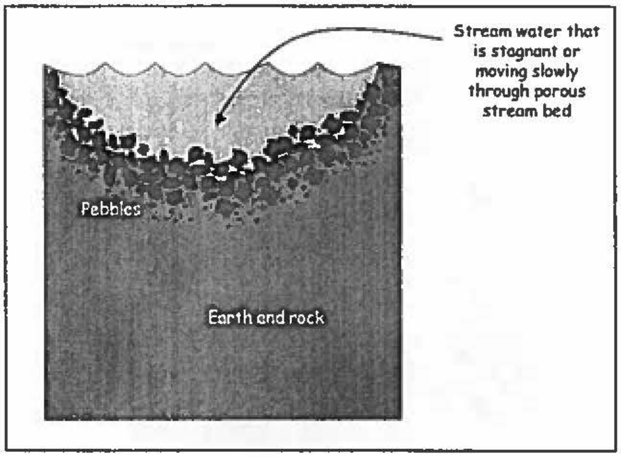

Figure 14. Conductive Heat Flux to a Pebbled Stream Bed

Alsea Watershed Study

The Alsea Watershed Study remains one of the classic experiments testing the role of riparian vegetation in minimizing stream temperature response to harvesting. Three watersheds were calibrated and then one was nearly completely clearcut, a second patch cut with buffers left on the mainstem reaches, and a third remained as a control watershed. Recording thermographs were used to measure stream temperature. Locations and number of recording thermographs varied over the years. Moring (1975) reported that "...in most years prior to 1969, six units were positioned along Needle Branch, eleven units were placed along Deer Creek, and one unit was located at the stream gauging station in Flynn Creek." Temperature monitoring stations changed after 1969 to two units in Deer Creek, six units in Needle Branch, and one unit in Flynn Creek.

Prior to harvesting, the three Alsea Watershed Streams had stream temperature patterns that were very similar (Table 1). Annual mean water temperatures recorded during the pre-logging period were 9.7°C, 9.6°C, and 9.6°C, respectively, for Flynn Creek, Deer Creek, and Needle Branch. Diurnal fluctuations were similar for these three streams. Minimums and maximums recorded were 7.2 to 16.7°C for Flynn Creek, 6.7 to 16.1°C for Deer Creek, and 6.7 to 16.1°C for Needle Branch.

Table 1. Comparison of Water Temperatures (°C) of the Alsea Watershed for Pre-treatment (1959-1965), Post-treatment (1966-1973), and NAWS[a]

	Flynn Creek			Deer Creek			Needle Branch		
	Pre	Post	NAWS	Pre	Post	NAWS	Pre	Post	NAWS
Maximum Di-Flux	3.3	3.3[b]	2.7	5.6	5.6[a]	4.1	4.4	15.6	2.7
Maximum	16.7	15.0	16.1	16.1	17.8	16.7	16.1	26.1	16.1

[a] New Alsea Watershed Study (NAWS) begun in 1989 to assess long-term hydrologic recovery

[b] pre-treatment maximum diurnal fluctuations not exceeded in post-treatment years (Moring 1975)

Following logging, Deer Creek and Needle Branch both showed changes. However, those changes were dramatically larger for Needle Branch, which was without the riparian buffer provided in the Deer Creek watershed. Studies by Brown and Krygier (1970) found maximum diurnal fluctuations during 1965 (prior to harvesting and site preparation in Deer Creek and Needle Branch) of 3.3°C, 5.6°C, and 4.4°C respectively, for Flynn Creek, Deer Creek, and Needle Branch. In 1967, after harvesting, Deer Creek had an increase in maximum stream temperature of 1.7°C above the pre-treatment maximum. The maximum diurnal temperature fluctuation of 5.6°C observed in 1965 was not exceeded in 1967. In contrast to these modest changes, Needle Branch experienced large maximum stream temperature increases and increases in diurnal temperature changes. In 1967, at one upstream gage on Needle Branch, a maximum temperature of 29.5°C was measured (15.6°C increase over the 1965 maximum for the same station).

Harvesting and site preparation had both immediate and more prolonged effects on stream temperature. Prior to harvesting (1959 through 1965), monitoring at the gauging station on Needle Branch had never shown a stream temperature greater than 16.1°C (August 1961). In 1966, after harvesting but before site preparation, Needle Branch at the gauging station had a maximum stream temperature of 22.8°C. In 1967, following burning and removal of debris in the stream channel, the stream temperature maximum at the gauging station was 26.1°C (July). A maximum of 30°C was observed in the upper reaches of Needle Branch (Brown and Krygier 1970). Deer Creek had a pre-harvest maximum of 16.1°C at the gauging station in August of 1961. Maximum temperatures observed in 1966 and 1967 were 16.7°C and 17.8°C, respectively. In comparison, Flynn Creek had a pre-harvest-period maximum stream temperature of 16.7°C (August and September 1961) but experienced a maximum temperature of only 14.4°C and 15.0°C in 1966 and 1967, respectively. Figure 15 (Moring 1975) shows the temperature pattern of the days of annual maximum temperatures for an upstream Needle Branch monitoring station, before and after treatment, compared to the temperatures observed for Flynn Creek. It is clear that harvesting of the forest canopy in Needle Branch opened up the stream to increased solar radiation and warming. The prescribed burn and stream clean-up further exposed Needle Branch.

Perhaps the most dramatic demonstration of the role of direct solar radiation on stream temperature and the modifying influence of riparian shade is the pattern of temperature response observed in Needle Branch. Recovery in 1973 to nearly the original temperature pattern was accomplished even though the watershed-wide reforestation of the watershed was a decade away. After harvesting and site preparation, most of Needle Branch was seeded to Douglas-fir, but regenerations was poor. By 1973, reforestation on the upper portions of the watershed was mostly lacking. However, riparian alder had grown abundantly during that same time, and resulted in an almost complete recovery of the temperature pattern.

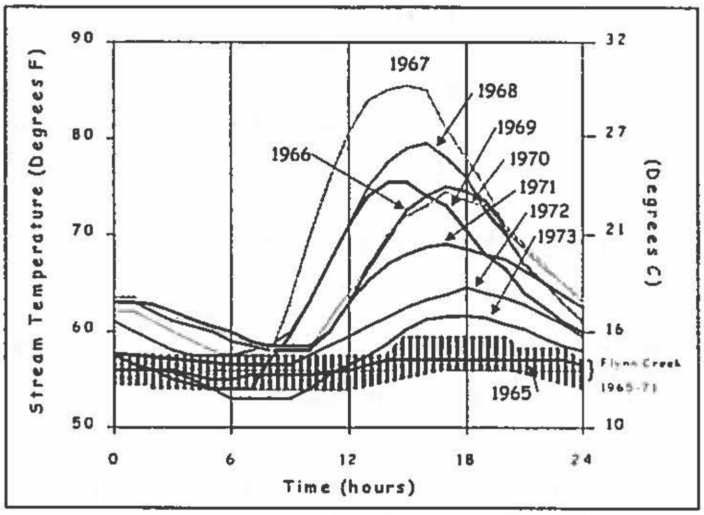

Figure 15. Comparison of Temperature Pattern for the Days of Annual Maximum Temperatures of Needle Branch Creek vs. Flynn Creek, Before and After Treatment

H. J. Andrews Small Watershed Studies

A similar pattern of temperature response was found for Watersheds 1, 2, and 3 on the H. J. Andrews Experimental Forest in the Oregon Cascades (Johnson and Jones 2000). Three small watersheds were monitored, beginning in 1952, as part of a paired watershed study. Watershed 2 served as a control. Watershed 1 was completely clearcut between 1962 and 1966, but no roads were built. All trees, including those in the riparian zone, were harvested and the watershed was broadcast burned in 1966. Watershed 3 had 2.6 km of road built between 1959 and 1961 and 25% of the basin was harvested in three patch cuts. In Watershed 1 a dense stand of alder developed and provided canopy closure 15 years after harvest. Debris flows in 1964 and 1996, mainly resulting from sidecast road failures, scoured the channel of Watershed 3, opening much of the channel to direct solar radiation.

Johnson and Jones (2000) report that Watersheds 1 and 3 had very similar patterns in summer maximum temperatures. Watershed 1 had maximum stream-water temperatures of 23.9°C in 1967 and 1968 and then returned to pre-harvest temperatures by the 1980's. Maximum temperatures for Watershed 3 after patch cutting and debris flows increased to 21.7°C and 23.9°C in 1967 and 1968. Stream temperatures for the unshaded watersheds had much greater diurnal temperature fluctuations. Johnson and Jones noted that "...the largest increases in stream temperature after riparian removal occurred not at the usual time of maximum stream temperatures, but in early summer, which coincides with the timing of maximum solar inputs." Stream temperatures in Watershed 1 returned to normal with recovery of the riparian cover (alder). Watershed 3 continues to show elevated temperatures as a result of both shade loss and changes in channel conditions.

4.0 INFLUENCE OF SHADE FROM RIPARIAN VEGETATION AND OTHER SOURCES ON SHADE

Measures of Shade or Canopy Cover

Canopy cover is the percent of the sky covered by vegetation or topography. Shade is the amount of energy that is obscured or reflected by vegetation or topography (SSMT 2000).

As discussed earlier, it is difficult to provide a single measure of shade. The angle and orientation of the sun on the southern horizon is changing constantly so the shadows created by obstructions also change. However, there are a number of surrogates that have been used to estimate the canopy cover or shade provided by riparian vegetation.

How the Canopy Affects Radiation

In our discussion about view-to-sky we assumed that obscuration meant complete blockage of short-wave radiation. Radiation can be transmitted, absorbed, or reflected through a forest canopy. About 10% of short-wave radiation is estimated to pass through a complete forest canopy with 80% absorbed and 10% reflected (Black 1991). But there are differences between forest types and species. Waring and Schlesinger (1985) found that, "although complex radiation models have been developed to accommodate the heterogeneity of forest canopies..., the most common approach is simply to consider the canopy as accumulated layers of foliage through which solar radiation is absorbed exponentially as the amount of area increases." A first estimate of where hardwood or conifer forests might provide greater or lesser shade for streams might use differences in leaf area index (LAI). Alder (*Alnus rubra*) provides one potential modification to this generalization. Alder is unique in its ability to lean toward openings in the canopy.

Shade does not occur from the live vegetation alone. Topographic shading can occur, particularly, where steep canyon walls surround an east to west flowing stream, resulting in topographic shading from the south bank. Even when topographic shading does not directly provide shade it may raise trees along the bank to provide more effective shade (NCASI 1999). Dead material and slash can also provide shade. In the Alsea Watershed Study, removal of slash from Needle Branch was found to elevate stream temperature. In a study of small, non-fish-bearing headwater streams in Washington, Jackson (2000) found that streams without buffers could not be shown to have increases in temperature, probably because they were buried by slash. In the Elk River Watershed in southern Oregon, McSwain (1987) found that where streams became subsurface due to sediment accumulation, they had lower maximum temperatures. Hagan (2000a) monitored significant reductions in stream temperature for a 300 m reach in a headwater stream in Maine where the channel went subsurface.

View-to-Sky – The view-to-sky estimates the proportion of the sky that can be seen from the stream (Figure 5). It is recommended that this be estimated by averaging readings across the stream. Again, a fully exposed stream has a view-to-sky of 100% or 1.0. If half of the view is obstructed then the view-to-sky is 0.5.

Ocular Estimates of Canopy Closure – Computer-generated cards can be used to calibrate observers so that they can make estimates of canopy closure. The observer attempts to match the observed overhead canopy closure with the image on the card (Figure 16). This approach is used by the National Forest Health Monitoring Program (Lewis and Conkling 1994). This same method is provided in the *Forestry Handbook* (Wenger 1984) to estimate percent crown closure.

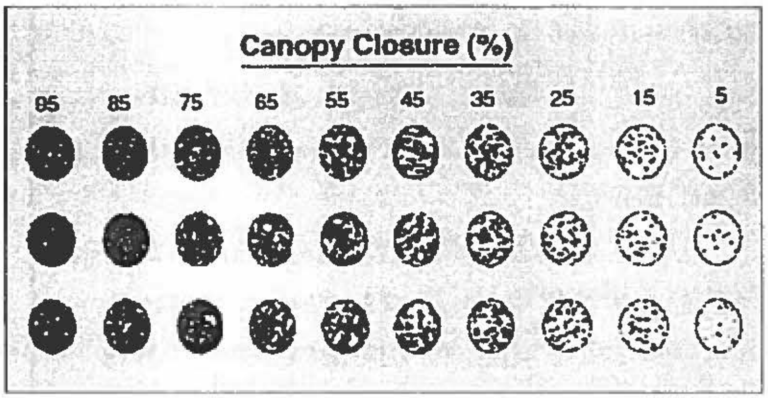

Figure 16. Ocular Estimates of Canopy Closure (FSP 2000)

Spherical Densiometer – Perhaps the most commonly used surrogate measure of shade is the spherical densiometer. This is a relatively simple tool that provides a measure of canopy cover to a stream. The densiometer is a round mirrored lens with lines etched on the surface (Figure 17). There are two versions, one with a convex lens which cover a 180° field of view and another with a convex which cover a 60° cone view of the sky. The convex spherical densiometer is probably more widely used but the convex model may provide a better evaluation of shade contribution when the solar angle is high.

Looking down at the densiometer provides a reflection of the canopy. In each square created by the lines are four dots. Canopy cover is estimated either by measuring where canopy intersects dots (when low level of canopy) or subtracting the number of "clear sky" hits. Since only 96 dots are provided, correction methods are used to provide relatively unbiased estimates of canopy cover. Specific protocols are employed to provide more consistent results, such as the use of a string to insure consistent distance between the observer and the densiometer. All of these methods fail to adjust for the angle and orientation of the sun, using average cover characteristics as a surrogate for the actual shade effects at the critical time.

The spherical densiometer protocol recommended by the Oregon Stream Shade Monitoring Team (SSMT 2000) involves a modification of the densiometer as shown in Figure 18, with a "V" taped on the surface of the densiometer. This leaves 17 intersections etched between the "V". Shade can be estimated by counting how many intersections show canopy cover. At each station along a stream reach four measurements are taken in the middle of the stream, one each facing the banks, facing upstream, and downstream. The "V" method was originally developed by Strickler (1959) to overcome problems caused because some "squares" image shade already counted when the observer changed orientation. Stream edge measurements are also taken facing toward the bank. This is a total of six measurements per station. Eleven evenly spaced measurements are recommended through the reach. Measurements are taken at 0.3 m above the water surface. Addition details are provided including treatment of complex, multi-channeled streams.

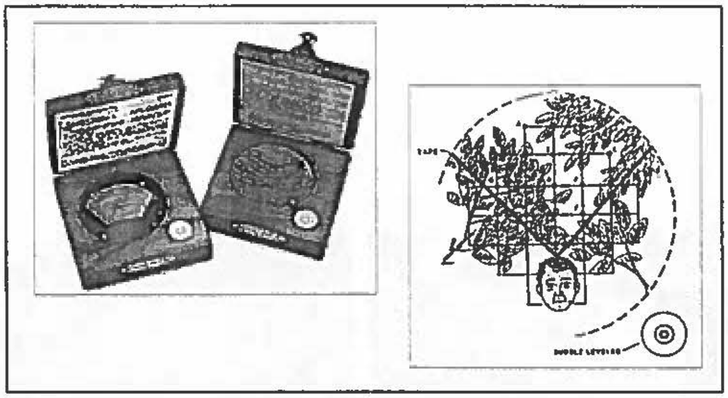

Figure 17. Spherical Densiometer Showing Concave and Convex Lens and SSMT Protcol

Angular Canopy Density – Canopy density is expressed as a vertical projection of the canopy onto a horizontal surface. Angular canopy density (ACD) "…is a projection of the canopy measured at the angle above the horizon at which direct-beam solar radiation passes through the canopy. This angle is determined by the position of the sun above the horizon during that portion of the day (usually 10 A.M. and 2 P.M. in mid to late summer) during which solar heating of a stream is most significant" (Beschta et al. 1987). Brazier (1973) developed this approach to better account for radiation loss at the critical time of day. He used a flat mirror angled to reflect shade at the critical period when observed from above.

A modified version of measuring ACD uses the spherical densiometer (NCASI 1999). Observers orient their view of the densiometer in the direction of the sun during the maximum water temperatures (210° SW) and count only the middle 48 dots that represent canopy density for the steepest solar angles.

Solar Pathfinder – The solar pathfinder uses a transparent reflector dome to create an image of nearby topography and vegetation. A sunpath diagram below the dome is designed for specific latitudes and provides a guide for where the sun path is at different times of the day and year. "The sun path diagram has 12 parallel sun path arcs, one for each month of the year…Vertical lines that represent solar time intervals of 30 minutes intersect these arcs. These segments of each monthly solar arc are assigned values that represent the percentage of solar radiation available during each 30-minute interval. The total value of all segments for a solar path arc is 100. The values vary by month as day length and solar azimuth change. For example, tracing the August solar arc in the sun path diagram, it can be determined that 6% of total daily solar radiation is available during the 30-minute period of 11:30 A.M. to 12:00 P.M. Following the December solar arc it is apparent that 10% of the daily solar radiation is available during that same time period. Shade is simply a tally of those sun path arc segments that are partially or completely shaded. Actual energy reaching the stream can also be calculated" (SSMT 2000). Since energy inputs are greater in the summer than in winter, appropriate adjustments need to be made to calculate energy available to the stream.

Hemisphere Photography – An increasingly popular method is the fish-eye or hemisphere photograph, combined with computer analysis (FSP 2000). Black and white hemispherical negatives are scanned and the images are processed using a software package (HemiView) for estimating direct and diffuse solar radiation (Figure 18). Photos are taken with magnetic north at the top of the photo. HemiView, with an understanding of where shade is occurring and the solar path on any day, can calculate diffuse and direct sunlight for anytime of the day and time of the year. The hemisphere photo and computer analysis provides the first method that can account for shade at all times of the day and year.

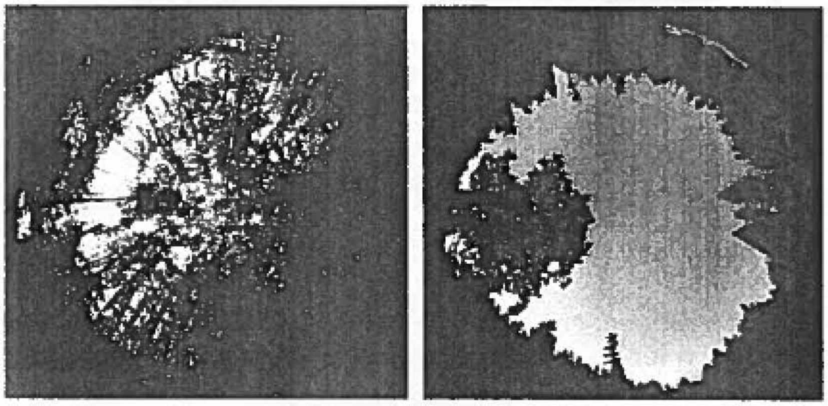

Figure 18. Hemisphere Photography

A Test of Cover Estimate Reproducibility

Cost, difficulty or methods, and advantages/disadvantages of these and other cover and shade measurement methods very greatly (Table 2). One question is how much agreement there is between methods and between different observers using the same method.

The Forest Science Project (2000) tested the reproducibility of visual and spherical densiometer measurements, compared to the hemisphere photograph method. They found that on one stream there was good comparison between methods while on another stream, the spherical densiometer and visual assessments underestimated the canopy measured by the hemisphere photo methods. Variability between observers was also observed for visual assessments. SSMT (2000) provides additional information on method reproducibility and inter-comparability.

Table 2. Comparison of Shade Measurement Methods (Adapted from SSMT 2001)

Method	Description	Advantages	Disadvantages	Cost of Instrument
View-to-Sky	Clinometer or abney measure of percent open sky over 180° arc	Quick and easy. Procedure widely used	Does not measure shade directly. Tends to lump a site into high or low category	$100
Ocular Estimate	Use computer cards to calibrate observers	Quick and easy. Potentially low cost. Procedure used in national program	Does not measure shade directly. Variable results between observers	$0
Spherical Densiometer	Spherical mirror reflects sky. Count etched dots or grids to determine canopy cover	Procedure widely used. Inexpensive, quick, and easy. Equipment rugged and light-weight	Measures canopy cover, not shade. Difficult to keep level and to account for variable opacity	$100
Angular Canopy Densiometer	Flat mirror measures canopy at critical sun position	More direct measure of shade when stream heating critical	Not commonly used. Equipment not commercially available	$200
Solar Pathfinder	180° diagram of sky is hand drawn on solar path chart	Fairly easy and quick. More direct measure of shade. Commercially available	Not rugged. Difficult use in rapidly flowing streams. Extensive data reduction required	$200
Hemisphere Photography	180° photograph of sky analyzed by computer	High quality permanent record of canopy cover. Computer analysis can analyze for shade throughout the year	Expensive, heavy, and delicate. Not simple and easy to use. Different lighting can cause problems. Requires data reduction	$4000 to $8000
LAI or Direct Energy Measurement	Pyroheliometer measurement of energy	Directly measures energy at the stream surface	Fluctuations due to clouds, time of year, day, etc. Point-to-point variability	$1000

Artificial Shading Experiments

Moore et al. (1999) conducted a tank experiment to demonstrate the importance of direct short-wave solar radiation in stream heating. Four tanks, two deep and two shallow, were insulated on all sides and placed on a trailer. The deep tanks were approximately twice the depth of the shallow tanks. One of each depth tanks was shaded with plywood but a 12-inch headspace was maintained to provide for air exchange. Thermistors recorded temperatures in each of the tanks and weather data was also collected. Figure 19 shows results from one of the experiments. The authors concluded that shade was a very important factor influencing the rate of heating and cooling of water. As depth decreased, the rate of heating and cooling increased, given the same surface area. Based on the pattern of when warming and cooling occurred relative to air temperature and solar radiation patterns, air temperature had relatively little influence on the rate of heating and cooling of the tanks.

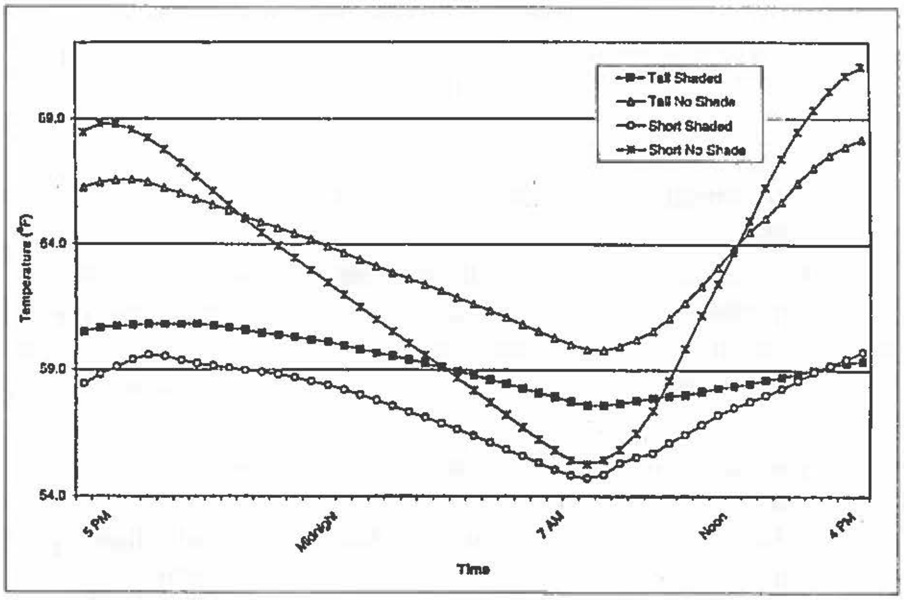

Figure 19. Tank Shade Experiments (Moore et al. 1999)

Peterson, Stringham, and Krueger (in press) artificially shaded an irrigation ditch with reflective, light resistant, silver tarps to measure the effect on stream temperature. Shade values ranging from 100% (completely covered) to 20% (80% of the ditch reach unshaded) were compared to an upstream unshaded reach. Because of irrigation demands, discharge and depth were not constant during the day or between days. Solar radiation and air temperatures also varied between days. The data from days with heavy clouds was discarded. Results are unequivocal about the importance of shade in reducing stream heating. Results are somewhat equivocal about the reduction in potential heating associated with different levels of shade, probably due to variables described above. Nevertheless, they show increasing protection with shade from about a 30% reduction in the maximum water temperature increase for 20% shade to nearly complete reduction in the maximum water temperature increase for 100% shading.

Johnson directly tested the role of shade by covering a small stream reach of Watershed 3 in the H. J. Andrews Watershed. The reach treated had experienced a debris torrent and was fully exposed and scoured to bedrock. Shade cloth was placed over a 200 m reach, and water temperature was monitored above and below the treated reach. Prior to placement of the artificial shading the reach consistently experienced increases in temperature of 1 to 3°C. After placement of the shade cloth, temperatures at the bottom of the reach were slightly less than the temperatures entering the reach.

As part of a study of headwater streams, Jackson (2000) measured changes in stream temperature. Of seven clearcuts studied, three showed no apparent change in temperature compared to a reference stream, one became cooler, one slightly warmer, and two became both cooler and warmer depending on where measurements were collected. These latter two streams showed significant warming (one increased an estimated 15°C). The difference in reference stream temperatures between pre-treatment and post-treatment years was quite large, which complicated analysis. The relative lack of response for clearcut streams was probably due to slash in the streams that provided shade, much like we observed for Needle Branch immediately after harvesting. Two buffered streams became warmer and one slightly cooler. A non-merchantable buffer provided less apparent shade than full buffers and the stream had greater increases in temperature. The Jackson study points out that assumptions about complete mixing in small streams may need to be reconsidered.

In 1996, Larson and Larson argued that riparian shade and its affects on solar radiation were over-estimated since direct short-wave radiation accounts for only about 25% of the ambient radiation (also diffuse solar radiation and long-wave radiation). Larson and Larson, using an example of a 40 ft wide stream and assuming a 50 ft tall tree adjacent to the stream, also argued that even when riparian vegetation could reduce direct solar radiation, its role was limited. Beschta (1997) argued that net long-wave radiation between a stream and space essentially balances, making direct solar radiation the most important component for heating. Solar radiation available to the surface of an unshaded stream increases rapidly during the day in mid-July (Figure 20). The example of the 40 ft wide stream is probably not appropriate. Beschta reported that 90% of the fish-bearing stream miles in the Upper Grande Ronde River Basin had average wetted widths of 10 ft or less, and often vegetation was substantially taller than 50 ft.

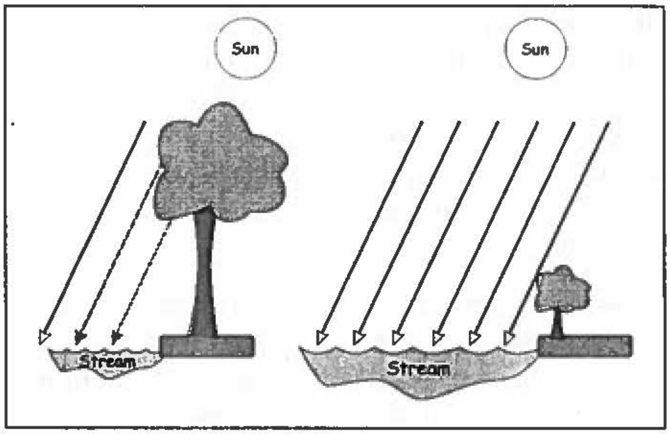

Figure 20. Shaded vs. Unshaded Solar Radiation

Answering Specific Questions on Vegetation and Shade

A series of specific questions were asked of the temperature workshop panelists. Five of the questions dealing with direct solar radiation involved the role of vegetation in buffers. Many of these questions are addressed, if not completely answered, by a shade study underway by the Oregon Department of Forestry (ODF). ODF is using hemisphere photography to measure shade in buffers across Oregon (Liz Dent, Oregon Department of Forestry, personal communication).

Do asymetrical buffers (e.g., riparian buffers stacked on the south side of the stream) or one-sided buffers provide water temperature protection? What recent research has occurred on the subject? Is there any ongoing research on the subject? From a theoretical perspective, an east to west or west to east flowing stream will receive virtually all of its shade from the south bank. While reflected short-wave solar radiation and long-wave radiation inputs may be attenuated by vegetation on the north side of the stream, the reduced inputs tend to be balanced by the reduced outputs. There is scant empirical evidence to support this theoretical perspective. Zwieniecki and Newton (1999) measured stream temperature through three units with 12 m screens of shrubs or trees left only between 120 to 270° or within the arc of the sun between 9 AM and 6 PM. Zwieniecki and Newton reported that "…to the north of each stretch of open water, there was no cover except where trees or shrubs along the south exposure of another reach provided cover because of the meandering of the stream." The average maximum temperatures of these streams did not change appreciably across three 800 m clearcuts where buffers were only left on the south side of the stream. The ODF shade study has been assessing whether one-sided buffers are effective. For coastal Oregon preliminary data suggests that the north-side shade variables are not significant as far a providing shade. Preliminary data from another region finds north side vegetation does contribute to shade but less than the south side vegetation. Stream size and overhanging vegetation may be confounding factors where vegetation on the north side of a stream actually contributes to the canopy on the south side of the stream.

Do conifer-dominated riparian stands provide better protection of surface water temperatures than alder stands of a comparable age? How significant is the difference? Is there field research on this issue? Again, as with all of these questions, there is scant empirical information. Which stand type provides greater shade at a comparable age depends on whether one is looking at younger or older stands. Alder is a very vigorous pioneer species. In the Alsea Watershed Study, riparian alder had grown 16 to 20 ft after three years, providing increasingly abundant shade. Older alder stands (40 to 80 yrs) began to breakup, creating more openings in the canopy. The ODF shade study is comparing hardwood, conifer, and mixed stand types and preliminary analysis shows little difference in shade between these stand types. However, there appears to be some evidence that there is more of a difference in shade between older unharvested conifer stands and younger conifer stands than is seen for older hardwood stands and younger, managed hardwood stands. Sam Chan with the USDA Forest Service reports that a Coastal Oregon Productivity Enhancement Project did look at leaf area index (LAI) and available radiation through riparian canopies. Data from the study is not yet fully analyzed. Conifer stands of about 40 yrs may have slightly higher LAI (6) than a 50 yr old alder stand (5). More important than LAI in this case was the difference in canopy architecture, with the alder stands having fewer lower branches. This translates into approximately 5% of available energy passing through the conifer stand compared to as much as 16% for the alder stand. Chan speculated that younger alder stands might have greater LAI and more lower branches.

Does multiple layered shading resulting from a tree canopy and understory brush provide better shade protection than a single layer of shade? Are there any field studies that document a difference in the surface water temperature response? Again, the ODF shade study is attempting to address this question by taking pictures with the hemisphere camera at 3 ft (brush contribution to shade included) and 10 ft heights above the stream (above brush shade contribution). However, there is some concern that the data at 10 ft does not completely eliminate the contribution of brush/understory to shade. Shade-producing understory plants, such as salmonberry and vine maple, can exceed the 10 ft height, especially when they are on steep slopes. Conceptually, understory brush can contribute to shade. The differences between the 3 and 10 ft measurements do not appear to be large.

Does reflected solar radiation (i.e., radiation reflected through the riparian understory from an upslope clearcut) result in a measurable increase in solar radiation and/or water temperature? It is unlikely that significant solar radiation can be reflected from an adjacent clearcut unit off riparian vegetation and into the stream. Reflection of solar radiation will be greatest when the radiation angle is shallow. This is also when energy is low. Only a small portion of the clearcut unit is likely to even have the potential to contribute at any time. Reflected radiation hitting the riparian vegetation can be adsorbed or reflected. Because leaf architecture is relatively random, only a portion of the re-reflected energy has the potential to impact the stream, and if it is at a shallow angle then it may be reflected once again.

Current Washington State forest practices requires the use of a hand-held convex spherical densiometer to measure shade from all points of the compass. Is there better equipment or field methods to measure the temperature effects of solar radiation to the water's surface? Hemispherical photography methods are becoming an increasingly popular research approach, with a presumption that they provide more realistic estimates of energy attenuation. Although there have been some limited comparisons between different canopy/shade/energy monitoring methods, there remains uncertainty about whether gains going from easy spherical densiometer methods to more costly hemispherical photography can be justified. We would propose that a study be undertaken to compare the results of these methods to integrated direct radiation measures.

5.0 RELAXATION FROM ELEVATED STREAM TEMPERATURES

If a stream reach is exposed to direct solar radiation through an open reach and experiences an increase in temperature and then re-enters a shaded reach will it come back to equilibrium with the environment it is experiencing? The answer, of course, is yes; but there are different mechanisms and rates involved for different stream systems. Adams (NCASI 2001) uses the term relaxation to indicate that this is an elastic response back toward the characteristic stream temperature profile.

At one time, thinking about the cumulative effects of forest practices on stream temperature focused around the use of the mixing ratio (Brown 1980):

$$T_{final} = (Q_m T_m + Q_t T_t)/(Q_m + Q_t)$$

Where:
Q_m = discharge for the mainstem
Q_t = discharge for the tributary
T_m = temperature for the mainstem
T_t = temperature for the tributary
T_{final} = final temperature below the confluence

The thinkings was that if tributaries could be cooled then there were be cumulative benefits downstream. The mixing ratio is still a useful tool to calculate temperature immediately downstream from a confluence, but temperature, like all pollutants, is non-conservative. This means that departures from the temperature that will be in equilibrium with the environment will result in loss or gain of heat from the stream, proportional to the difference in the equilibrium temperature and actual temperature.

We have shown that one of the most important factors influencing rate of heating is stream depth (Brown Equation). This is also true for the rate of relaxation. In Figures 21 and 22, Adams (NCASI 2001) provides some simulation examples of an energy budget for shallow and deep streams with otherwise similar conditions. If any stream continues under the same conditions long enough it will come into (near) equilibrium with the surrounding environment. This equilibrium occurs rapidly for a shallow stream and takes longer for a deeper stream. Figures 23 through 26 show how temperature might increase through a clearcut (no buffer) for otherwise similar streams of different depths. What is noticeable is that the increases in temperature are more dramatic for the shallow stream but the increases relax more quickly to the characteristic temperature profile.

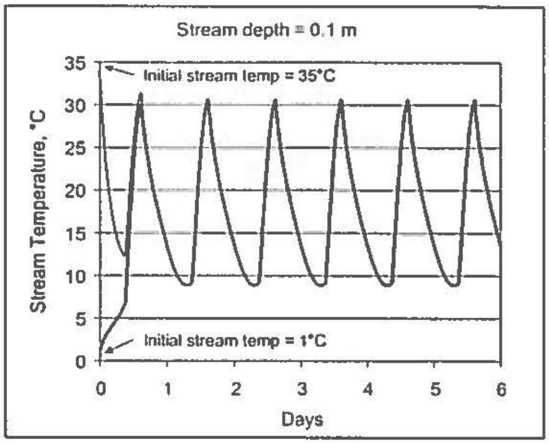

Figure 21. Relaxation of a Shallow Stream to Equilibrium

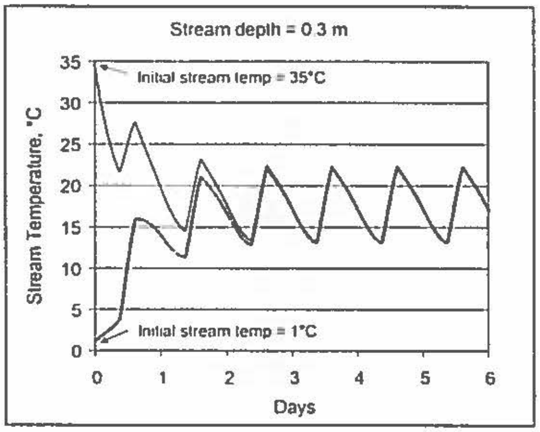

Figure 22. Relaxation of a Larger Stream to Equilibrium

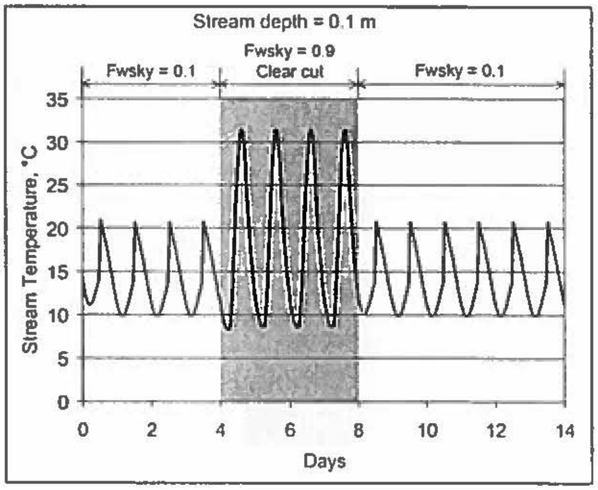

Figure 23. Simulated Impact of a Clearcut on Stream Temperature for a Stream of 0.1 m Depth

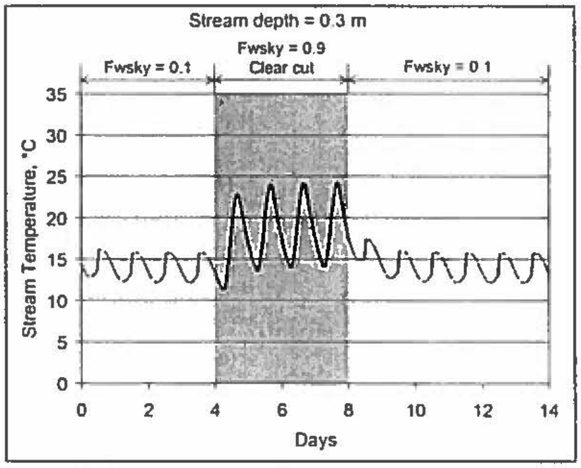

Figure 24. Simulated Impact of a Clearcut on Stream Temperature for a Stream of 0.3 m Depth

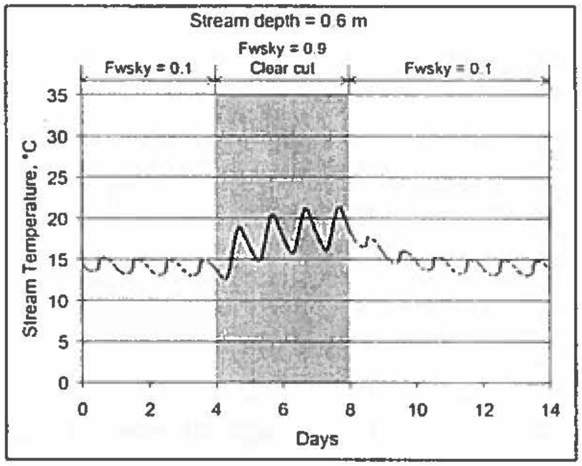

Figure 25. Simulated Impact of a Clearcut on Stream Temperature for a Stream of 0.6 m Depth

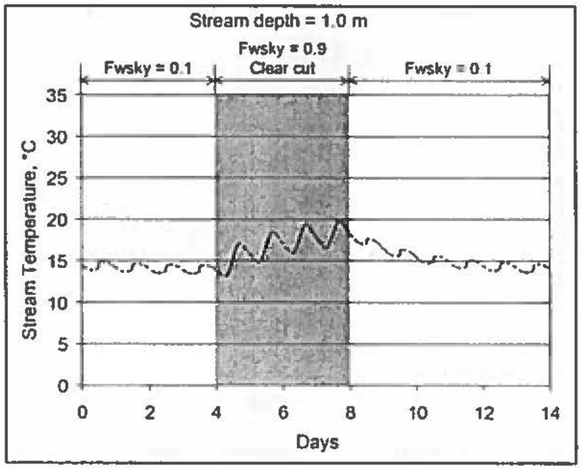

Figure 26. Simulated Impact of a Clearcut on Stream Temperature for a Stream of 1.0 m Depth

A range of characteristic relaxation times can be developed which represents the range of typical conditions experienced in Washington forest streams (Figure 27).

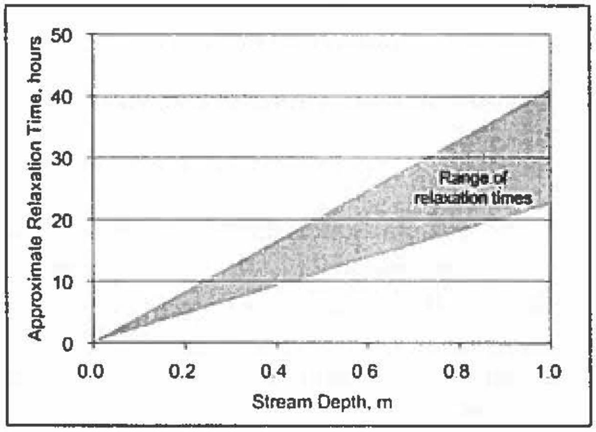

Figure 27. Relaxation Time as a Function of Stream Depth

Clearly, changes in stream temperature have the potential to be cumulative. But, equally clearly, heat is a non-conservative pollutant. It is constantly moving toward equilibrium with the environment, so any increase will not persist. Figure 28 is another simulation by Adams showing the results of a stream with constant conditions along its path, compared with a similar stream that has three clearcuts that completely expose the stream to direct solar radiation, separated by shaded reaches. The clearcuts increase the stream temperature through the openings and immediately downstream, but the streams return to the temperature profile expected for the stream.

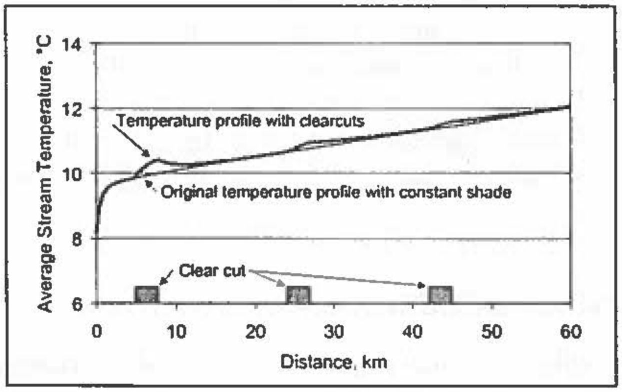

Figure 28. Simulation of Cumulative Temperature Profile with Three Clearcuts

Field studies confirm these patterns. Zwieniecki and Newton (1999) found that small increases in stream temperature through buffered clearcuts returned to the normal temperature trend line within 150 m downstream. Even for Needle Branch with no buffer along the study reach, elevated temperatures in the upper headwater reaches did not continue to increase downstream and instead were lower at the main gauging station.

The very rapid recovery to the characteristic temperature trend line in some small streams is probably largely due to inflow or exchange with hyporheic water and groundwater. In Johnson's artificial shading study in the H. J. Andrews Watershed, she found increases in temperature for a stream that was fully exposed through a reach scoured to bedrock and a slight decrease in temperature through the same reach when it was shaded. However, within a few hundred meters, the temperature showed no response to the upstream treatments (open or shaded), apparently showing an extremely rapid response due to hyporheic exchange and other cooling processes. This was occurring in the debris torrent depositional zone where there was abundant exchange of water.

Holaday (1992) provides a classic demonstration that temperature changes in headwater tributaries may have little influence on mainstem stream temperatures when there is sufficient relaxation time. Steamboat Creek in the Cascades of Oregon is an important salmon- and trout-producing stream and is an important tributary to the Umpqua River. Stream temperatures for Steamboat Creek and key tributaries were monitored from 1969 through 1990 to observe changes associated with recovery of riparian vegetation. Clearcutting without buffers, removal of vegetation for a dam site, and scouring of the stream channel during the 1964 floods resulted in a basin where all the tributaries had sometimes dramatically reduced shading. By 1990, however, with new policies and restoration efforts to re-establish riparian vegetation, all tributaries experienced decreases in temperature. This was evident also in the upper mainstem, where several monitoring sites indicated significant reductions in stream temperature. However, by the time the water reached the mouth of Steamboat Creek, it was at the same temperature it had been in 1969.

Of course one additional mechanism demonstrated for relaxation of temperature increases for the Steamboat Creek, as well as the Alsea and H.J. Andrews Watershed studies, was re-growth of vegetation. Andrus and Froehlich (1988) found that angular canopy densities for small streams in the Oregon Coast Range, where fire or clearcutting had removed streamside vegetation, recovered to the values measured for old-growth stands in 8 to 12 yrs. Summers (1982) found similar patterns but rates of recovery varied for different regions and tended to be slower than those found by Andrus and Froehlich. Stream size will also influence the effectiveness of vegetation re-growth. Small streams can be rapidly overtopped by riparian vegetation and even shadows cast by short south bank vegetation can cover the entire stream. Once trees adjacent to a wide stream are removed it can take years of re-growth for the vegetation to again provide significant shading of the stream.

6.0 DISCUSSION AND CONCLUSIONS

The Oregon Independent Multidisciplinary Science Team (IMST) recently held an experts' workshop similar to this one to determine the influence of human activities on stream temperature (IMST 2000). Some of the expert panel conclusions were as follows:

- Solar radiation is the principal energy source that causes stream heating.
- Direct absorption of solar radiation by the stream and the streambed warms water; interception of solar radiation by vegetation reduces potential warming.
- Shading (vegetative and/or topographic cover) reduces direct solar radiation loading and stream heating.

- The factors that human activities can affect to influence stream temperature are vegetation, stream flow (hydrology), channel morphology, and subsurface/surface interactions (factors not listed in order of importance).
- The influence of vegetation decreases with increasing channel width.
- The type of vegetation and its influence on temperature varies over time.
- Streams tend to heat in the downstream direction.
- Stream temperature tends to move toward equilibrium temperatures based on the energy balance, which is a function of several variables. As these variables change in time and space, the energy balance and equilibrium temperatures also change.
- It is more efficient ecologically to use shade to protect cool water from warming than to attempt to cool water that has already warmed.
- Vegetation is an important influence on microclimate, which may affect stream temperature if it sufficiently changes the stream environment.
- Riparian vegetation influences other aspects of the thermal environment of streams other than simply intercepting solar radiation.
- The change in temperature is a function of energy input, water surface area, and discharge.
- An increase in the surface area/volume ratio (or width/depth ratio) increases the rate of temperature change when there is a constant input of energy.

Among the gaps in knowledge identified by the IMST workshop were:

- What are the causes of the observed rates of stream temperature change in shaded reaches?
- How much vegetation is required to change the thermal environment and stream temperature?
- What is the comparability and usefulness of various shade and canopy cover measurement techniques?

In Washington, elevation is used to determine acceptable shade levels, but why? There is potentially greater direct solar radiation for high elevation sites than lower elevation sites due to reduced atmospheric scatter (small difference). Remember that stream temperature is controlled by several heating processes and will tend to move toward an equilibrium with air temperature. Lower elevation sites tend to have warmer air temperatures and stream will move toward equilibrium with those air temperatures. To meet a given temperature standard, more shade will be needed where the base temperature is higher.

Adams (NCASI 2001) concludes that solar heat flux is the major input that *raises* the stream temperature *above* the local air temperature. Ground water inflow is the major input that *lowers* the stream temperature *below* the local air temperature. All other heat flux terms involve both air and water temperatures, so the water temperature is always near the local air temperature. Headwater streams will also tend to occur at higher elevations than mainstem reaches. Adams (NCASI 2001) used simulated data along a stream reach to show the type of gradient in heating environment that might occur for a stream. Figure 29 shows that as the stream moves farther downstream, average air temperature increases, as does stream depth. It has been previously demonstrated that the rate at which stream temperature approaches equilibrium and the rate of heating are strongly influenced by the average stream depth. Figure 30 shows that average stream temperatures at the upper reaches will be lower than farther downstream but the shallow stream at the headwater has a greater potential to heat.

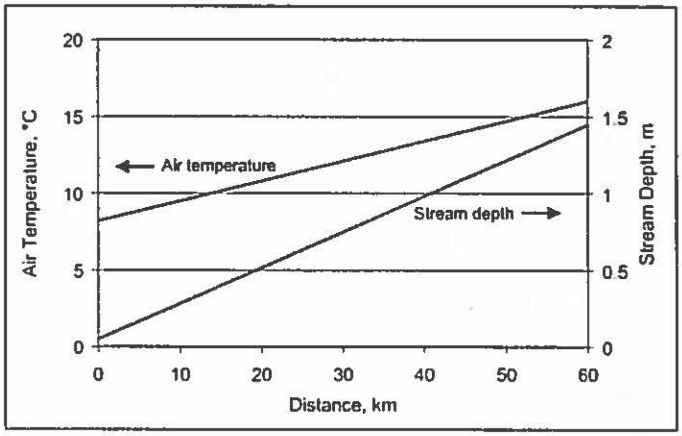

Figure 29. Air Temperature and Stream Depth Profiles for a Simulated Stream

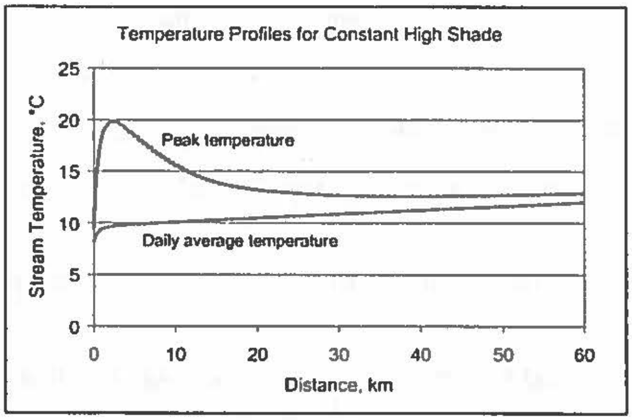

Figure 30. Average and Peak Temperature Profiles for a Simulated Stream

One apparent inconsistency, which challenges our observations is that in shallow streams it is often pool areas where the greatest changes in temperature occur. Does this mean that there has been some logic error? For example, Rashin and Graber (1992), Andrus (1995), and Hagan (2000b) have recorded significant heating through or from ponds. Several factors can contribute to these observations. First, beaver ponds usually increase both the width and depth of the stream, dramatically increasing the travel time through the reach. While we usually model against time, we observe temperature changes between points of space. Second, wider ponds may be more exposed, specifically beaver ponds, where potential shade may have been removed. Third, ponds can become stratified and warmer water may discharge off the top of the beaver dam.

Other heat processes and management impacts can contribute to changes in maximum stream temperatures for streams. But, for small forest streams, change in solar radiation due to modified riparian vegetation is the most important factor in stream heating. This provides us with a practical tool to manage stream temperature changes.

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How Direct Solar Radiation and Shade Influence Temperature in Forest Streams and Relaxation of Changes in Stream Temperature

Dr. George Ice

Washington Temperature Workshop
Lacy, Washington
February 6-7, 2001

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- Judith Adamski, NCASI

Outline

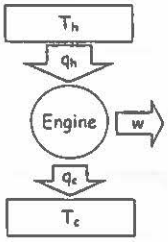
- Heat balance introduction
  - Thermodynamics primer
  - Earth/sun geometry
  - Simplified energy balance
- More detailed discussion of forest stream heating
- Role of riparian vegetation and shade
- Relaxation of increases in temperature

Riddle of the Sphinx

- If shallow streams heat more rapidly than deep streams, why do we sometimes observe the largest temperature increases in pools?
- When can riparian vegetation keep a stream cool and not cool a river?

Thermodynamics

- "Energy changes accompanying physical and chemical processes"
- How to build the most efficient engine to convert energy to work
- $\Delta E = T_h - T_c = q_h - q_c - w$
- $\Delta E = q - w$



Laws of Thermodynamics

- First law:
  Conservation of energy: the temperature change in a stream is proportional to the thermal energy added or removed from the stream.
- Second law:
  All systems tend to approach equilibrium: Heat (thermal energy) flows from hot to cold.
- Caution: Energy inputs can also add to kinetic energy

Definitions

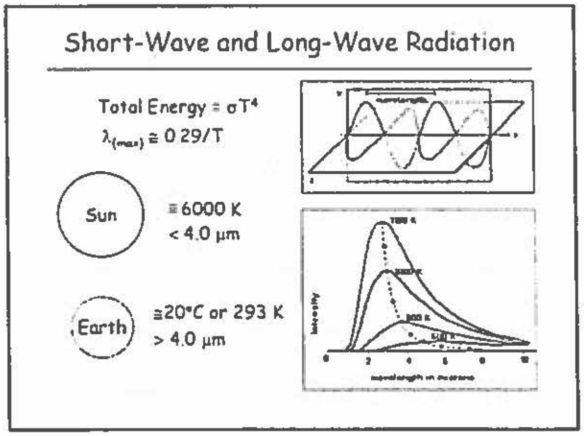
Specific Heat	Energy to raise one gram one degree C
Calorie	Energy to raise one gram of water one degree C
BTU	Energy to raise one pound of water one degree F (252 calories)
Heat of fusion	80 calories per gram
Heat of vaporization	540 calories per gram

Example of Conversion of Kinetic to Thermal Energy

- 1 lb of water dropping 1 ft over a rough streambed that slows the water to the initial velocity due to friction
- Potential (elevation) energy is converted to kinetic (motion) energy, which is converted to thermal energy by friction and turbulence
- Conversion from ft lbs to BTUs is 1/778 so a drop of 778 ft will add 1 degree Fahrenheit if other energy losses are ignored

Comparison of Temperature Scales

?



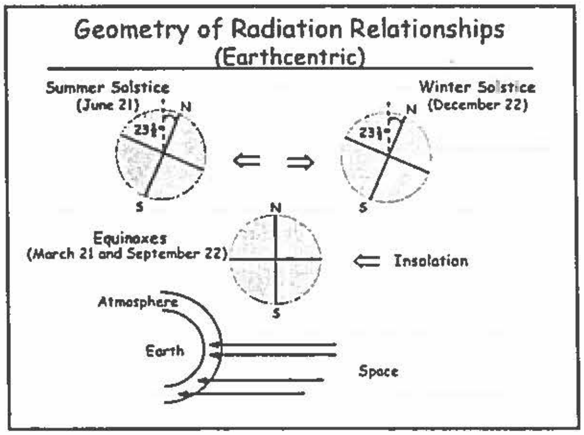
Short-Wave and Long-Wave Radiation

Total Energy = σT^4

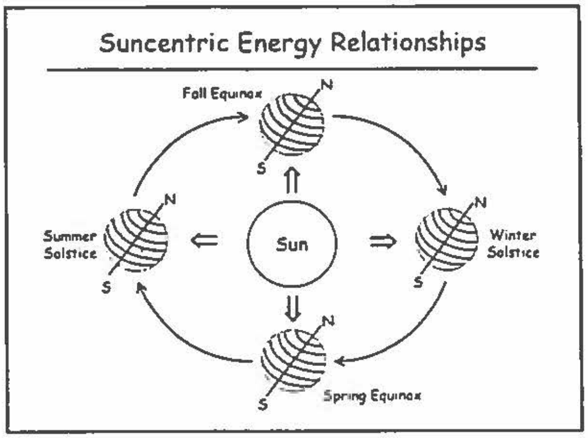
$\lambda_{(max)} \cong 0.29/T$

Sun ≅ 6000 K
< 4.0 µm

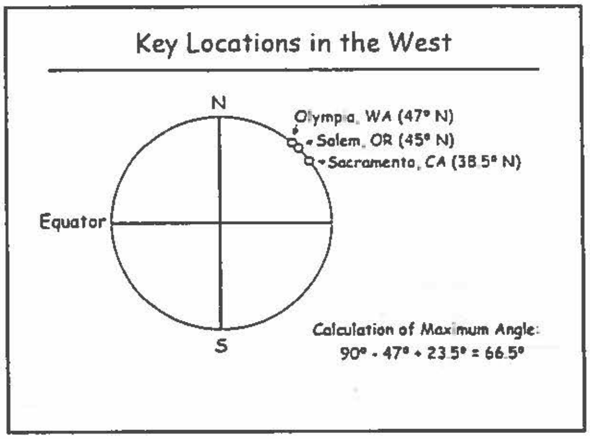
Earth ≅ 20°C or 293 K
> 4.0 µm



Geometry of Radiation Relationships (Earthcentric)

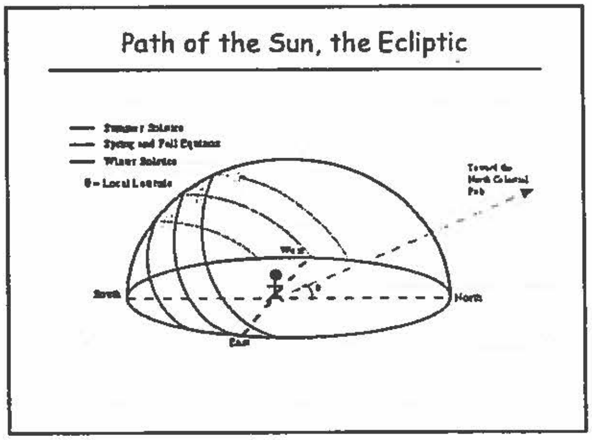


Suncentric Energy Relationships

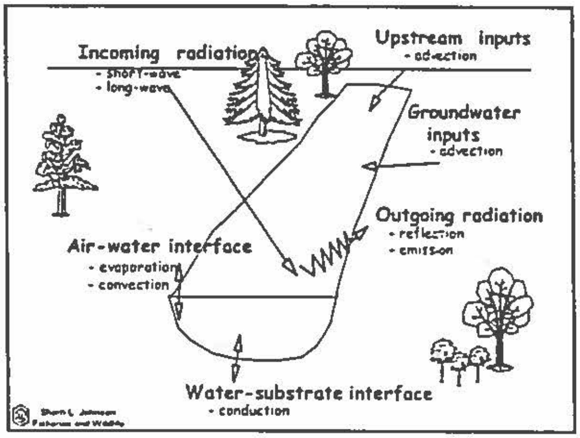


Key Locations in the West

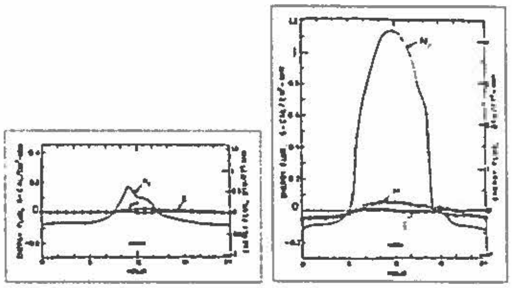
Calculation of Maximum Angle:
90° - 47° + 23.5° = 66.5°



Path of the Sun, the Ecliptic



Comparison of Energy Budget for Shaded and Unshaded Streams



Brown Simplified Energy Balance

$\Sigma H = N_r \pm E \pm H \pm C$

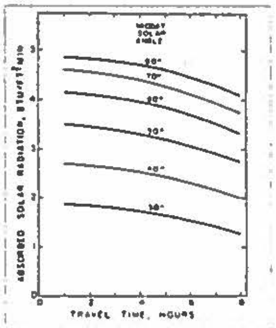
Total Heat = $\Sigma H \times A \times t$

$V = Q \times t$

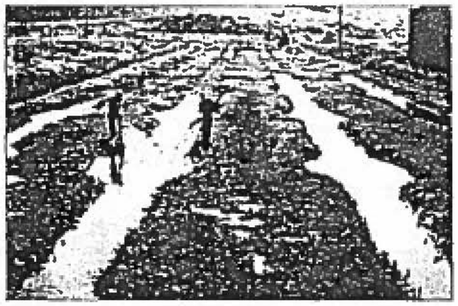
$\Delta T = \Sigma H \times A/Q$

$\Delta T = ((\Sigma H \times A)/Q) \times 0.000267$

Average Net Absorbed Solar Radiation



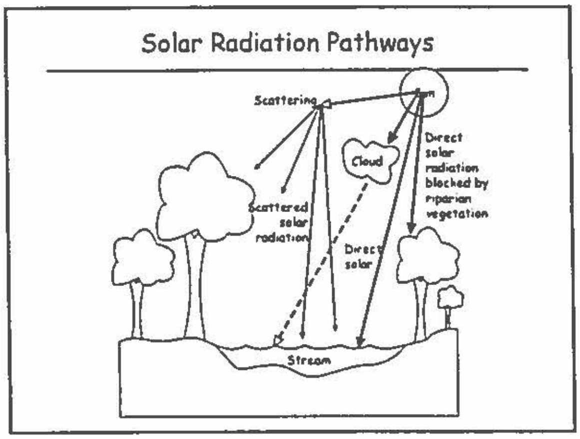
Lewiston Experimental Streams



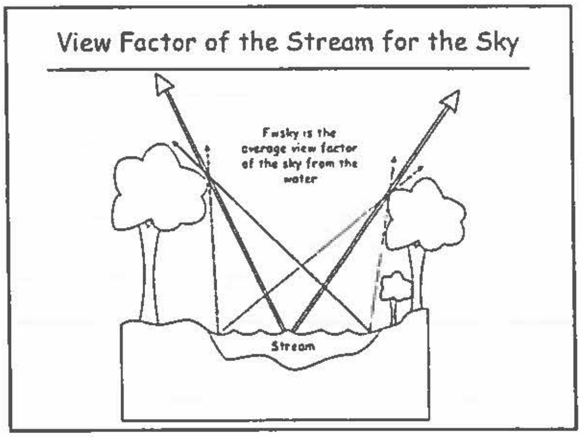
Lewiston Experimental Streams Example

$\Sigma H = 4.5$ BTU/ft^2-min
$A = 2300$ ft^2
$Q = 3$ cfs

$\Delta T = ((\Sigma H \times A)/Q) \times 0.000267$
$\Delta T = ((4.5 \times 2300/3) \times 0.000267$
$\Delta T = 1°F$

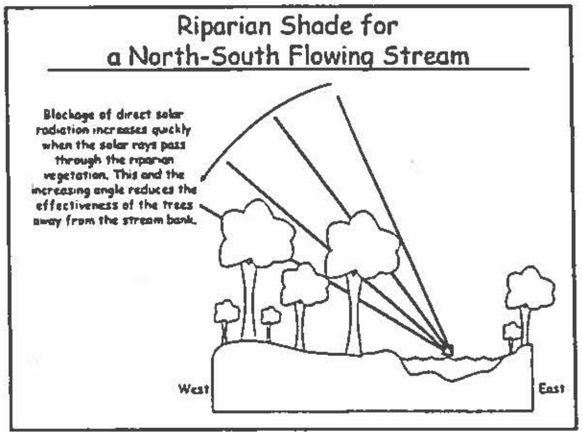


Solar Radiation Pathways



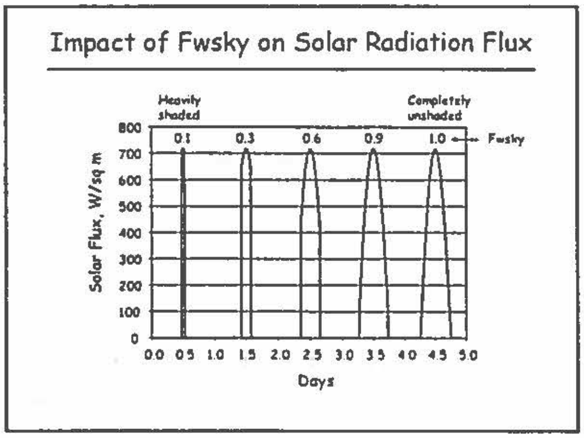
View Factor of the Stream for the Sky

Fwsky is the average view factor of the sky from the water

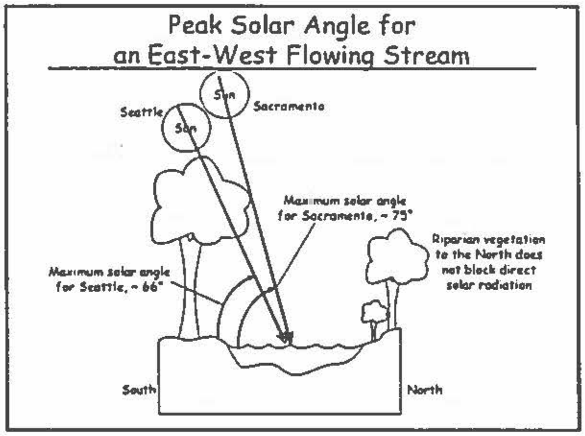


Riparian Shade for a North-South Flowing Stream

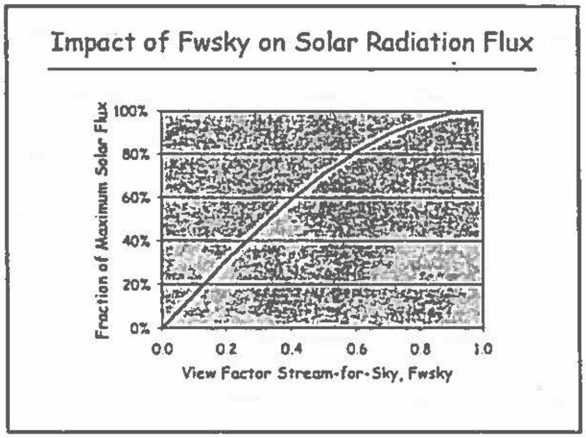
Blockage of direct solar radiation increases quickly when the solar rays pass through the riparian vegetation. This and the increasing angle reduces the effectiveness of the trees away from the stream bank.



Impact of Fwsky on Solar Radiation Flux

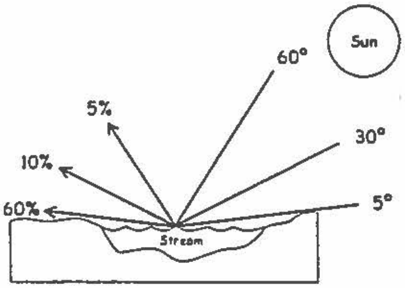


Peak Solar Angle for an East-West Flowing Stream



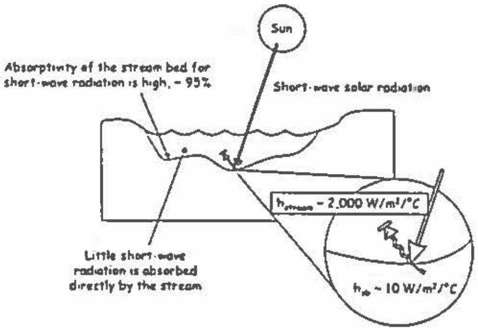
Impact of Fwsky on Solar Radiation Flux

Albedo* Change with Solar Angle
(Lee 1980)



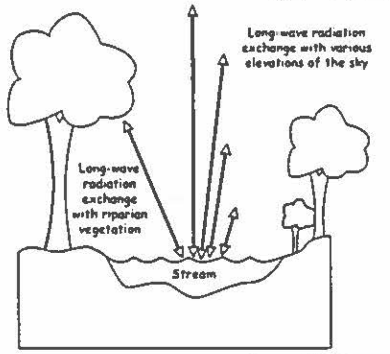
* Short-wave reflectivity coefficient

Solar Radiation Transfer to the Stream

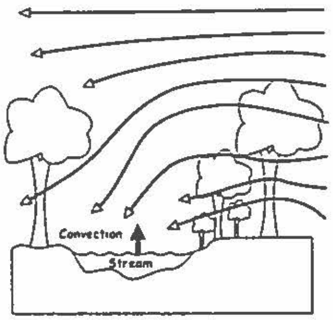


Solar Radiation Equations

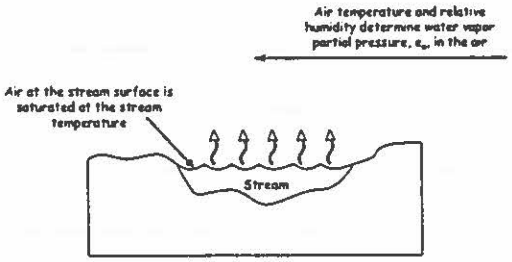
Long-Wave Radiation Exchange

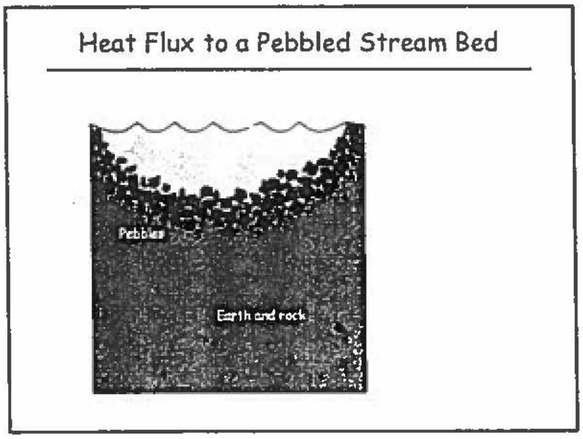


Heat Flux Due to Convection

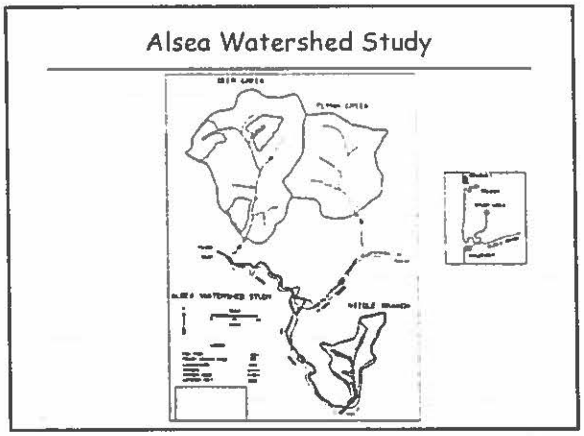


Heat Flux Due to Evaporation

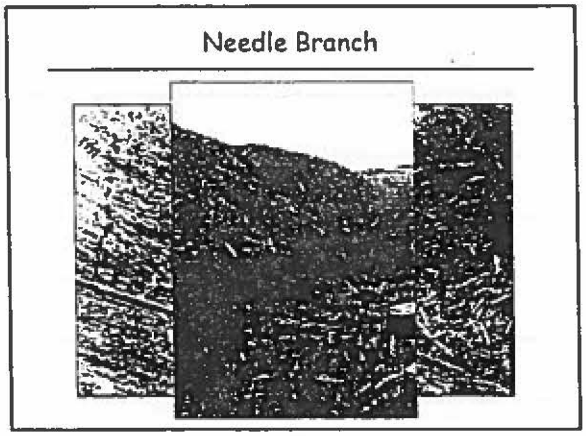




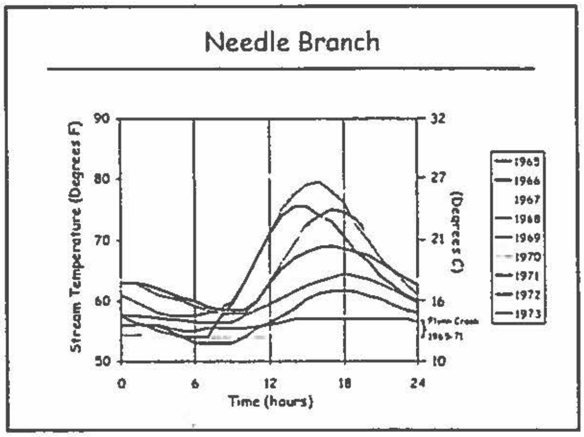
Heat Flux to a Pebbled Stream Bed



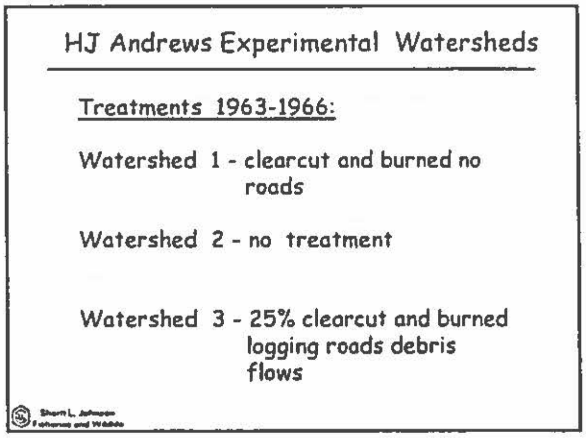
Alsea Watershed Study



Needle Branch



Needle Branch



HJ Andrews Experimental Watersheds

Treatments 1963-1966:

Watershed 1 - clearcut and burned no roads

Watershed 2 - no treatment

Watershed 3 - 25% clearcut and burned logging roads debris flows

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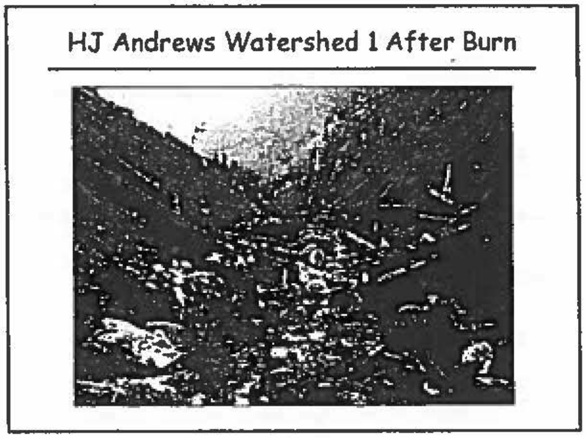
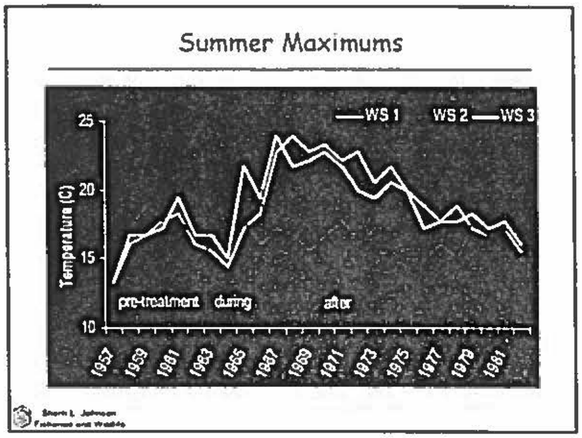


HJ Andrews Watershed 1 After Burn



Summer Maximums

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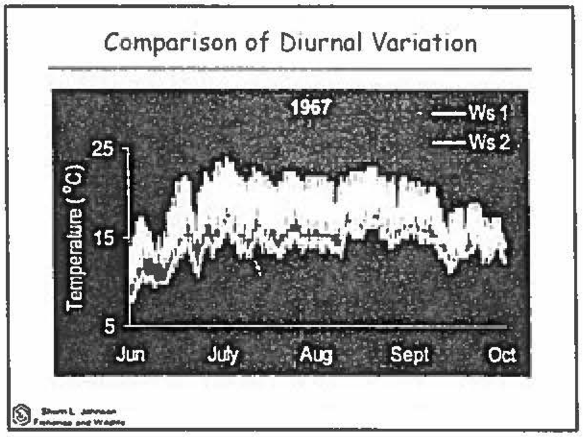

Comparison of Diurnal Variation

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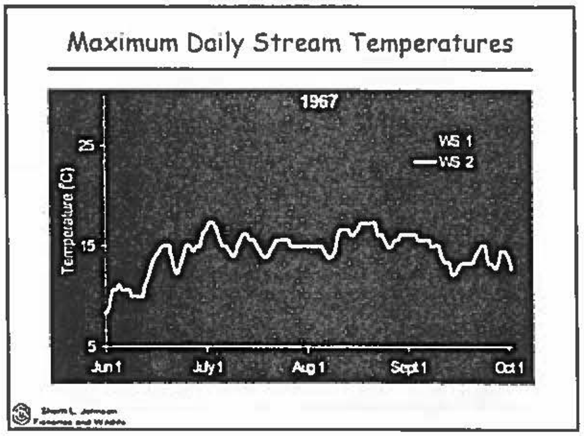

Maximum Daily Stream Temperatures

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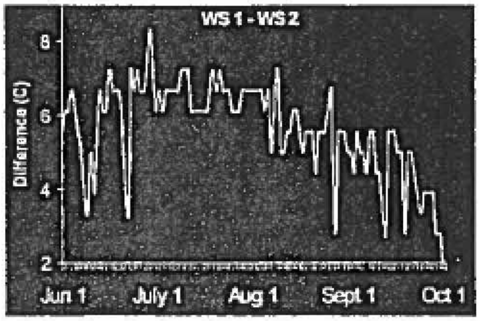
Difference Between Stream Temperatures



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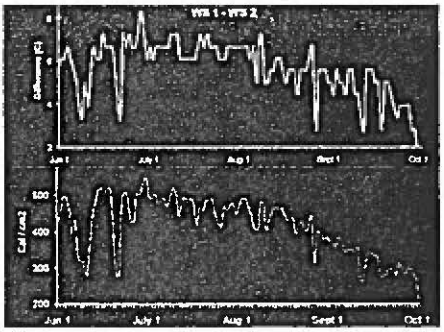
Temperature Difference and Radiation



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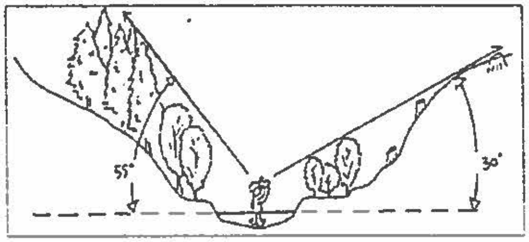
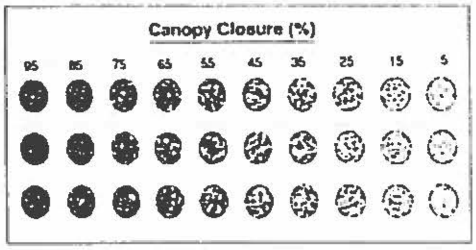
Canopy Cover Versus Shade

- Canopy cover is the percent of the sky covered by vegetation or topography
- Shade is amount of energy that is obscured or reflected by vegetation or topography
  - Water Quality Monitoring: Technical Guide Book -Chapter 14 Addendum: Stream Shade and Canopy Cover Monitoring Methods

Clinometer View to the Sky

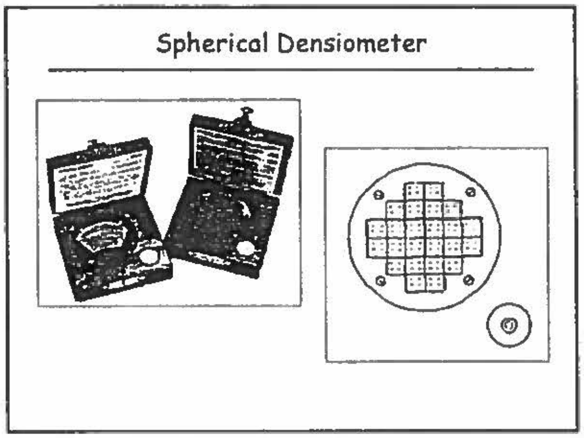


Ocular Estimates of Canopy Closure

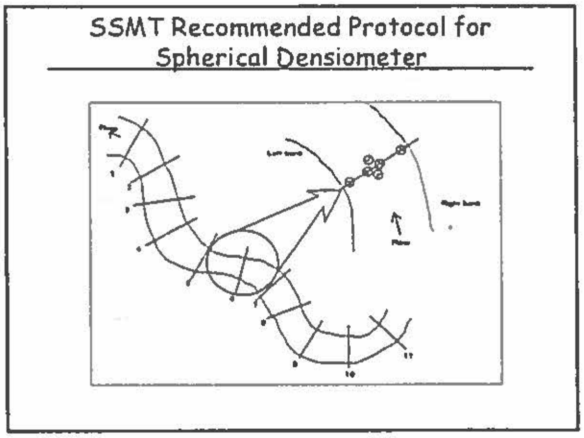


"Moose Horn" Densiometer

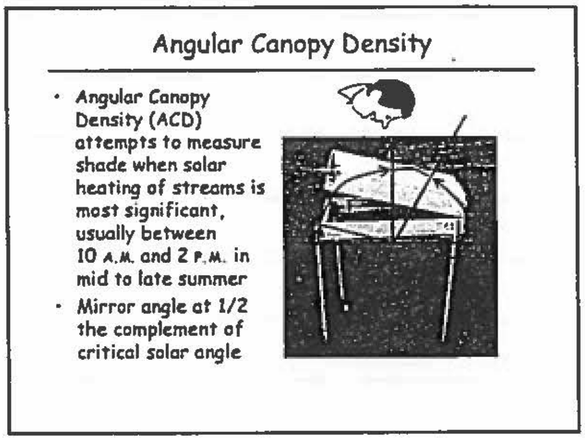

The 45 degree mirror and internal levels assure you of getting a perfect 90 degree view every time.



Spherical Densiometer

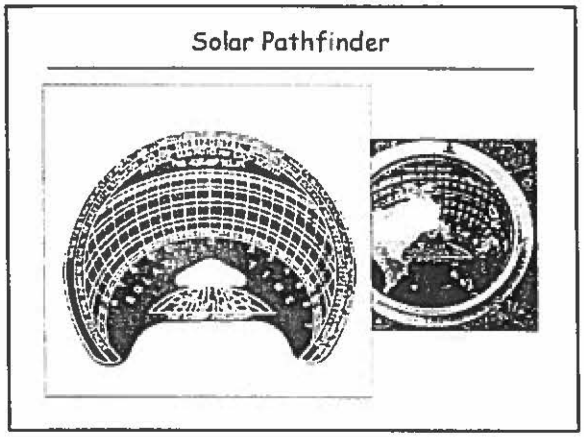


SSMT Recommended Protocol for Spherical Densiometer

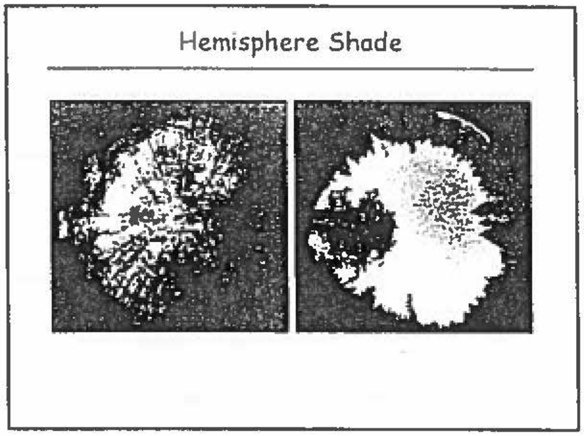


Angular Canopy Density

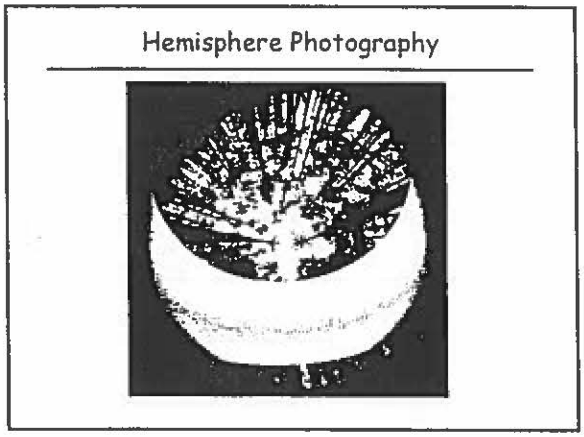
- Angular Canopy Density (ACD) attempts to measure shade when solar heating of streams is most significant, usually between 10 A.M. and 2 P.M. in mid to late summer
- Mirror angle at 1/2 the complement of critical solar angle



Solar Pathfinder

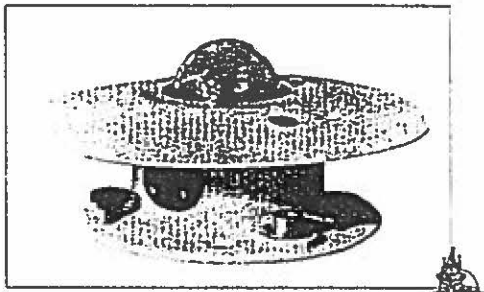


Hemisphere Shade

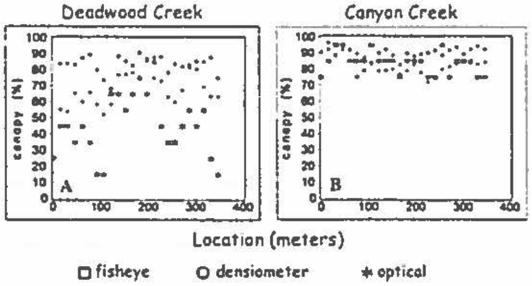


Hemisphere Photography

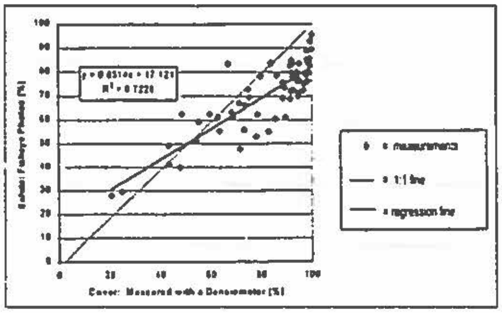
Direct Radiation Measurement with Pyroheliometer

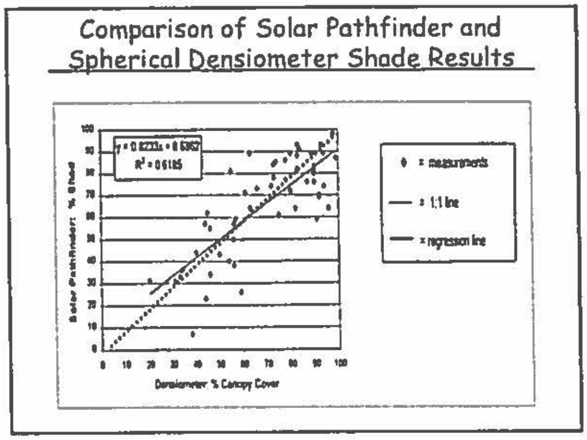


Comparison of Method Results

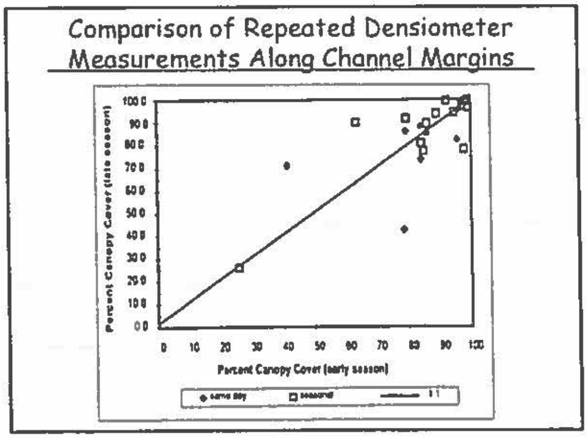


Comparison of Fisheye-Measured Shade and Densiometer-Measured Cover

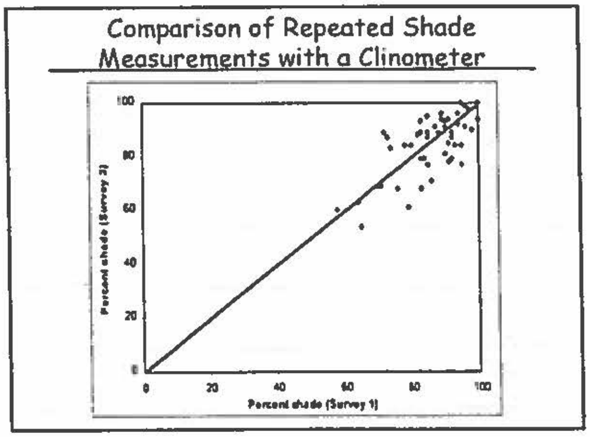




Comparison of Solar Pathfinder and Spherical Densiometer Shade Results

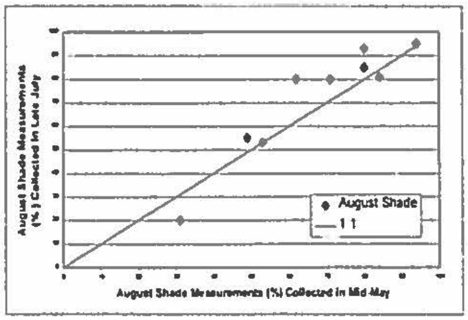


Comparison of Repeated Densiometer Measurements Along Channel Margins

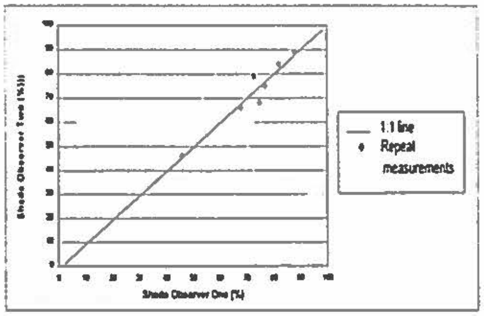


Comparison of Repeated Shade Measurements with a Clinometer

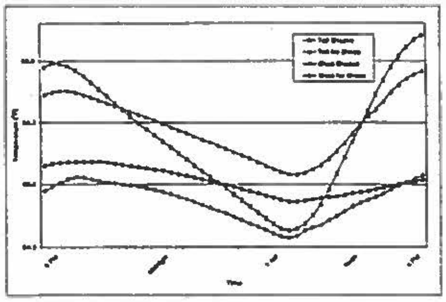
Reproducibility of Solar Pathfinder Results Taken May and August

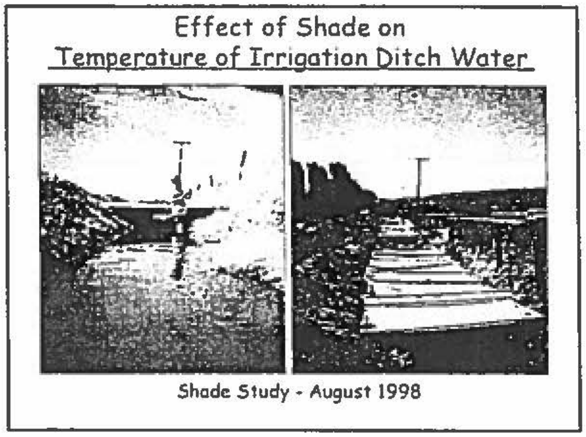


Solar Pathfinder Results from Two Different Observers



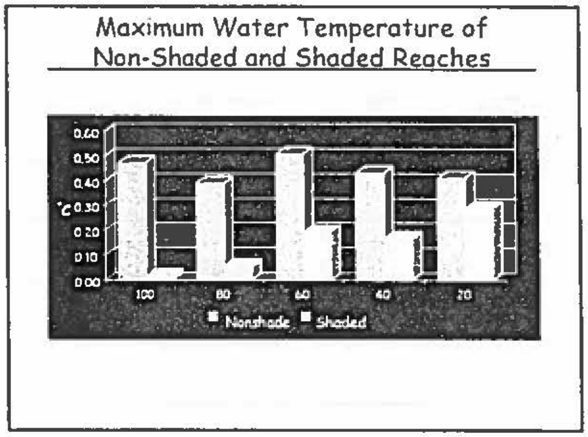
Tank Shade Experiments (Moore et al.)



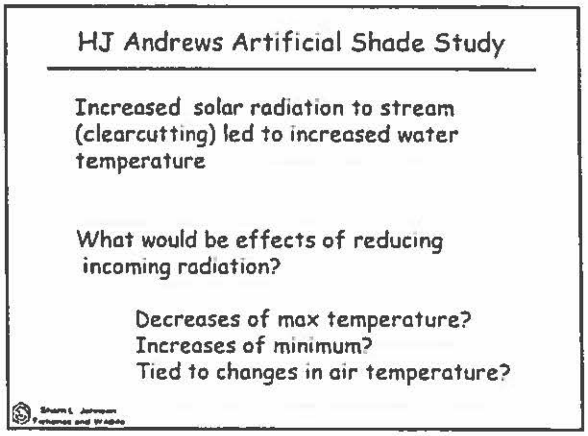


Effect of Shade on Temperature of Irrigation Ditch Water

Shade Study - August 1998



Maximum Water Temperature of Non-Shaded and Shaded Reaches

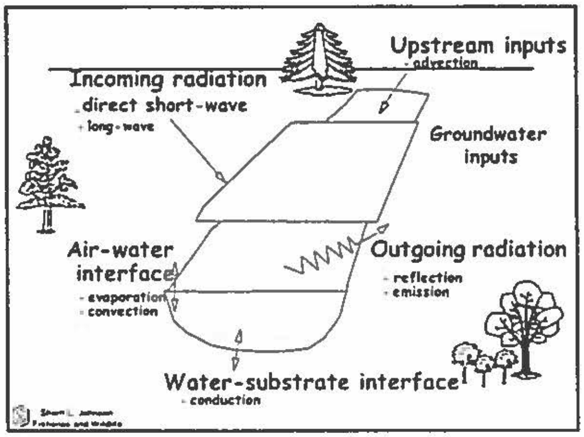


HJ Andrews Artificial Shade Study

Increased solar radiation to stream (clearcutting) led to increased water temperature

What would be effects of reducing incoming radiation?

Decreases of max temperature?
Increases of minimum?
Tied to changes in air temperature?



Upstream inputs
- advection

Incoming radiation
- direct short-wave
- long-wave

Groundwater inputs

Air-water interface
- evaporation
- convection

Outgoing radiation
- reflection
- emission

Water-substrate interface
- conduction

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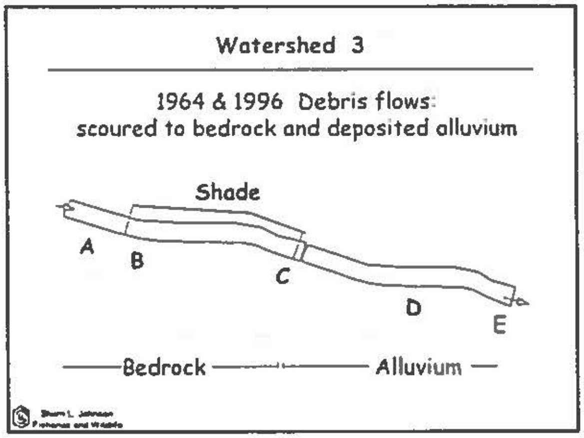

Watershed 3

1964 & 1996 Debris flows:
scoured to bedrock and deposited alluvium

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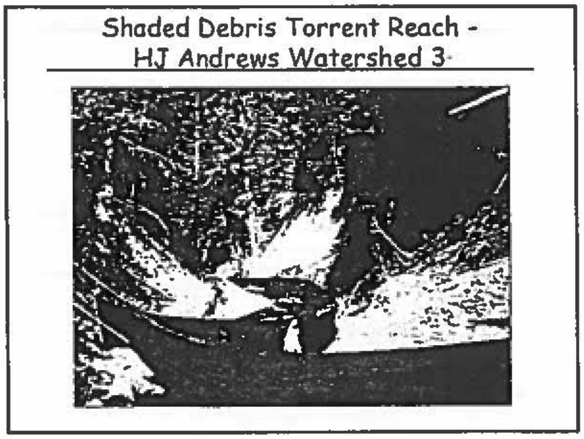
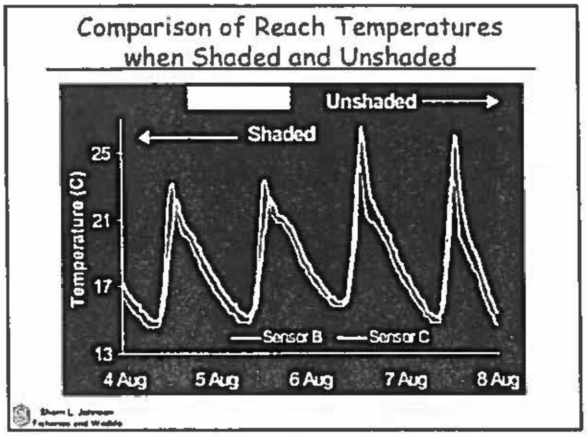
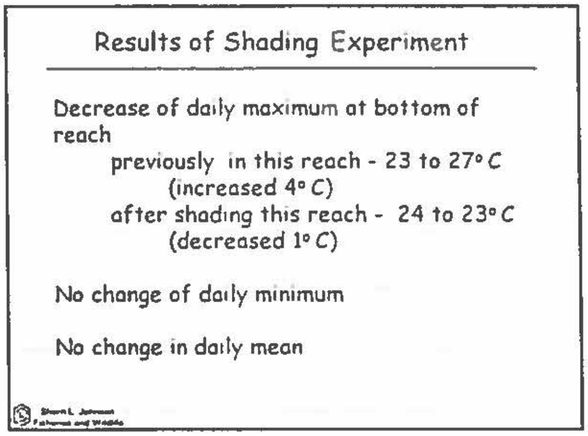


Shaded Debris Torrent Reach - HJ Andrews Watershed 3



Comparison of Reach Temperatures when Shaded and Unshaded



Results of Shading Experiment

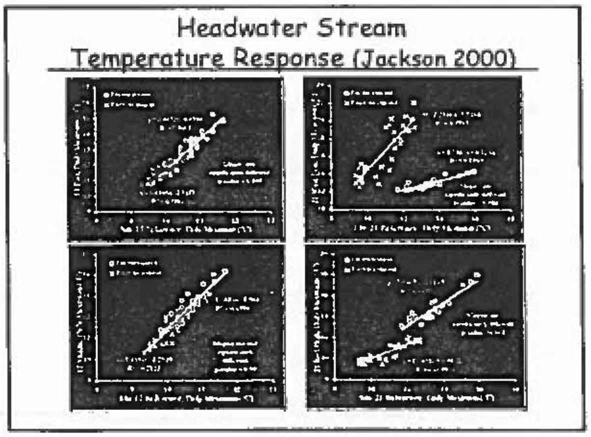
Decrease of daily maximum at bottom of reach

previously in this reach - 23 to 27° C
(increased 4° C)

after shading this reach - 24 to 23° C
(decreased 1° C)

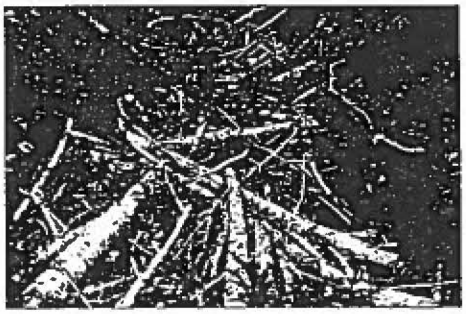
No change of daily minimum

No change in daily mean

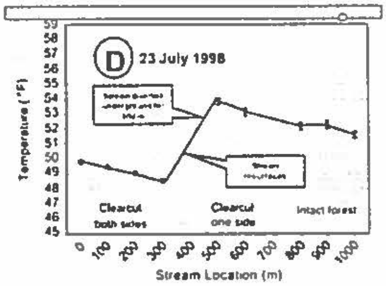


Headwater Stream Temperature Response (Jackson 2000)

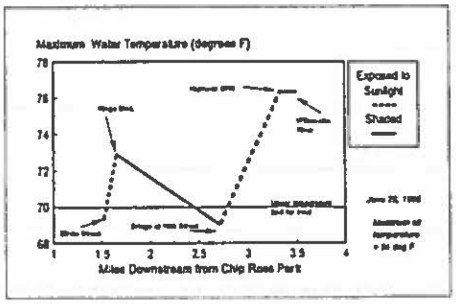
Headwater Stream Buried in Slash with Abundant Effective Shading



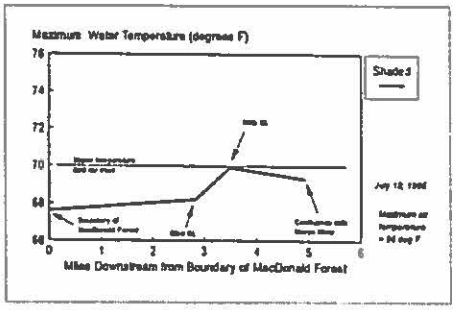
Headwater Stream Temperature Response (Hagan 2000)



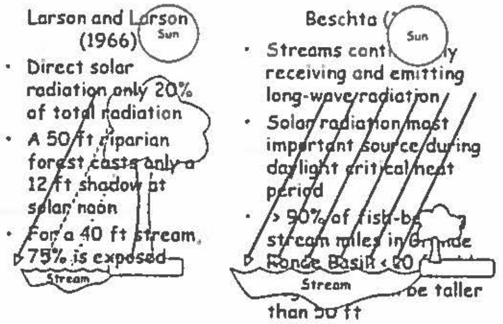
Dixon Creek Shade Response



Lower Oak Creek Response to Shade



Size Matters!!



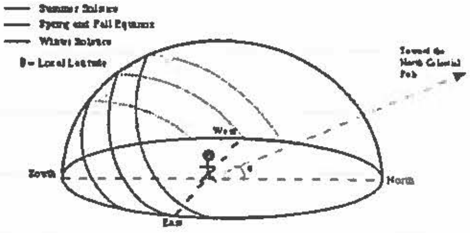
Larson and Larson (1966)

- Direct solar radiation only 20% of total radiation
- A 50 ft riparian forest casts only a 12 ft shadow at solar noon
- For a 40 ft stream, 75% is exposed

Beschta (

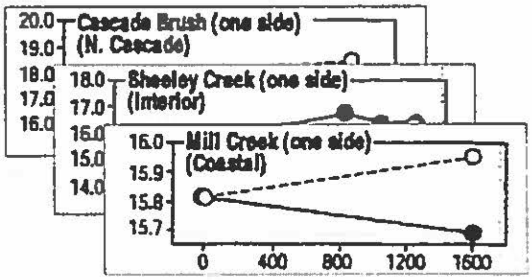
- Streams cont ly receiving and emitting long-wave radiation
- Solar radiation most important source during daylight critical heat period
- > 90% of fish-be g stream miles in Gr nde Ronde Basin < 20 be taller than 50 ft

Effectiveness of One-Sided Buffers



Effectiveness of One-Sided Buffers

(Zwieniecki and Newton 1999)



Conifer vs. Hardwood Shade

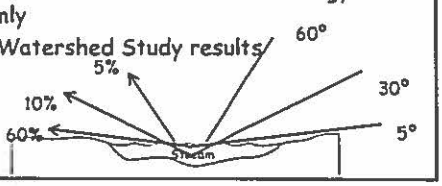
- Alder a vigorous pioneer species
- Alsea example shows rapid recovery and current temperature for Needle Branch no different than pre-treatment
- Conifer stands can persist longer
- ODF Shade Study shows little difference
- May be more difference between ages of stands
- COPE results similar

Multiple Layers

- Conceptually important
- COPE study results suggest lower branch pruning of alder riparian stand may result in increased energy to stream
- ODF Shade Study looking at different heights for hemispheric photography (3 and 10 feet)
- Chan suggests growth response to light

Reflected Radiation

- Unlikely that reflected solar radiation from a clearcut will significantly alter riparian energy input
- Reflected radiation most likely at low angles
- Vegetation scatters and adsorbs energy randomly
- Alsea Watershed Study results

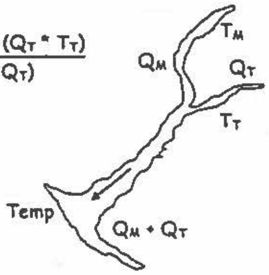


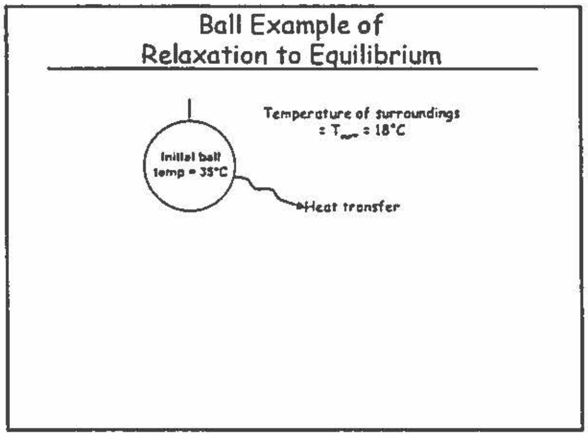
Better Methods to Measure Shade

- Hemispherical photos more complicated and costly but provide permanent record and more direct measure of shade at critical times
- Angular canopy density measurement methods might improve estimates of energy attenuation
- Need for study to determine whether improvements warrant extra cost and difficulty

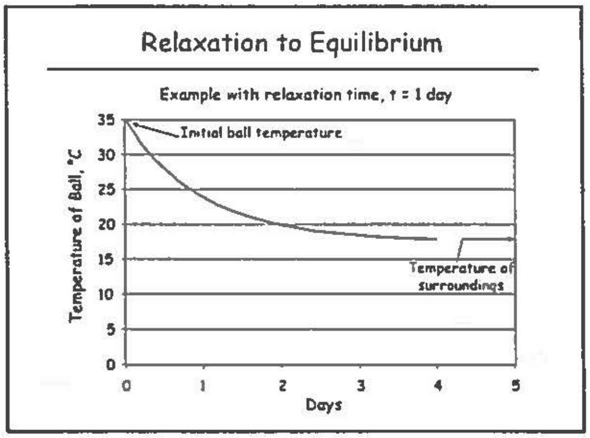
Mixing Ratio

$$\text{Temp} = \frac{(Q_M * T_M) + (Q_T * T_T)}{(Q_M + Q_T)}$$





Ball Example of Relaxation to Equilibrium

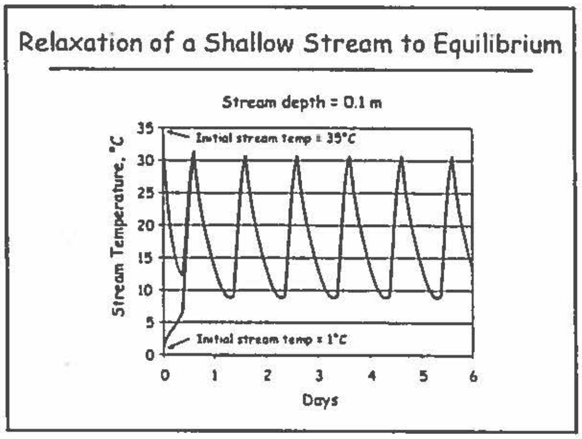


Relaxation to Equilibrium

Data for Stream Temperature Example

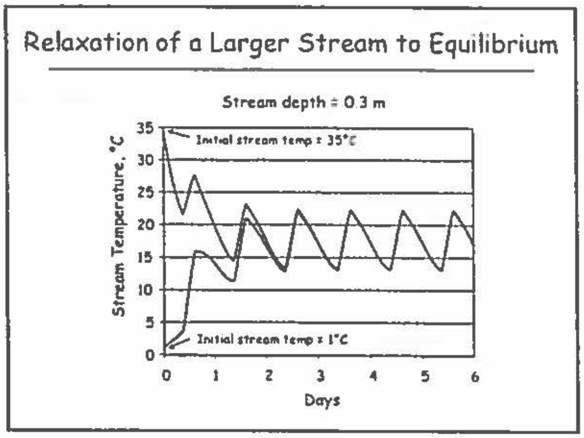
Example Data

Average air temperature	16 °C
Air temperature fluctuations	12 °C
Daily average solar insolation	280 W/sq m
Cloudiness factor	0%
View factor-stream for sky	50%
Air velocity	0.5 m/s
Water vapor in air	9.0 mbar
Stream depth	0.1 m
Groundwater inflow	0.0005 kg/sq m/s
Groundwater temperature	8 °C
Short-wave absorptivity	0.95
Long-wave absorptivity	0.95
Effective stream bed heat transfer coefficient	6.7 W/sq m/°C



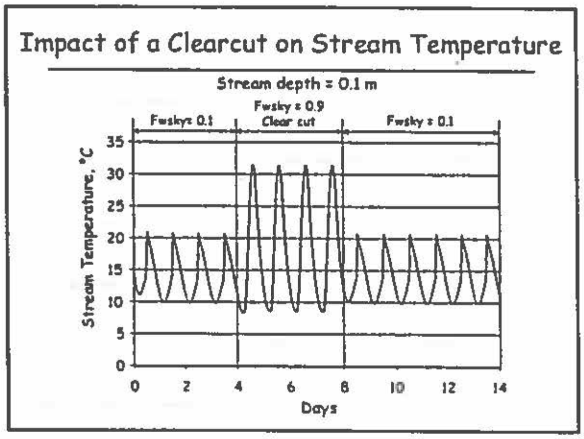
Relaxation of a Shallow Stream to Equilibrium

Stream depth = 0.1 m



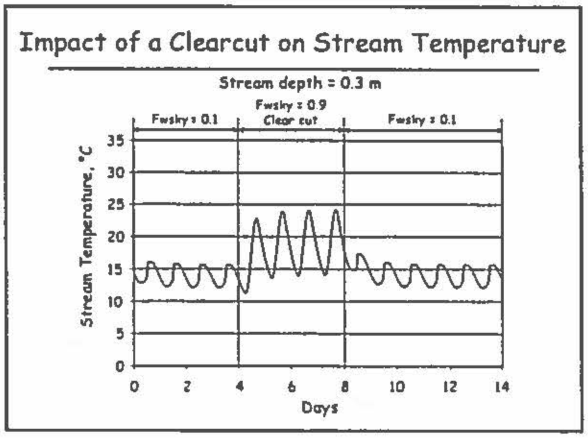
Relaxation of a Larger Stream to Equilibrium

Stream depth = 0.3 m

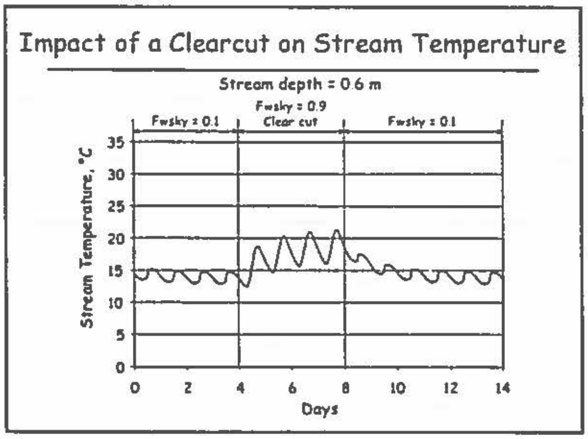


Impact of a Clearcut on Stream Temperature

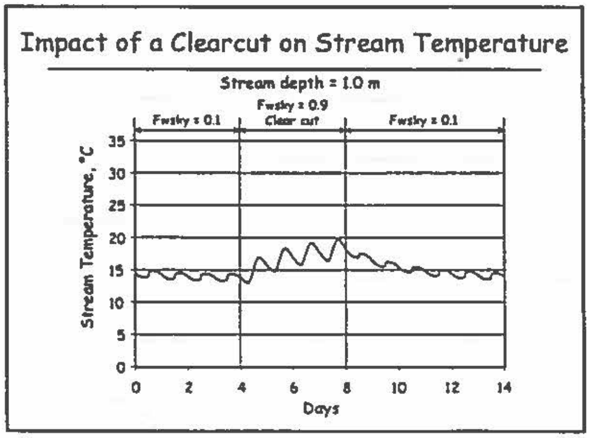
Stream depth = 0.1 m



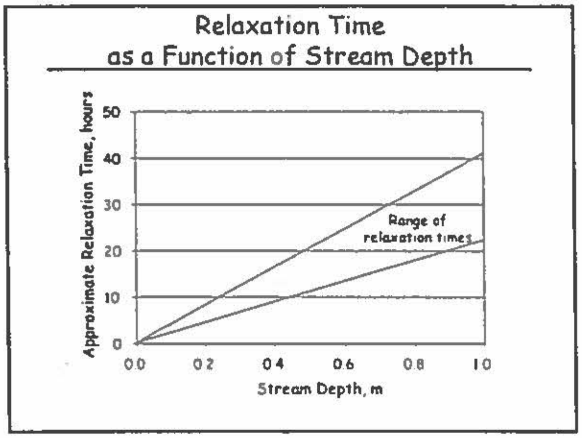
Impact of a Clearcut on Stream Temperature



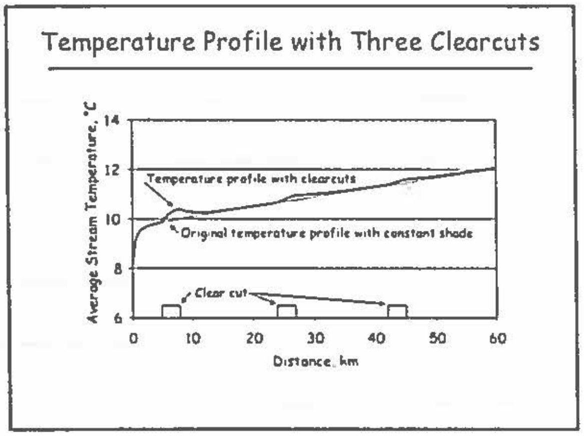
Impact of a Clearcut on Stream Temperature



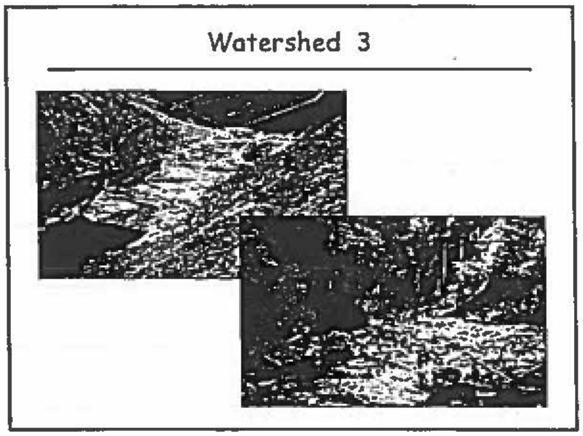
Impact of a Clearcut on Stream Temperature



Relaxation Time as a Function of Stream Depth

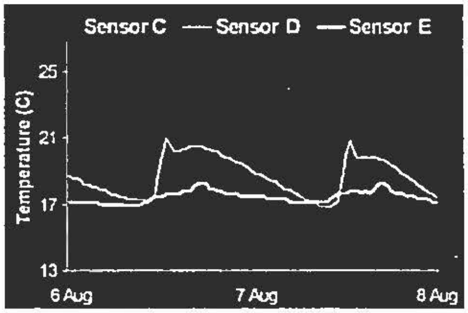


Temperature Profile with Three Clearcuts



Watershed 3

Unshaded Water Temperature

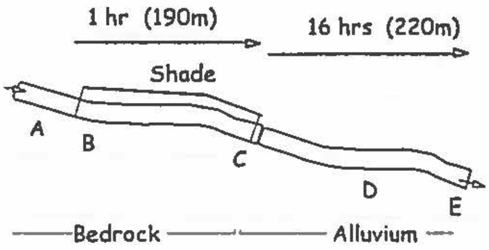


Water Transport/Retention Through Reach

Method	Velocity (m/s)	
	Bedrock	Alluvium
flow meter	0.20	0.15
leading edge dye	0.10	0.02
solute (median)	0.05	0.005

Watershed 3

Median water travel time

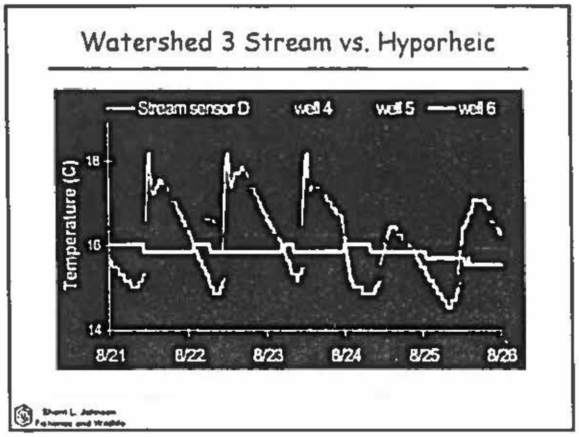

1 hr (190m)

16 hrs (220m)

Shade

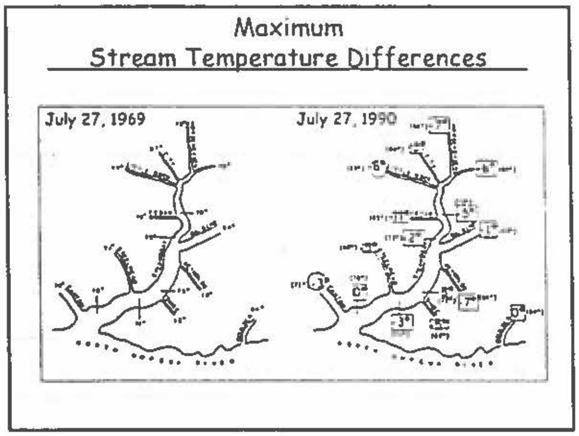
Bedrock

Alluvium

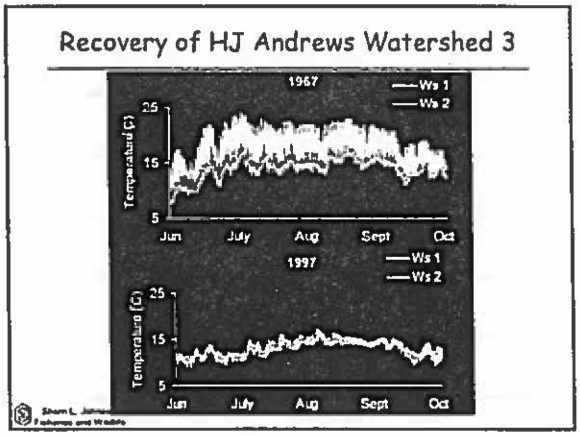


Watershed 3 Stream vs. Hyporheic

Sherri L. Johnson
Fisheries and Wildlife



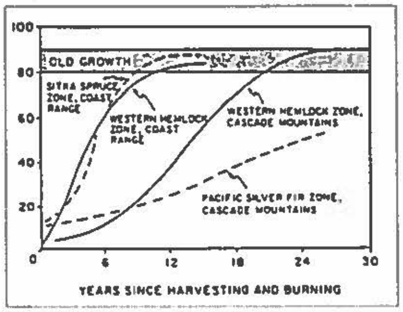
Maximum Stream Temperature Differences



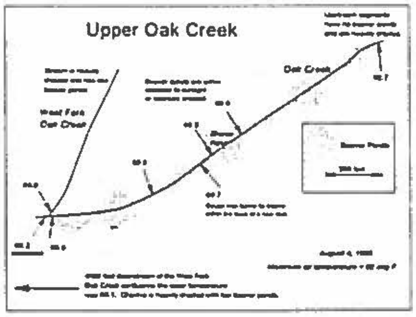
Recovery of HJ Andrews Watershed 3

Sherri L. Johnson
Fisheries and Wildlife

Relation Between Angular Canopy Density (ACD) and Stand Age



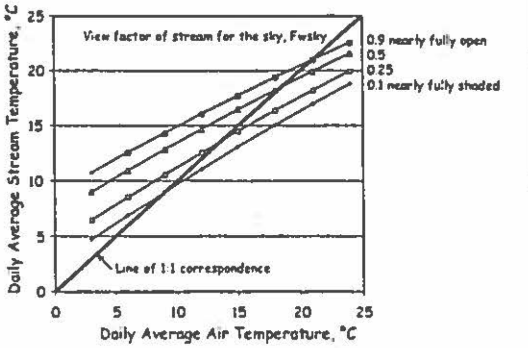
Role of Beaver Ponds in Upper Oak Creek



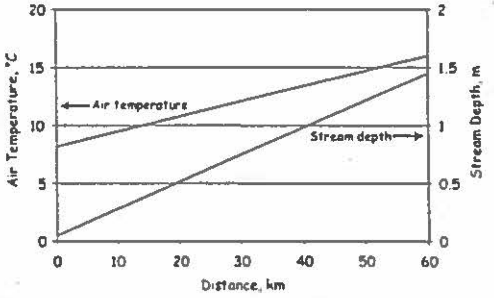
Independent Multidisciplinary Science Team (IMST) Conclusions

- Solar radiation is the principle energy source that causes stream heating
- Shading reduces direct solar radiation loading and stream heating
- The influence of vegetation decreases with increasing channel width
- Rate of changes increases with greater width/depth ratio
- Streams tend to heat going downstream
- Stream temperature tends to move toward equilibrium temperatures based on the energy balance

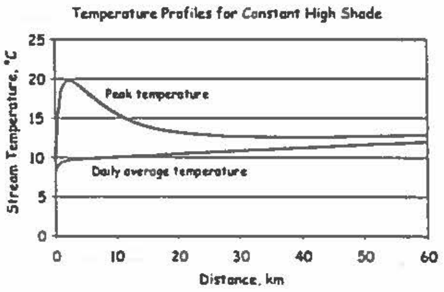
Average Stream and Air Temperature



Air Temperature and Stream Depth Profiles



Average and Peak Temperature Profiles



Conclusions

- Solar heat flux is the major input that *raises* the stream temperature *above* the local air temperature
- Ground water inflow is the major input that *lowers* the stream temperature *below* the local air temperature
- All other heat flux terms involve both the air and water temperatures, so the water temperature is always near the local air temperature
- Energy transfer between the stream and its local environment always tends to bring the stream into equilibrium, with a zero net heat flux for the day

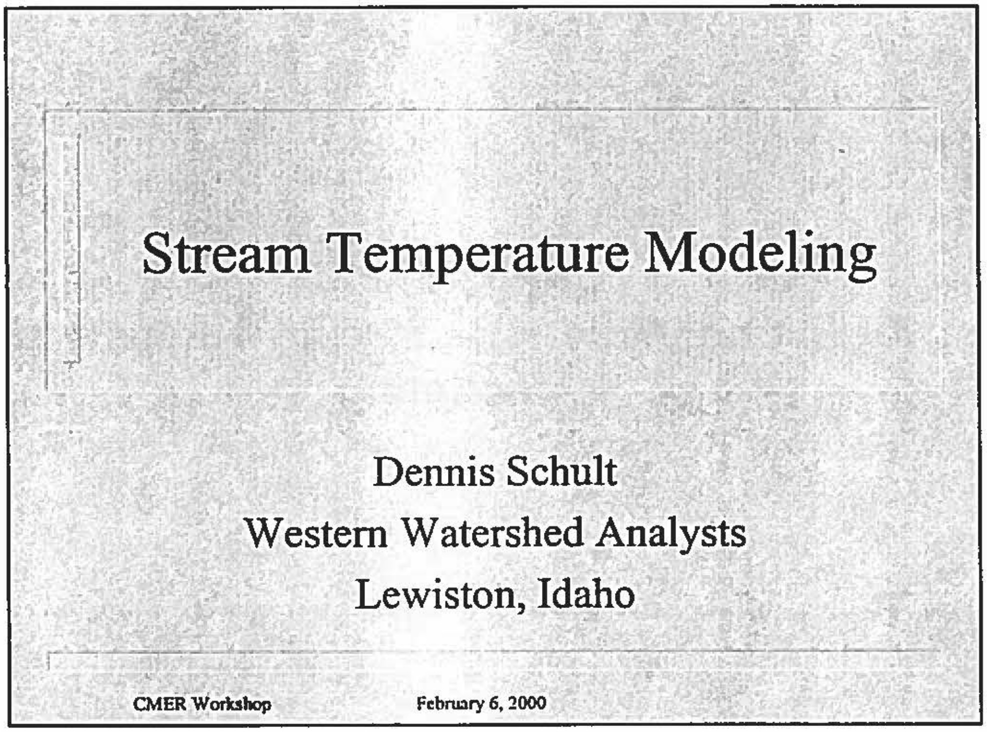
Conclusions (continued)

- The rate at which stream temperature approaches equilibrium is strongly influenced by the average stream depth
  - small streams relax toward equilibrium more rapidly than large streams
- The slow response of larger streams to changes in the environment makes a stream slow to respond to diurnal variations, thus reducing diurnal temperature variations

Conclusions (continued)

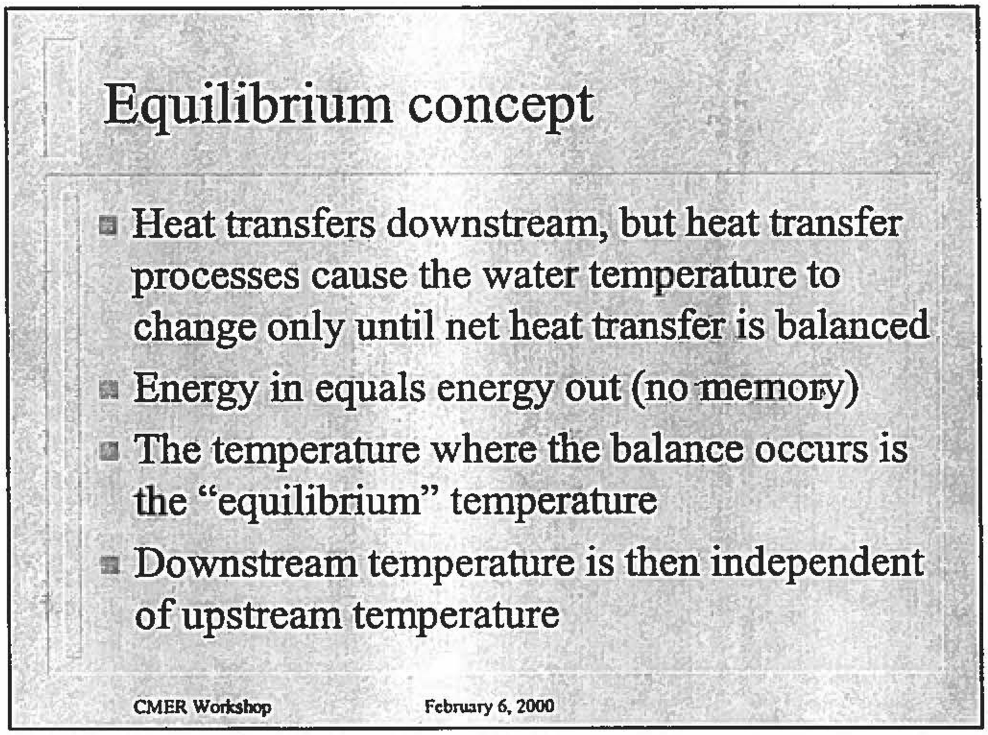
- The shade factor, here represented by the view-of-the-stream-for-the-sky, Fwsky, is important in both mean and peak stream temperatures
- Other shade and cover measures can be used to estimate the role of vegetation in reducing direct solar radiation inputs to a stream
- Shade from riparian vegetation offers a practical management option to control changes in stream temperature

Appendix C
Additional Material – Stream Temperature Modeling



Stream Temperature Modeling

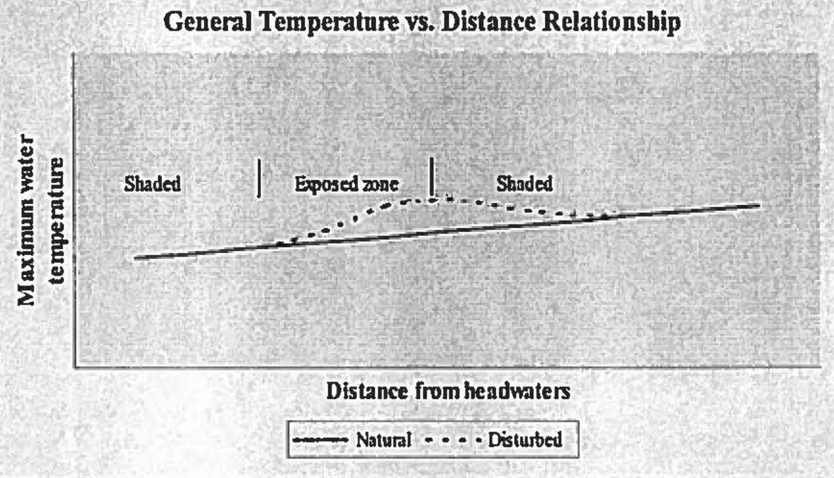
Dennis Schult
Western Watershed Analysts
Lewiston, Idaho



Equilibrium concept

- Heat transfers downstream, but heat transfer processes cause the water temperature to change only until net heat transfer is balanced
- Energy in equals energy out (no memory)
- The temperature where the balance occurs is the "equilibrium" temperature
- Downstream temperature is then independent of upstream temperature

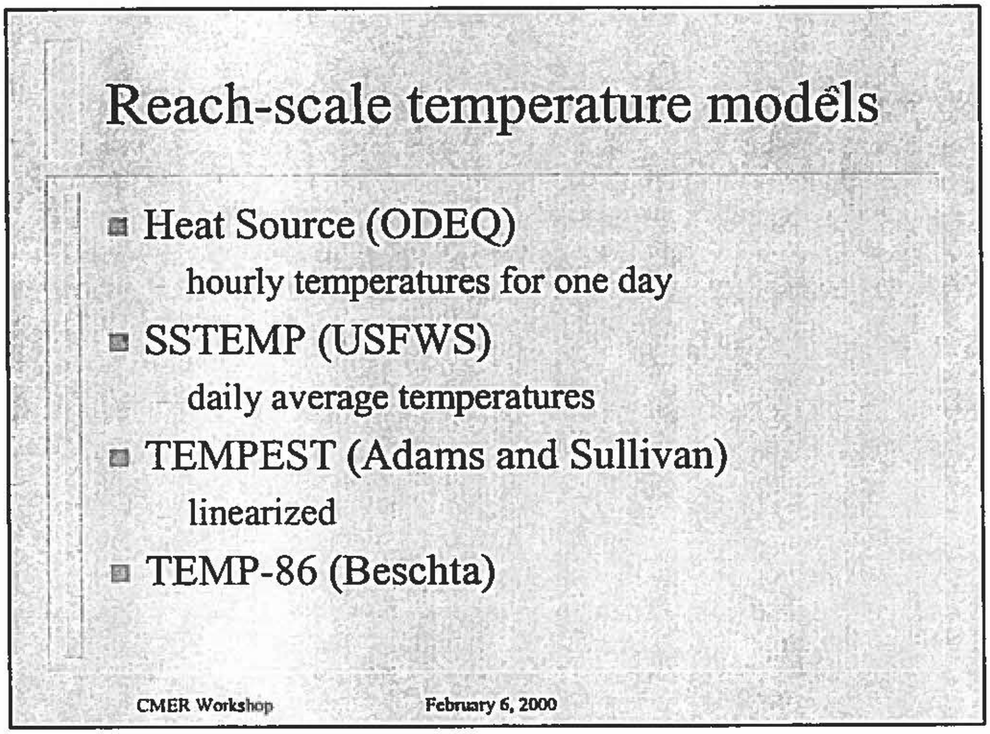
Equilibrium illustration



Influence of air temperature and stream depth

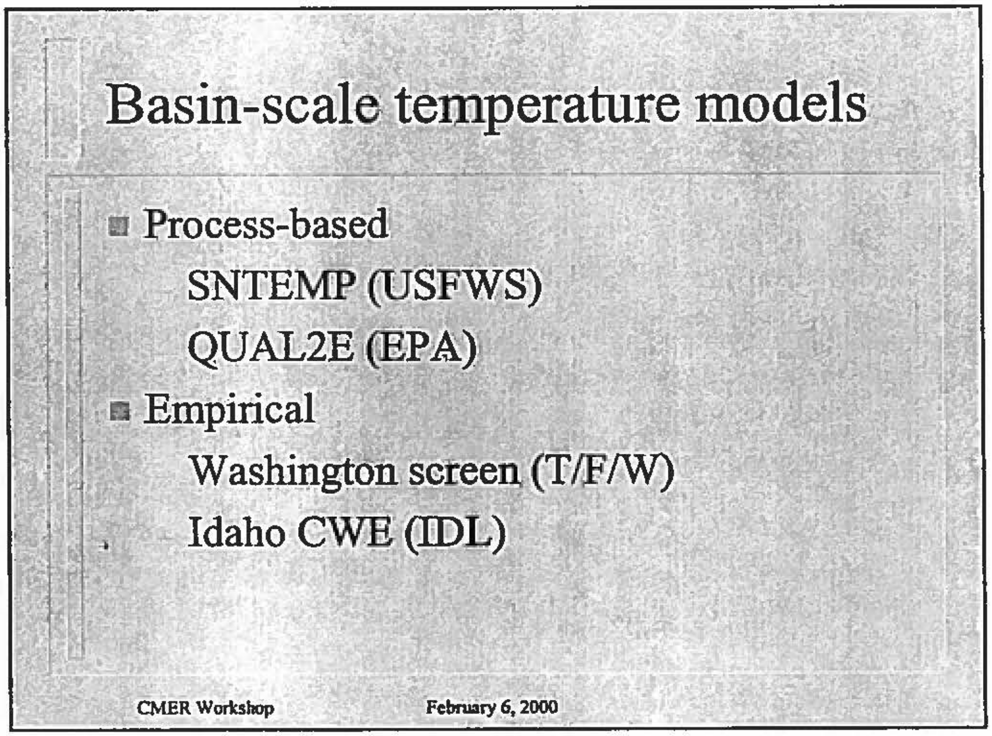
- At equilibrium, mean daily air and water temperatures are nearly the same
- Diurnal water temperature cycle is due to the cycle of solar radiation and air temperature
  - Diurnal water temperature fluctuations are always less than the diurnal air temperature fluctuations
- Water temperature variations are smaller for deeper streams, and time to equilibrium is longer

(Adams and Sullivan 1990)



Reach-scale temperature models

- Heat Source (ODEQ)
  - hourly temperatures for one day
- SSTEMP (USFWS)
  - daily average temperatures
- TEMPEST (Adams and Sullivan)
  - linearized
- TEMP-86 (Beschta)

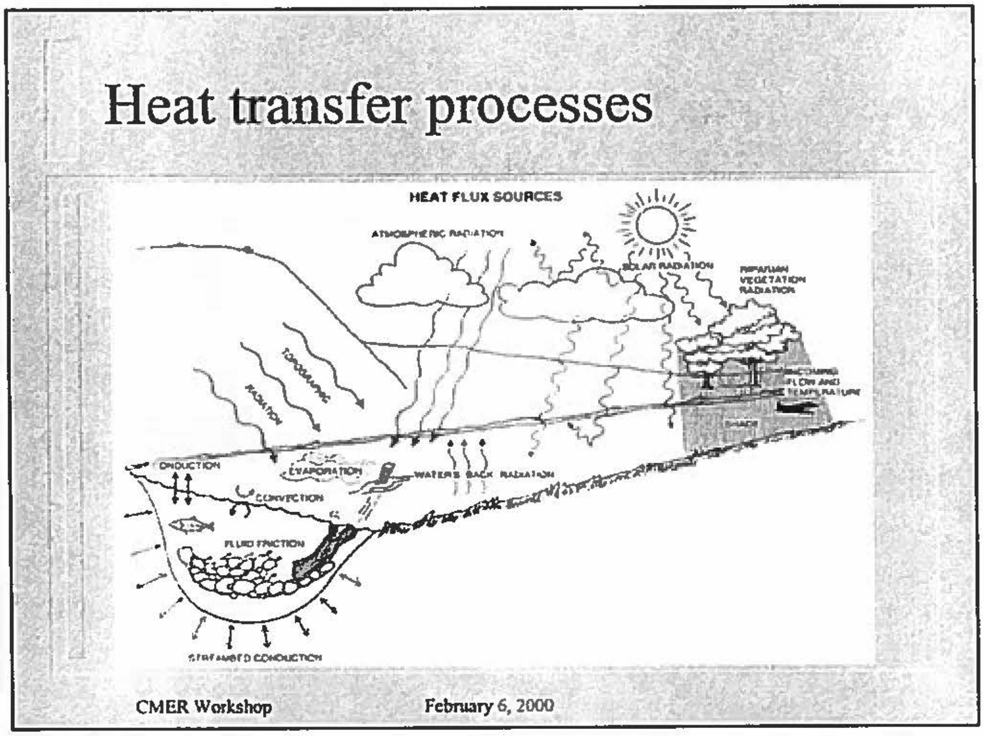


Basin-scale temperature models

- Process-based
  - SNTEMP (USFWS)
  - QUAL2E (EPA)
- Empirical
  - Washington screen (T/F/W)
  - Idaho CWE (IDL)

Fundamental modeling premise (process-based models)

- Stream temperature is the result of physical heat transfer processes
- + Net energy flux ⟶ temperature ↑
- - Net energy flux ⟶ temperature ↓

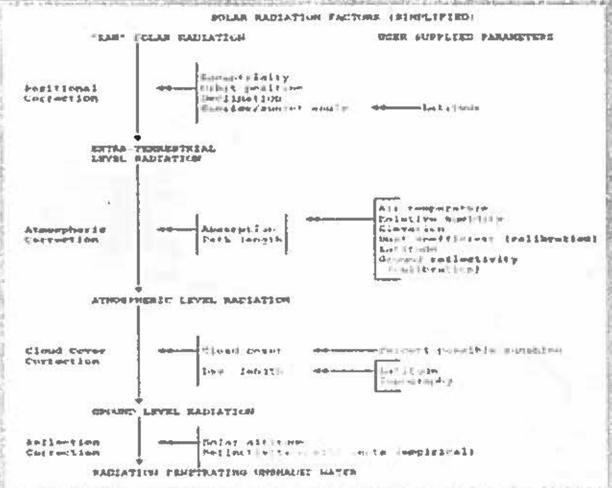


Heat transfer processes

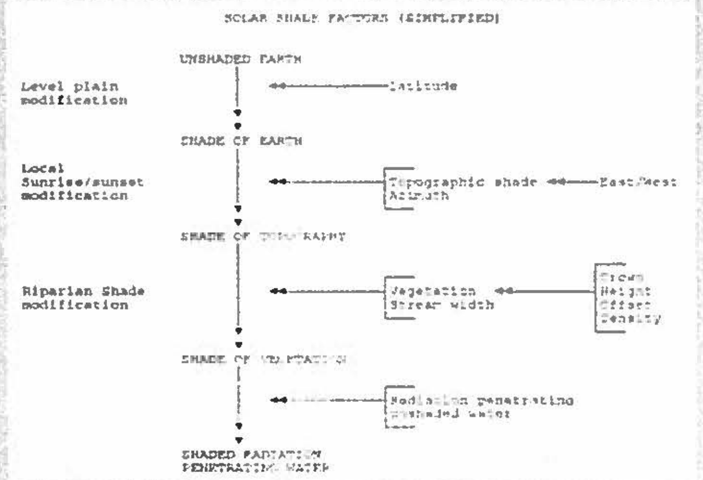
Heat transfer process modeling

- Solar radiation (shortwave)
- Stream / vegetation and sky (longwave)
- Evaporation from stream
- Convection between stream and air
- Conduction between stream and streambed
- Groundwater exchange

Solar radiation



Shade



SOLAR SHADE FACTORS (SIMPLIFIED)

UNSHADED EARTH

Level plain modification

Latitude

SHADE OF EARTH

Local Sunrise/sunset modification

Topographic shade

Azimuth

East/West

SHADE OF TOPOGRAPHY

Riparian Shade modification

Vegetation

Stream width

Crown

Height

Offset

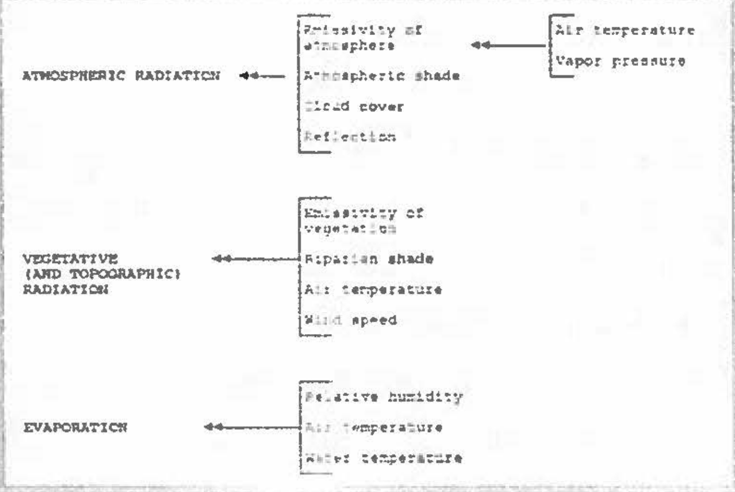
Density

SHADE OF VEGETATION

Radiation penetrating unshaded water

SHADED RADIATION PENETRATING WATER

Longwave radiation and evaporation



ATMOSPHERIC RADIATION

Emissivity of atmosphere

Atmospheric shade

Cloud cover

Reflection

Air temperature

Vapor pressure

VEGETATIVE (AND TOPOGRAPHIC) RADIATION

Emissivity of vegetation

Riparian shade

Air temperature

Wind speed

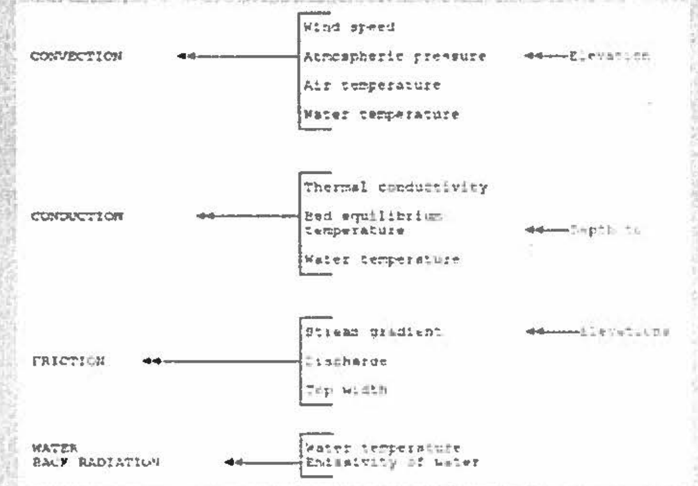
EVAPORATION

Relative humidity

Air temperature

Water temperature

Convection and conduction



CONVECTION ← Wind speed, Atmospheric pressure, Air temperature, Water temperature

Atmospheric pressure ← Elevation

CONDUCTION ← Thermal conductivity, Bed equilibrium temperature, Water temperature

Bed equilibrium temperature ← Depth to

FRICTION ← Stream gradient, Discharge, Top width

Stream gradient ← Elevations

WATER BACK RADIATION ← Water temperature, Emissivity of water

Process model input parameters

- Stream characteristics
  - aspect, depth, width, flow, etc.
- Riparian characteristics
  - buffer height, width, density, overhang, etc.
- Atmospheric conditions
  - air temperature, humidity, wind
- Upstream water temperatures
  - typically hourly throughout a day

Most sensitive input parameters to process models

- Air temperature
- Humidity
- Wind speed
- Stream depth
- Shade (buffer height, width, density)

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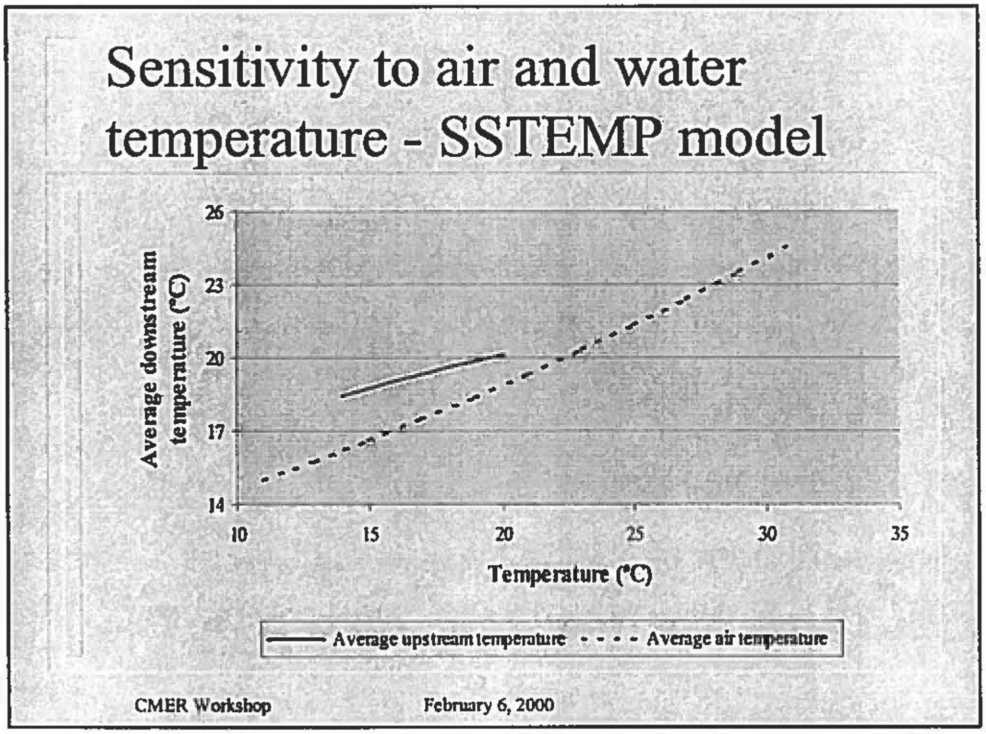

Sensitivity to air and water temperature - SSTEMP model

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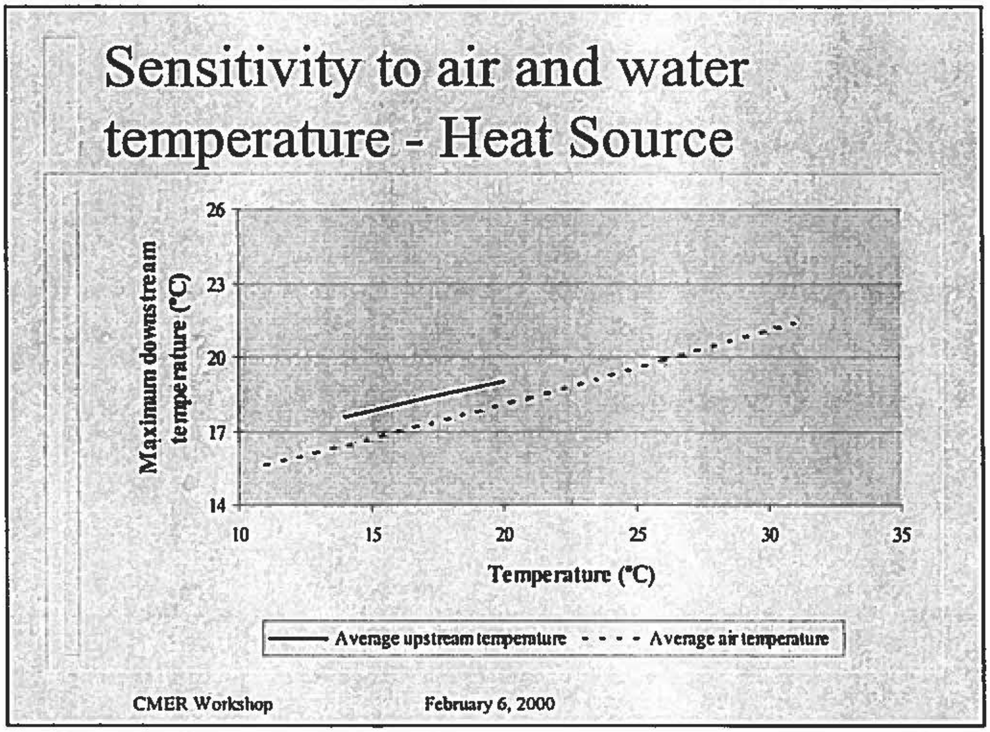

Sensitivity to air and water temperature - Heat Source

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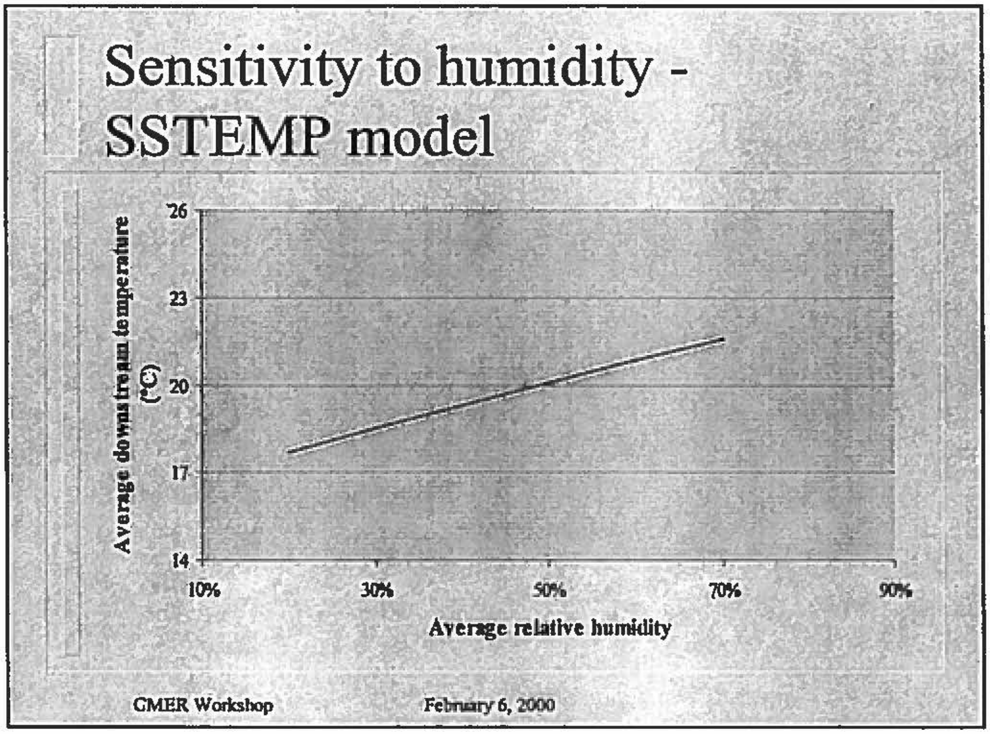

Sensitivity to humidity - SSTEMP model

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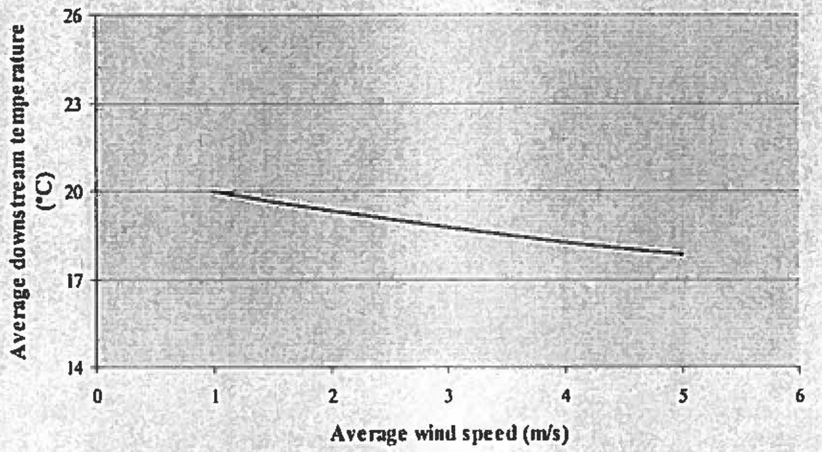
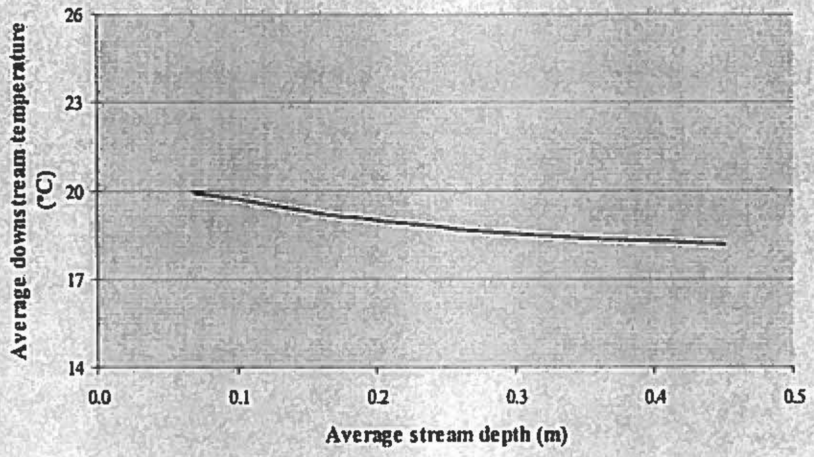
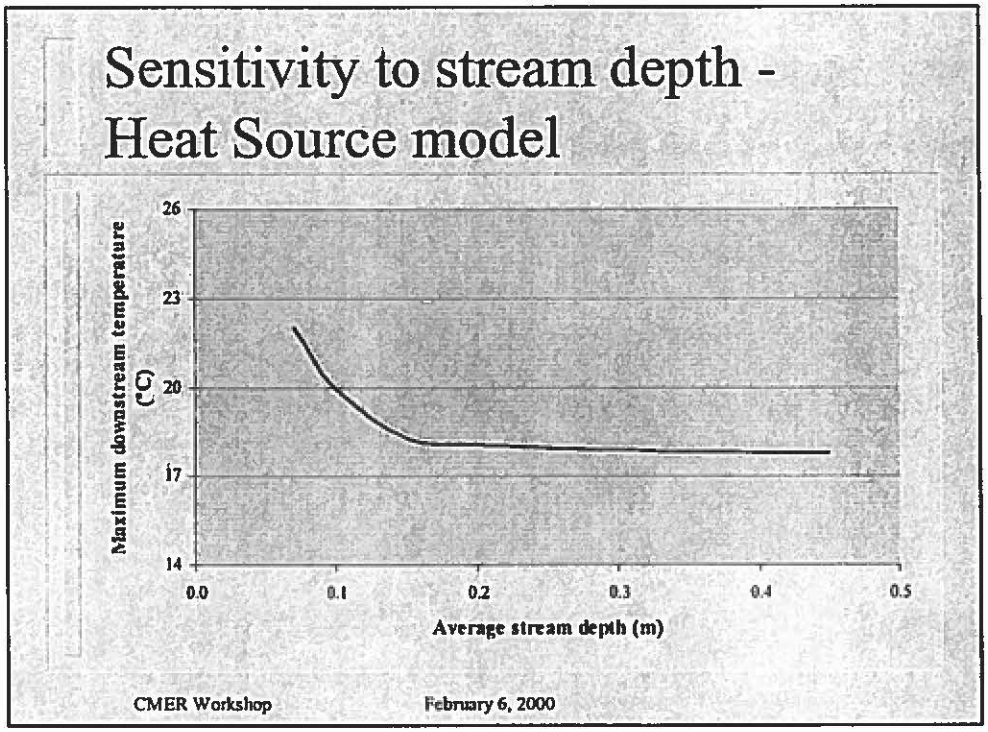
Sensitivity to wind speed - SSTEMP model



Sensitivity to stream depth - SSTEMP model





Sensitivity to stream depth - Heat Source model

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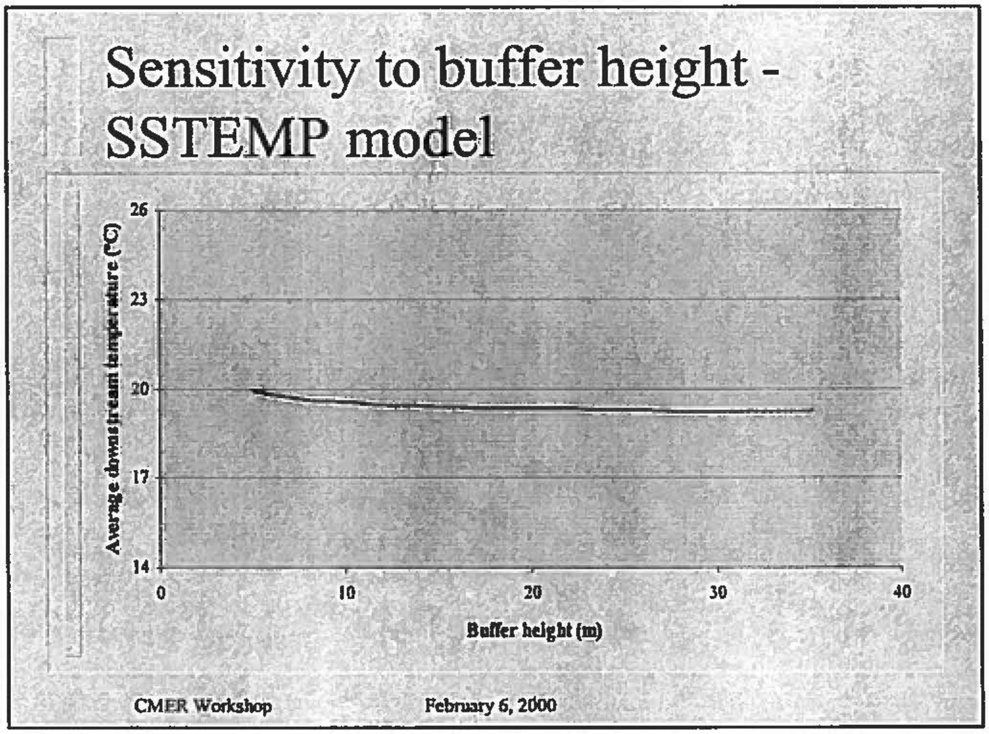

Sensitivity to buffer height - SSTEMP model

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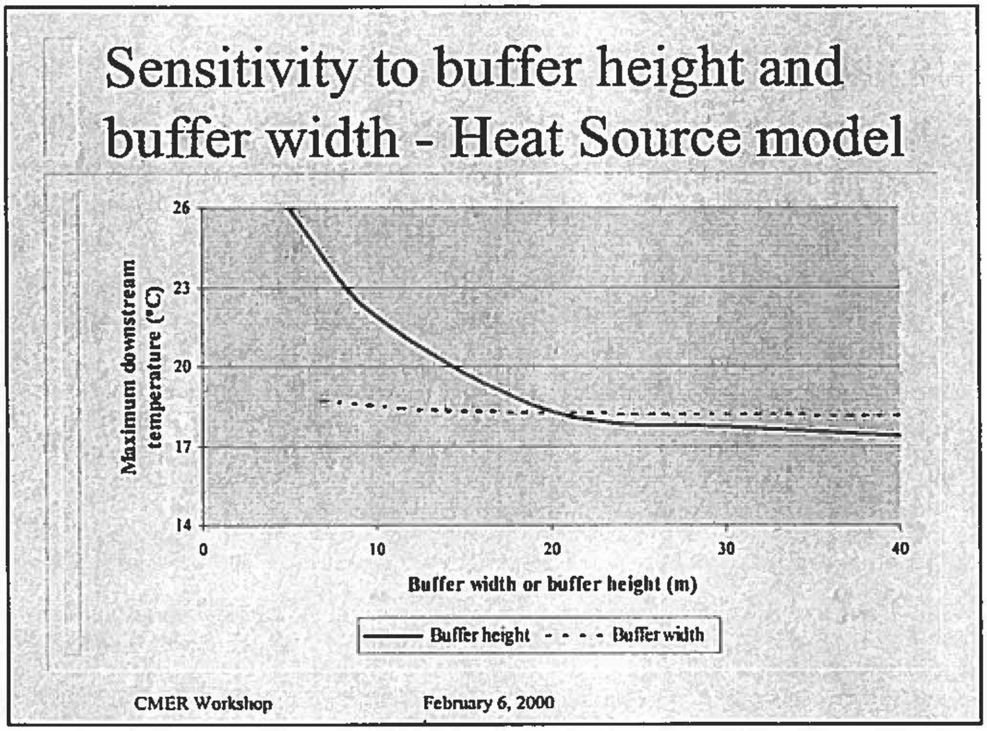

Sensitivity to buffer height and buffer width - Heat Source model

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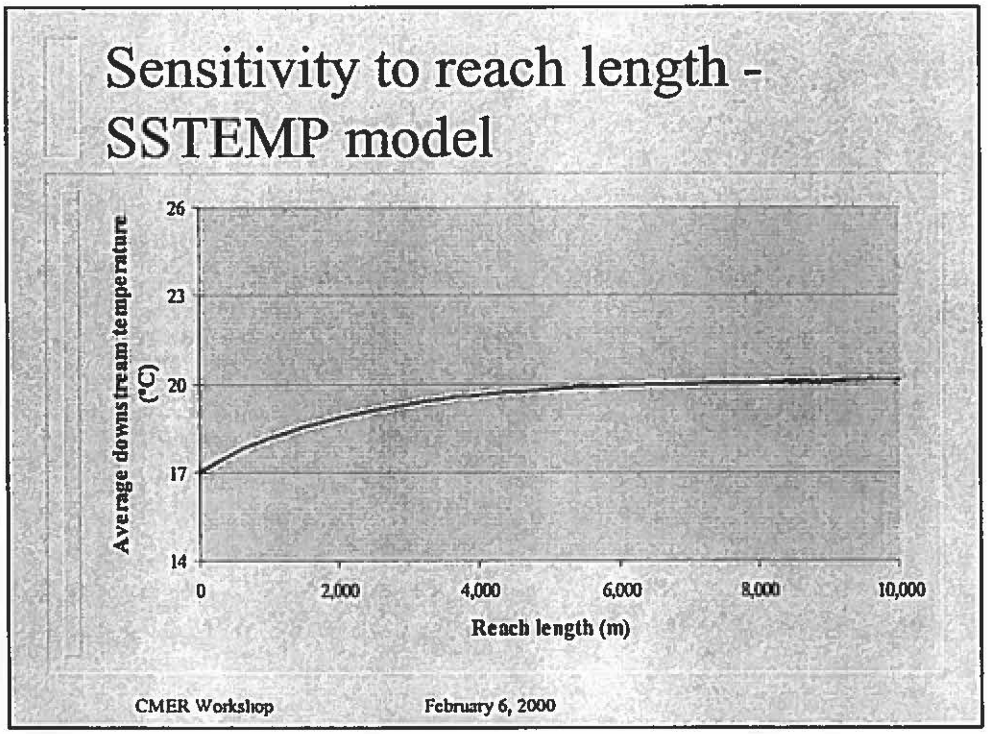

Sensitivity to reach length - SSTEMP model

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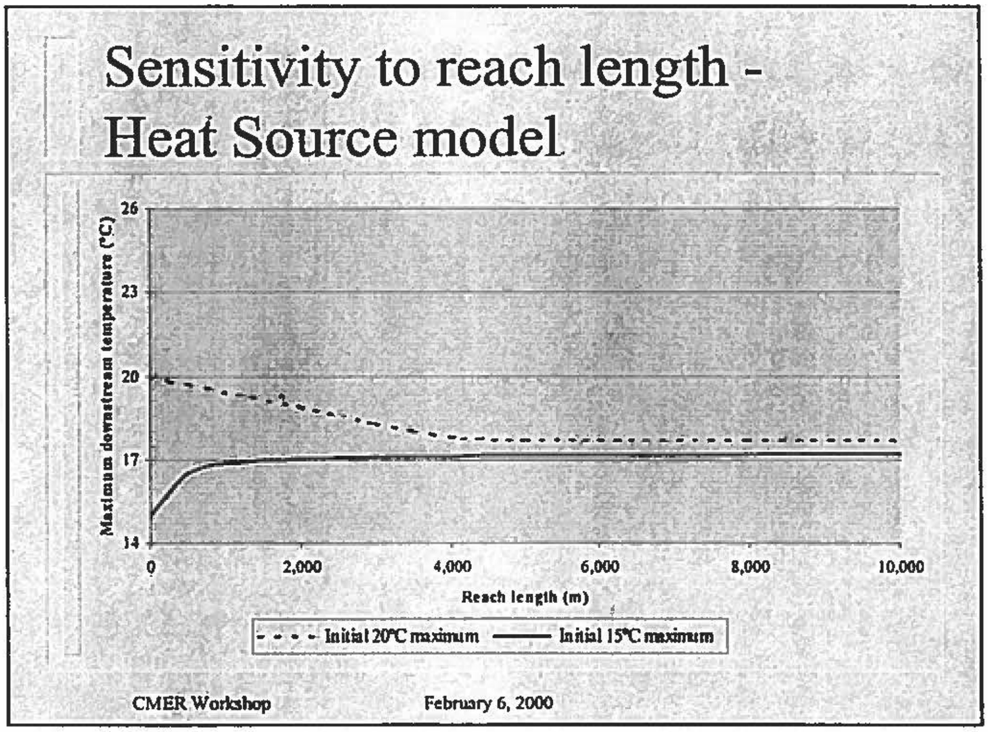

Sensitivity to reach length - Heat Source model

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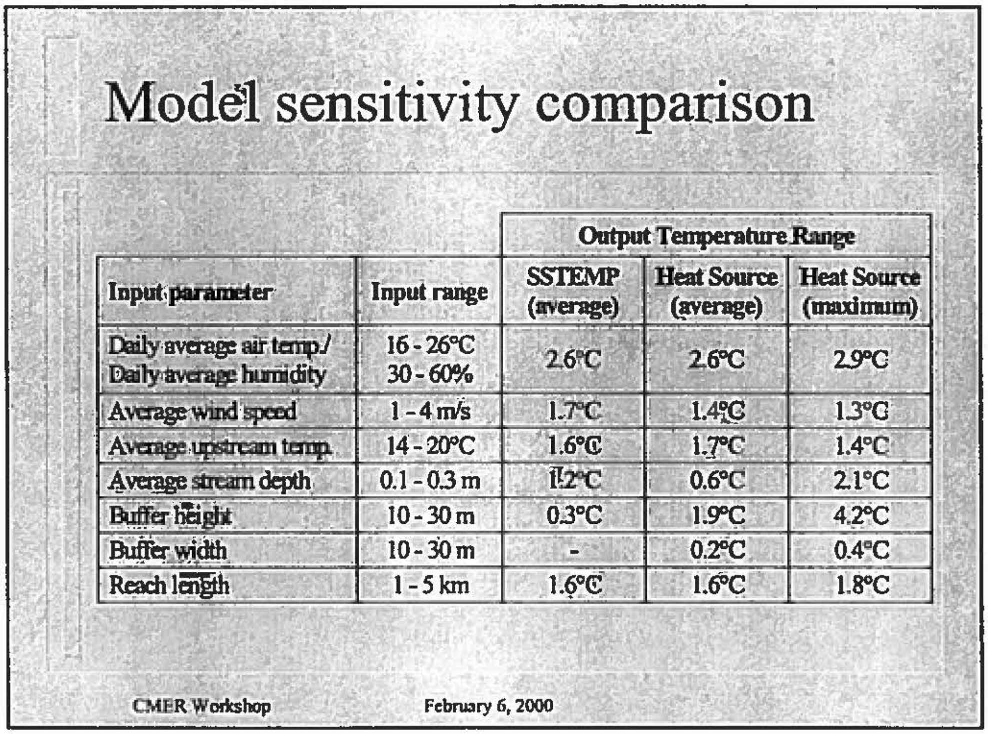

Model sensitivity comparison

Input parameter	Input range	Output Temperature Range SSTEMP (average)	Output Temperature Range Heat Source (average)	Output Temperature Range Heat Source (maximum)
Daily average air temp./ Daily average humidity	16 - 26°C 30 - 60%	2.6°C	2.6°C	2.9°C
Average wind speed	1 - 4 m/s	1.7°C	1.4°C	1.3°C
Average upstream temp.	14 - 20°C	1.6°C	1.7°C	1.4°C
Average stream depth	0.1 - 0.3 m	1.2°C	0.6°C	2.1°C
Buffer height	10 - 30 m	0.3°C	1.9°C	4.2°C
Buffer width	10 - 30 m	-	0.2°C	0.4°C
Reach length	1 - 5 km	1.6°C	1.6°C	1.8°C

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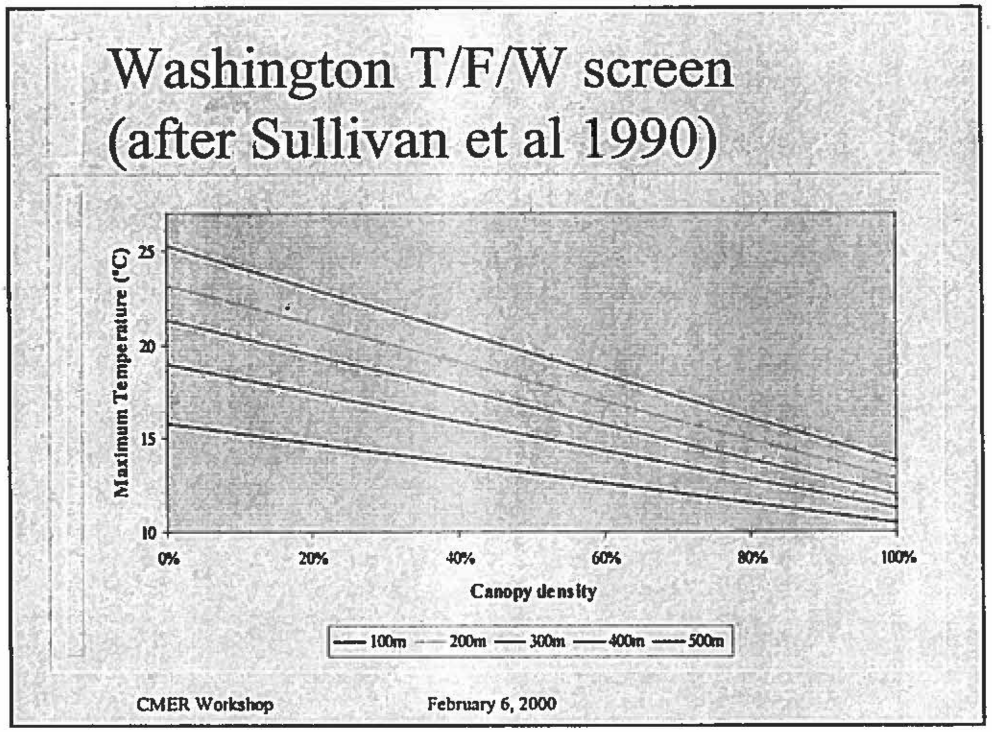
Calibration of process models

- Any process-based model requires some measured water temperature data in order to calibrate the model to local conditions
  - consistent times and locations
- Calibrate by adjusting input parameters
  - air temperature
  - humidity
  - wind speed
  - groundwater temperature

Empirical models

- Measured stream temperatures throughout a region are fit to a regression model utilizing selected input parameters
  - elevation
  - shade
  - stream size (width, depth, flow)
  - average air temperature
  - drought index



Washington T/F/W screen (after Sullivan et al 1990)

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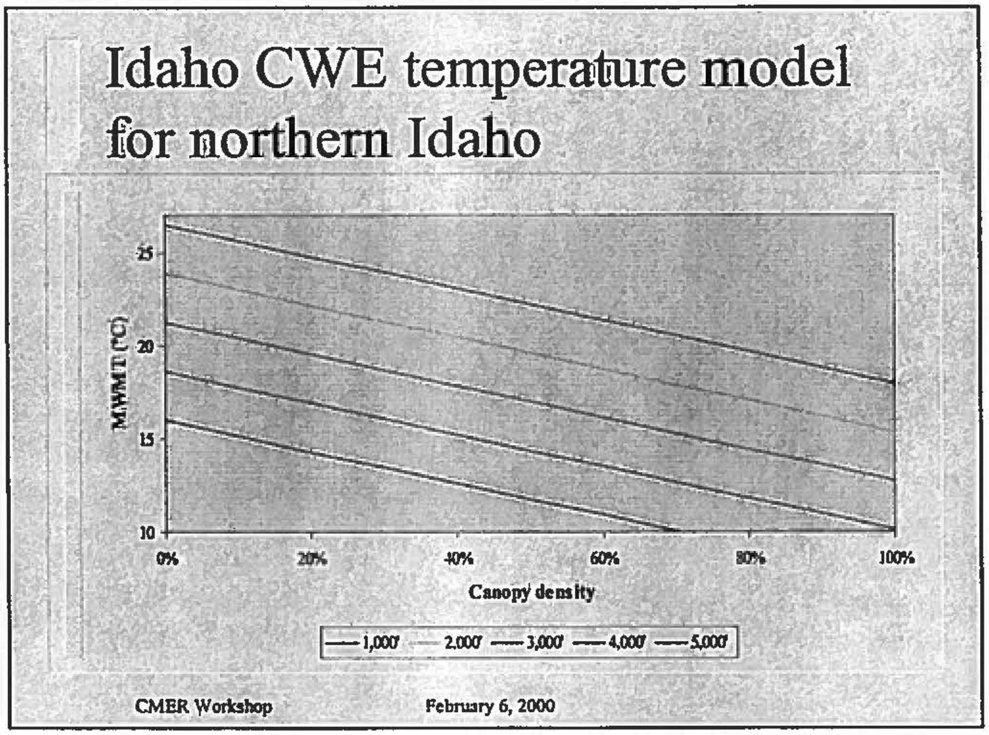

Idaho CWE temperature model for northern Idaho

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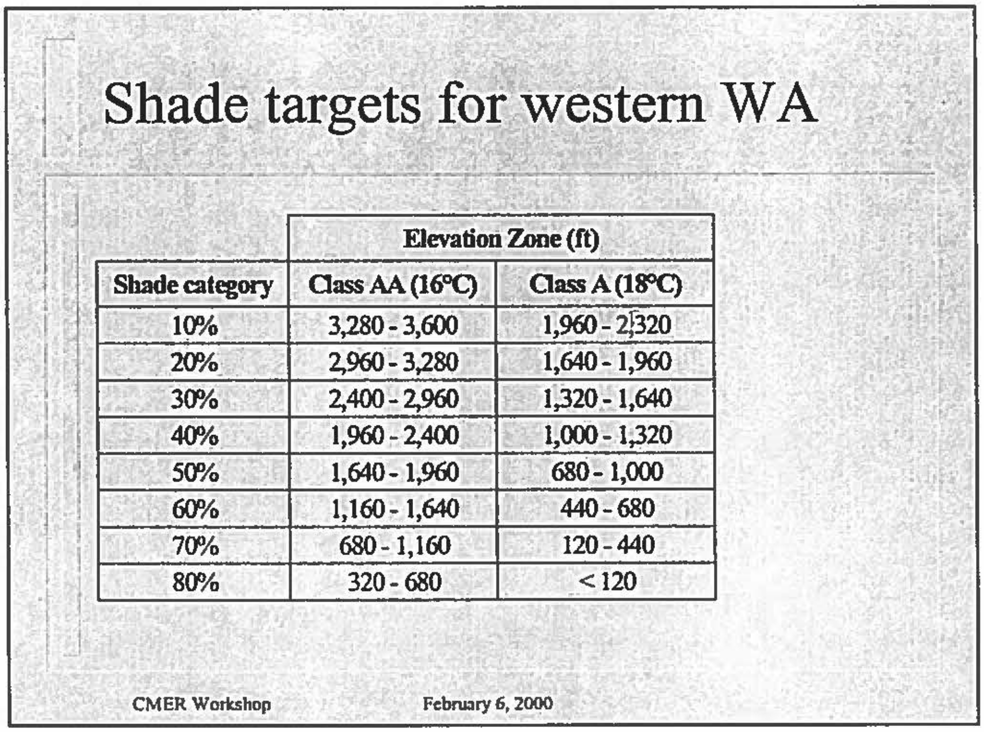

Shade targets for western WA

	Elevation Zone (ft)	
Shade category	Class AA (16°C)	Class A (18°C)
10%	3,280 - 3,600	1,960 - 2,320
20%	2,960 - 3,280	1,640 - 1,960
30%	2,400 - 2,960	1,320 - 1,640
40%	1,960 - 2,400	1,000 - 1,320
50%	1,640 - 1,960	680 - 1,000
60%	1,160 - 1,640	440 - 680
70%	680 - 1,160	120 - 440
80%	320 - 680	< 120

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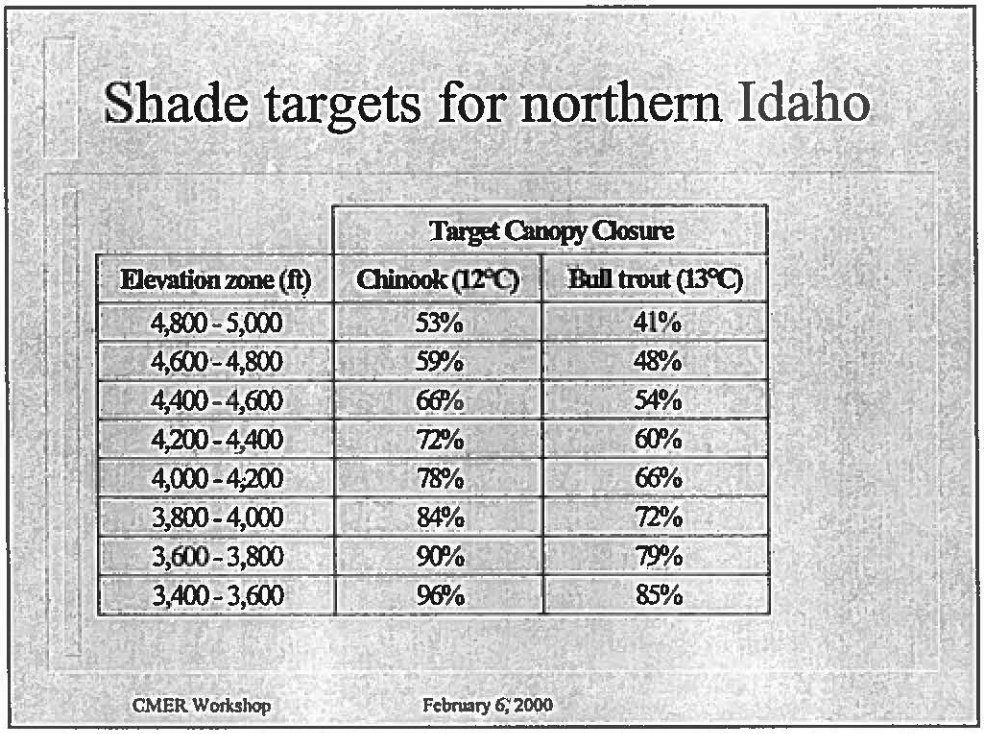

Shade targets for northern Idaho

	Target Canopy Closure	
Elevation zone (ft)	Chinook (12°C)	Bull trout (13°C)
4,800 - 5,000	53%	41%
4,600 - 4,800	59%	48%
4,400 - 4,600	66%	54%
4,200 - 4,400	72%	60%
4,000 - 4,200	78%	66%
3,800 - 4,000	84%	72%
3,600 - 3,800	90%	79%
3,400 - 3,600	96%	85%

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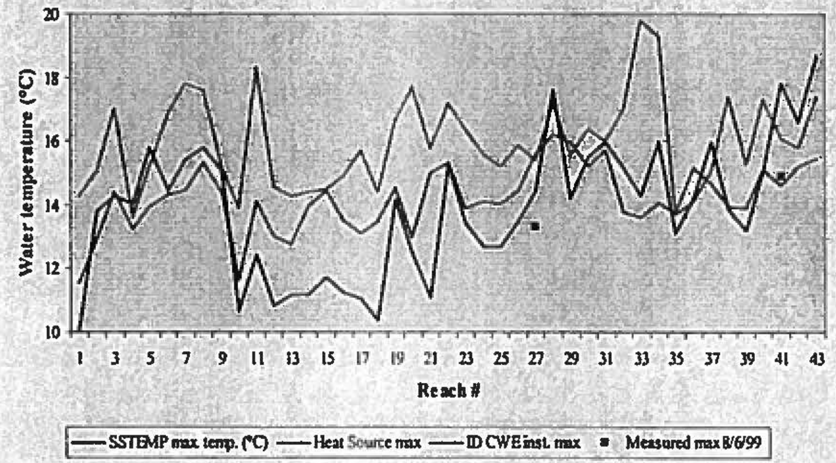
Model prediction comparison - Cold Springs Creek, ID 8/6/99



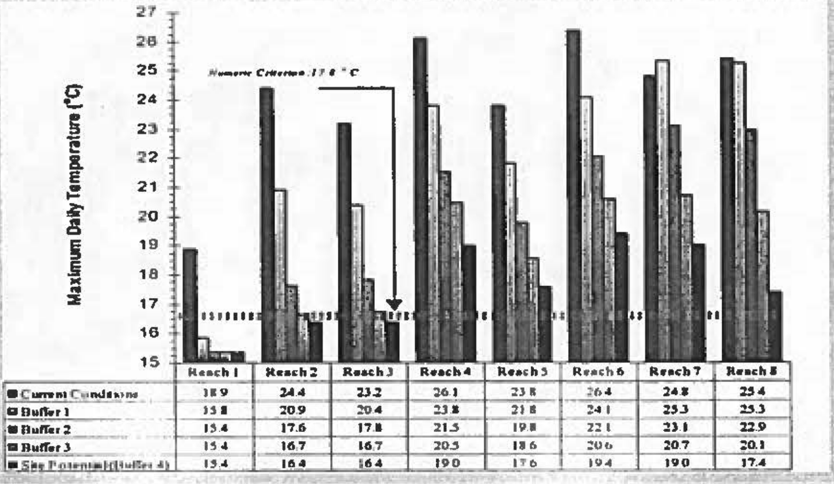
Process-based model pros & cons

- Advantages
  - predict temperatures for any conditions
  - detailed investigation of what-if scenarios
- Disadvantages
  - require numerous inputs
  - require calibration
  - SSTEMP poor predictor of max. temperatures

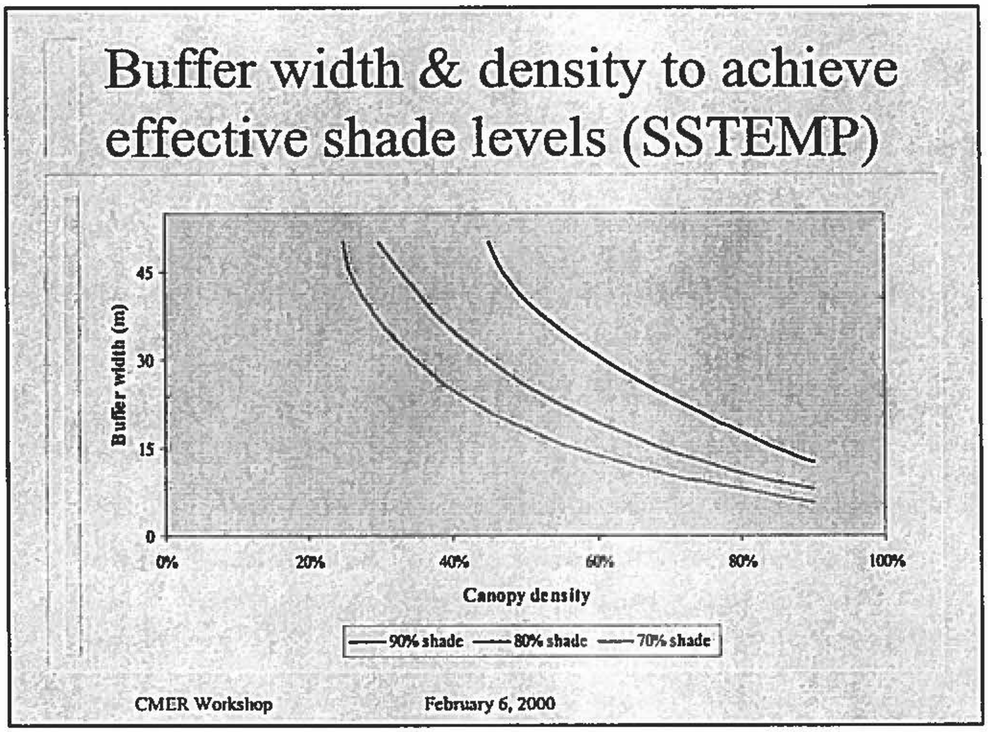
Empirical model pros & cons

- Advantages
  - few input parameters (no calibration)
  - rapid execution
  - models already exist for many NW regions
- Disadvantages
  - require substantial data input up front
  - regressions fit to specific temperature parameters (e.g., summer maximum)

Upper Grande Ronde TMDL



	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8
Current Conditions	18.9	24.4	23.2	26.1	23.8	26.4	24.8	25.4
Buffer 1	15.8	20.9	20.4	23.8	21.8	24.1	25.3	25.3
Buffer 2	15.4	17.6	17.8	21.5	19.8	22.1	23.1	22.9
Buffer 3	15.4	16.7	16.7	20.5	18.6	20.6	20.7	20.1
Site Potential (Buffer 4)	15.4	16.4	16.4	19.0	17.6	19.4	19.0	17.4



Buffer width & density to achieve effective shade levels (SSTEMP)

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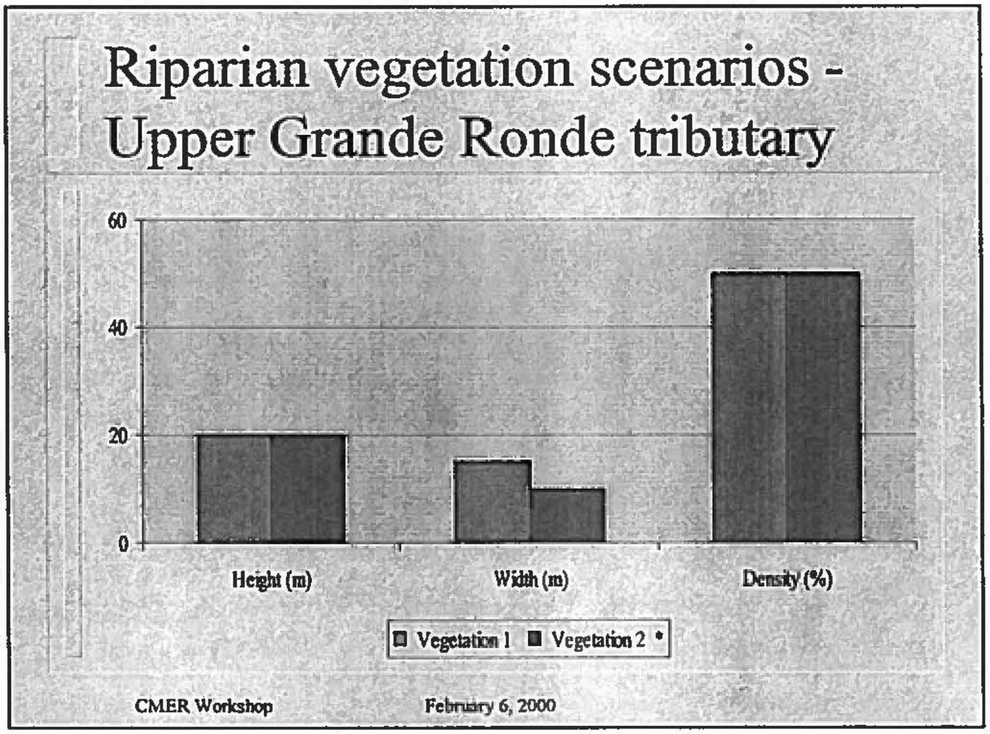

Riparian vegetation scenarios - Upper Grande Ronde tributary

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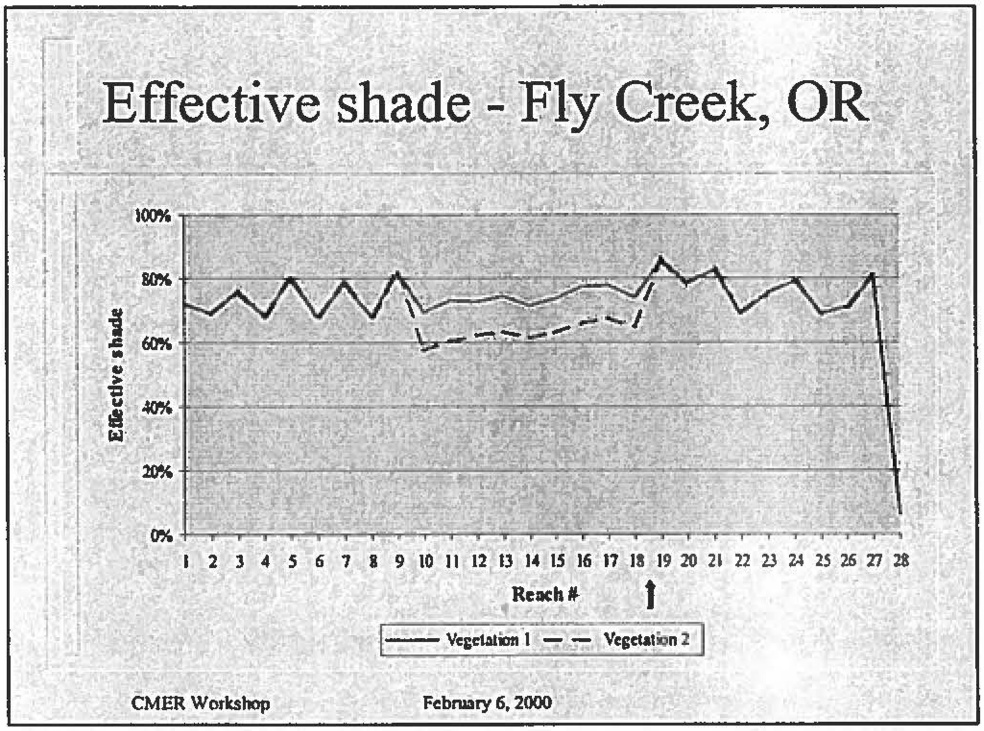

Effective shade - Fly Creek, OR

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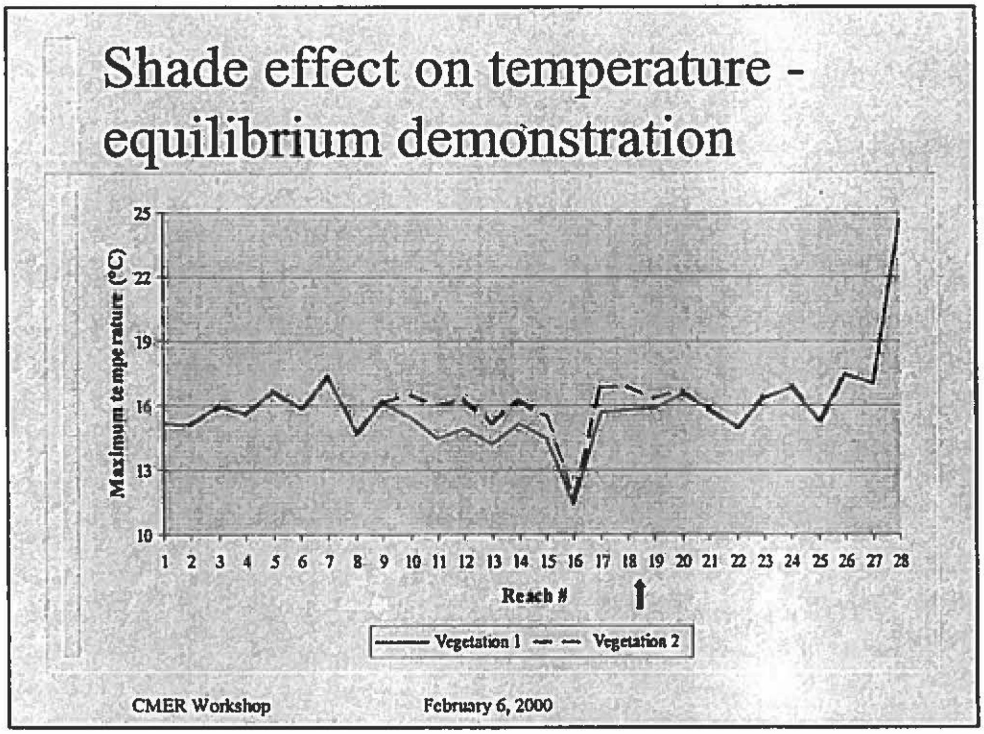

Shade effect on temperature - equilibrium demonstration

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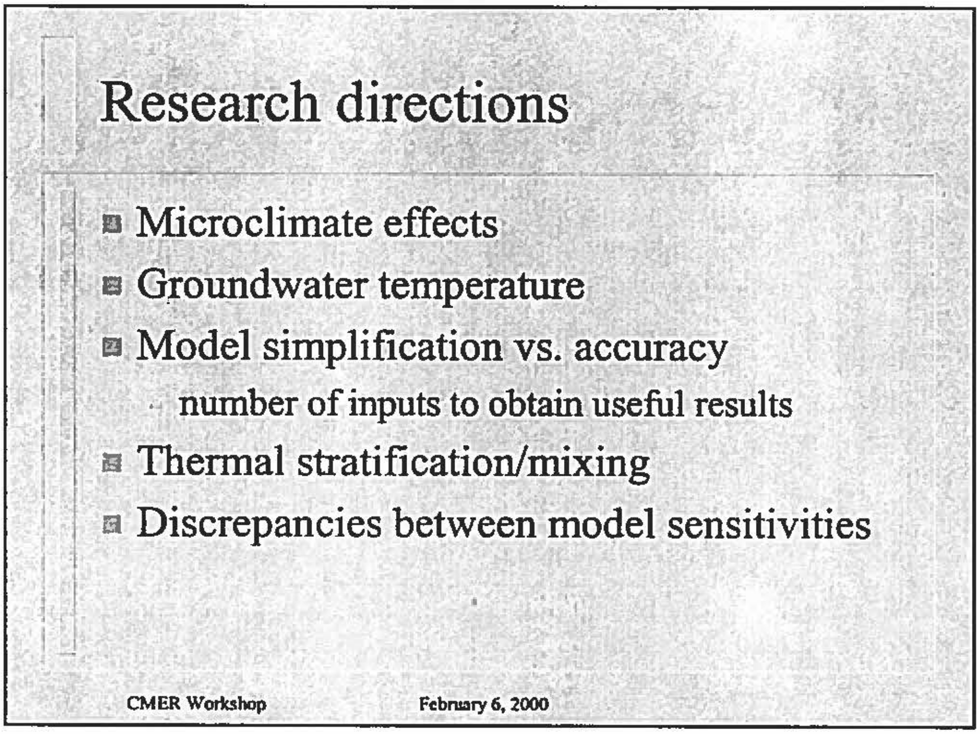

Research directions

- Microclimate effects
- Groundwater temperature
- Model simplification vs. accuracy
  - number of inputs to obtain useful results
- Thermal stratification/mixing
- Discrepancies between model sensitivities

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Appendix D
Additional Material – Groundwater

INTRODUCTION

There are numerous studies on heat transfer by subsurface water flow. However, there has been little published work on the effects of vegetation removal on the subsurface water thermal regime and subsequently surface water thermal regime. In my search so far, I found no published "benchmark" studies (on this issue) for forested ecosystems in the PNW. The few studies that look at this issue were conducted in Japan and Australia.

Subsurface heat transfer has been analyzed to estimate subsurface water fluxes (e.g., Stallman 1963; Bredehoeft and Papadoupulous, 1965; Cartwright 1974; Taniguchi 1993) and sources of groundwater contributions to streams (Shanley and Peters, 1988; Olson 1995, Olson and Wissmar 2000). None of these studies considered the question of vegetation change on groundwater temperatures.

Studies have been conducted on the effects of global warming on soil and groundwater temperatures beneath wetlands and montane meadows (e.g., Bridgham et al 1999; Harte et al 1995) and heat contributions to streams from groundwater (Meisner 1990, Nakano et al 1996, Sinokrot et al 1995). The studies indicate that subsurface temperatures would increase from 1-4° C. Sinokrot et al 1995 found that the influence of groundwater discharge temperature on stream temperatures was still evident at 48 km downstream of the inflow point. The streams evaluated are 3-4th order streams where groundwater contributed 50% of the baseflow (26 cfs). The investigators made assumptions regarding the subsurface water thermal regime but groundwater assessments were not conducted. Again, the question of the effect of forest harvest on groundwater temperatures was not addressed.

Studies show that the shallow subsurface temperature of soil increases following forest harvests (e.g., Peck and Williamson 1991; Brosofske et al 1997). Brosofske et al found that stream temperature correlated with soil temperature (measured at 5 cm depth) and hypothesized that streams were receiving water from groundwater and harvesting influenced the groundwater temperatures. Hewlett and Fortson (1982) first offered this hypothesis suggesting that exposure of lower slopes caused an increase in the groundwater temperature as if flowed toward the stream. They assumed the effect would be more substantial for areas where groundwater table is near the surface. None of these studies did subsurface flow investigations either.

Other studies indicate that heat energy can be transported vertically (20-40 meters) and horizontally (> 1 km) through the unsaturated and saturated zones for considerable distances before it is attenuated (Cartwright 1974; Taniguichi and Sharma 1993; Taniguichi et al 1997; Bundschuh, 1993). Variation in subsurface flow and thermal regimes can also be attributed to the type and extent of subsurface flow systems (Olson and Wissmar 2000).

Two published studies evaluate thermal regimes under different forest conditions. Taniguichi and Sharma (1993) used thermal profiles to calculate groundwater flux at recharge and discharge areas. They found that the seasonal change in soil temperature was greater for a sparse pine area (basal area=9.5 m^2 ha^{-1}) than a denser pine area (basal area=30 m^2 ha^{-1}). The soil temperature wave was delayed between 1.5 and 2.5 m depths. The phase delay was 15 days for the sparse pine site and 17 days for the dense pine site.

Taniguichi et al (1997) evaluated changes of subsurface temperatures following clearcutting and partial harvest. Temperature-depth profiles were measured to maximum depths of 40-50 meters. They found, for clearcut units, a 2.2° C warming at 10 m depth decreasing to 0.5° C warming at 50 m depth (climate, cool wet winter, warm dry summers, annual precipitation: 1200 mm yr^{-1}). Under the partial clearing unit, the subsurface temperature increased 1.6° C at 10 m depth and 0.5° C at 40 m depth.

The presentation will address the topics below. The concepts will be illustrated using published studies and unpublished data from the Sauk River watershed.

Subsurface Heat Transport

1. The characteristics and interaction between the unsaturated zone (or vadose zone) and the saturated groundwater system will influence subsurface heat transport. A groundwater flow system is defined as an interdependent unit of groundwater and surface water, and all associated physical, chemical, and biological characteristics and processes. A groundwater flow system can be composed of a hierarchy of flow systems that are interactive and not confined to separate stratigraphic units or separate aquifers (Toth 1963, 1996; Freeze and Witherspoon 1967; Winter 1976 1987; Engelen and Kloosterman 1997). The sizes of the flow systems range from small, local systems to large, regional systems. The recharge-discharge patterns for the flow systems are generally a subdued replication of the topography with recharge occurring at topographic highs and discharge occurring at topographic lows. There are exceptions to this general condition such as when surface water discharges to groundwater. The recharge-discharge patterns of smaller, local flow systems are influenced by local topographic highs and lows. The recharge-discharge patterns of larger, regional flow systems are generally governed by basin topography. The flow system boundaries are dynamic and fluctuate depending on quantity of recharge, location of recharge points to discharge points, and the quantity of discharge. Heat transport and damping are a function of recharge-discharge dynamics.
2. Heat energy is transported through the unsaturated porous media by conduction and convection (for example, Philip and deVries 1957; Stallman 1963, 1965; Cartwright 1974; Andrews and Anderson 1979; Shanley and Peters 1988; Bach 1989; Jaynes 1990; Miyazaki 1993, Bundschuh 1993; Olson 1995). The depth of heat energy attenuation is dependent on the soil moisture content, unsaturated hydraulic conductivity, porosity, thermal conductivity, heat capacity, slope, and temperature of the unsaturated environment. Within forested systems with high infiltration rates and hydraulic conductivity, transport of ground heat by conduction would be more important during dry to intermediate soil moisture

conditions (Philip and deVries 1957). These conditions generally occur during summer to early fall. However, summer storms can produce subsurface runoff (Fannin et al 2000, Olson 1995) which leads to convective transport. Heat transport by convection (transport by water) would dominant during intermediate to saturated soil moisture conditions (Cartwright 1974, Miyazaki 1993, Taniguichi and Sharma 1993). During May-July when soil moisture content is still above intermediate levels and solar radiation is high, heat is transferred to depths greater than 2 meters with little damping (Cartwright 1974, Bundschuh 1993, Taniguichi 1993, Olson 1995).

3. Bundeschuh (1993) found that conductive transport dominated at Darcy velocitys < 0.2 m yr^{-1}, whereas at velocities at 20 m yr^{-1}, convection dominated 90% of the heat transport. Most infiltration rates and groundwater velocities in forested regions are much greater than 20 m yr-1 (0.000015 m s^{-1}). The Peclet number defines the boundary between conductive and convective flow. When the Peclet number is greater than 1.0, convective flow dominates.
4. Once heat reaches the saturated zone, it will be transported more quickly because horizontal saturated flow generally moves faster than unsaturated vertical flow. Sediment hydrologic characteristics, topographic features, and slope all control heat transported from each contributing recharge area to a discharge area. The more quickly heat is transported the less opportunity for it to be absorbed by the environment (Parsons 1970). Groundwater velocity is a measure for travel time. Groundwater velocities tend to increase as slopes increase and porosity decreases (lower permeability). Groundwater velocity is higher through preferential flow paths such as buried, coarse-grained relict channels, fractures and macropores than the less conductive surrounding soil matrix (Germann 1990, Jones 1990).
5. The type and extent of subsurface flow systems will influence the surface and groundwater interactions. The hydraulic and thermal characteristics of the contributing flow systems control heat transport to streams. Subsurface water temperatures and seasonal differences will be damped with depth. However, the depth to equilibrium depends on many variables including matrix thermal and hydraulic properties. Soil or sediments with higher porosity generally have lower hydraulic and thermal conductivity and higher storage capacity and volumetric heat capacity. These variables are transient because they are a function of moisture content and temperature. Generally, this type of porous medium would buffer external influences on subsurface temperature. This case does not hold for areas that have structure supporting preferential or macropore flow.
6. In local groundwater flow systems, the factors governing the processes of recharge and discharge also control the transport and modification of heat energy (Cartwright 1974, Bundschuh 1993, Taniguchi 1993). Infiltration rates and air, precipitation and sediment temperatures govern recharge temperatures. The temperature of the discharged water is a function of the time retained under unsaturated and saturated conditions and flow resistance (e.g., Forster and Smith 1988). Long retention or storage periods in the saturated zone produce more constant emerging subsurface water temperatures because of mixing and high heat capacity of water. The temperature of groundwater has less influence on heat

transported by percolation when subsurface flow is rapid. Rapidly drained alluvial soils are assumed to have a positive relationship and fluctuate with surface soil and precipitation temperature as a result of high hydraulic and thermal conductivity and low heat capacity. Water temperatures in fine floodplain deposits and lacustrine soil are less variable than in coarser deposits. The variability is less because these soils have lower hydraulic and thermal conductivity and higher heat and storage capacity than coarser sediments.

7. Superimposed on hydrologic and thermal characteristics is the seasonal climatic pattern consisting of a wet season and a dry season in western Washington. The wet season, the cooler months from November-April, is generally characterized by low to moderate intensity storms (<16 mm d^{-1})of long duration (>24 hrs) with lower levels of evapotranspiration and solar radiation. April through June can still be very wet but solar radiation and evapotranspiration increases. Increased solar radiation warms soils, but evapotranspiration cools through release of latent heat. Solar radiation, soil temperatures and evaporation are significant controls on ground heat flux during the dry season (e.g., Cartwright 1974, Jaynes 1990, Brosofske et al. 1997, Bridgham et al 1999). Studies indicate that the cooling effect of evapotranspiration is not enough to offset heat gains through solar radiation (e.g., Bridgham 1999, Qui 1999). Warmer temperatures increase density dependent variables such as thermal and hydraulic conductivity. On the other hand, drier soil conditions decrease conductivities. Storms during summer can supply sufficient moisture to increase soil moisture content and produce subsurface runoff (Fannin et al 2000; Olson 1995). Heat transport from the surface soil layers can then be transported to discharge points.

8. Groundwater contributes to streams as storm flow and baseflow. In the summer, groundwater discharge temperatures are generally cooler than stream temperatures (e.g., Sinokrot et al 1995; Webb and Zhang 1997). Sinokrot et al 1995 found that the influence of groundwater discharge temperature on stream temperatures was still evident at 48 km downstream of the inflow point. The streams evaluated are 3-4th order streams where groundwater contributed 50% of the baseflow (26 cfs). However, the groundwater hydrologic and thermal regime will be strongly influenced by the type of groundwater flow systems (local, intermediate or regional) and the physical characteristics of the systems (Olson and Wissmar 2000). Local flow systems will be more susceptible to non-episodic external actions, natural and management, than intermediate and regional systems. Shallower local and intermediate flow systems with limited storage capacity and high hydraulic and thermal conductivity will be the most vulnerable during the summer. Local and intermediate flow systems in more porous sediments (lower hydraulic and thermal conductivity) will have a higher heat capacity. Once warmed, they will maintain heat longer than the coarser sediments. This heat will be flushed out to streams during storms.

9. During late summer to early fall, streams in the PNW often have coincident influent and effluent conditions (Newcomb 1952; Reiter and Beschta 1992; Wondzell and Swanson 1996; Turney et al 1995; Olson 1995, 1996, 1997 a,b). These conditions influence the direction of flow between surface water and

groundwater and water temperatures (Ozaki 1988; Lapham 1989; Mitchell et al. 1990; Jaynes 1990; Constanz et al. 1994, Constanz 1997; Olson 1995, 1997b). Castro and Hornberger (1991), Constantz et al. (1994), Constantz (1997) and Olson (1995, 1997b) found that diurnal stream temperatures varied more in influent reaches than effluent reaches. These studies and Jaynes (1990) also concluded that seepage from surface water to groundwater increased as the stream temperature became warmer. This is caused partially by increased thermal gradients between surface and subsurface water temperatures and increased hydraulic conductivity. The temperature regimes in the effluent reaches tend to be more stable.

Table 1. Description of potential vulnerability of groundwater to thermal modification.

Type of groundwater system	Characteristics
Shallow, local flow system	Low porosity sediments are more vulnerable to thermal modifications because of rapid delivery , short retention and travel times. Porous sediments are less vulnerable because they are more retentive. Recharge areas are sensitive because of short travel time to groundwater table.
Intermediate flow system	Moderate vulnerability depending on the depth to the system. Intermediate delivery time with intermediate times of travel and retention; recharge area more vulnerable because of shorter travel times.
Regional flow system	Not vulnerable to heat modifications from forest practices.

Table 2. Geologic and hydrologic characteristics that influence potential delivery of a contaminant (or heat energy) to a groundwater body.

Feature	Characteristic producing delivery rating		
	Slower delivery	*Moderate delivery*	*Higher or faster delivery*
	A. Lithological Framework		
Unsaturated zone	Thick (>10m), with high levels of clay & organic matter Fine-grained, compacted till with little to no weathering	Varying thickness with highly permeable materials interspersed in a matrix of lower permeable materials	1. Thin with high levels of sand, gravel, fractured rock, or rock of high permeability 2. Varying thickness and texture with macropores, fractures, and other features creating high secondary porosity 3. Higher permeable materials underlain by lower permeable materials
Unconfined unit		Coarse-grained glacial till and coarse to fine-grained moraines Fine-grained till that is weathered, fractured, or has more permeable lenses	Alluvial deposits connected to surface water
Confining unit	Thick confining unit of clay or shale above groundwater body Marl and clay sedimentary complexes	Thick or variable unit of clay or shale interspersed with lens of more permeable material (sand, gravel)	1. No confining unit 2. Fractured or fissured confining unit
Aquifer properties	Silty sandstone or shaley limestone of low permeability	Low permeability interspersed with lens of higher permeability or with fault lines	Karstic limestone, sandstone, sand and gravel, gravel, or basalt of high permeability

Table 2 cont. Geologic and hydrologic characteristics that influence potential delivery of heat to a groundwater body.

Feature	Characteristic producing delivery rating		
	Slower delivery	*Moderate delivery*	*Higher or faster delivery*
	B. Groundwater Flow System		
Recharge Rate	Negligible recharge rate (arid areas, ET>Ppt)	Moderate recharge rate (semi-arid to humid, ET=0.8-1.0 Ppt)	High recharge rate (humid areas, ET<Ppt)
Type of system and length of flow path	Deep, regional flow system with little flow	Regional and intermediate with long flow lines	Local and intermediate with shorter flow lines
Location within flow system (proximity to recharge and discharge areas)	Located in deep, sluggish part of a regional flow system	Located within an intermediate or regional recharge area	(1) Located in a discharge area, or (2) a recharge area of a small intermediate to local flow system
	C. Hydraulic characteristics		
Depth to water	> 40 meters	< 40 m and > 10 m	Shallow water table
Hydraulic conductivity	low	medium	high
primary porosity	high	medium	low
secondary porosity	none	discontinuous fissured	continuous fissure, fractures, macropores

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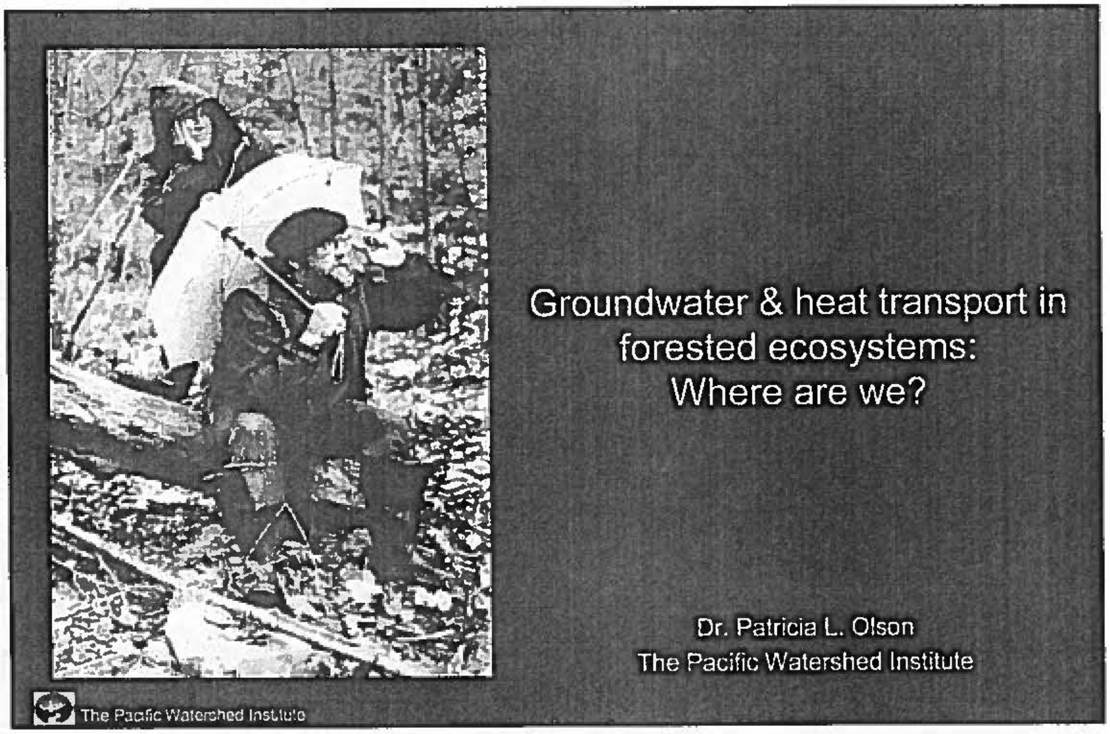

Groundwater & heat transport in forested ecosystems: Where are we?

Dr. Patricia L. Olson
The Pacific Watershed Institute

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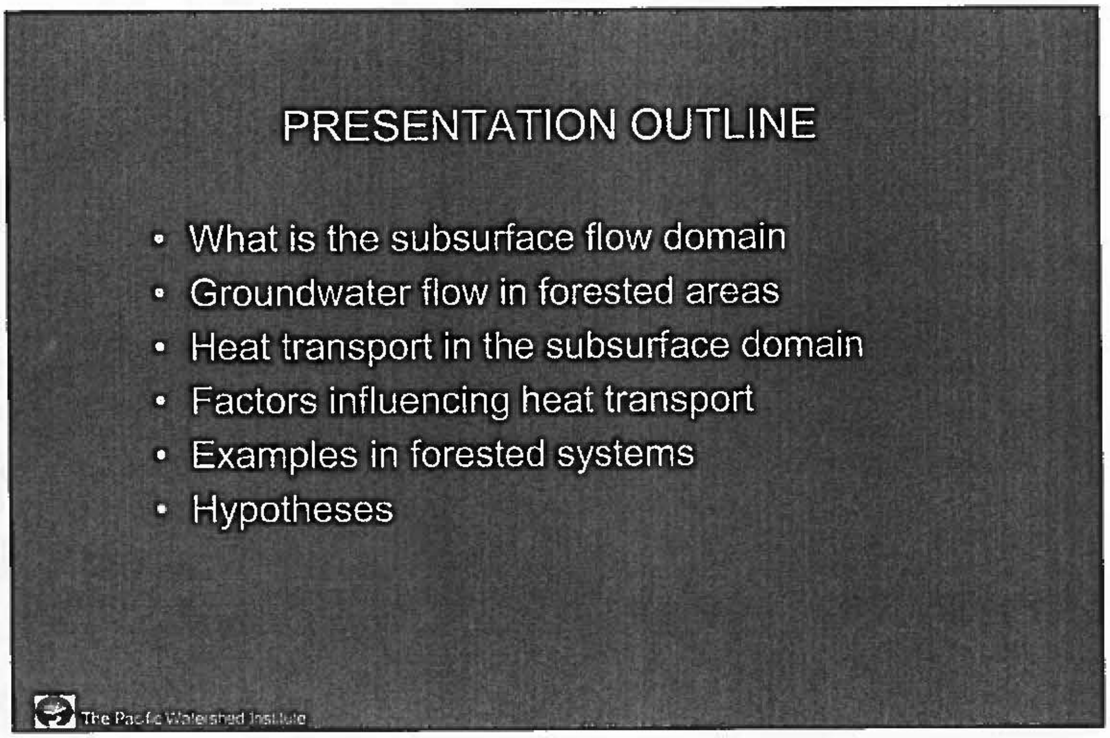

PRESENTATION OUTLINE

- What is the subsurface flow domain
- Groundwater flow in forested areas
- Heat transport in the subsurface domain
- Factors influencing heat transport
- Examples in forested systems
- Hypotheses

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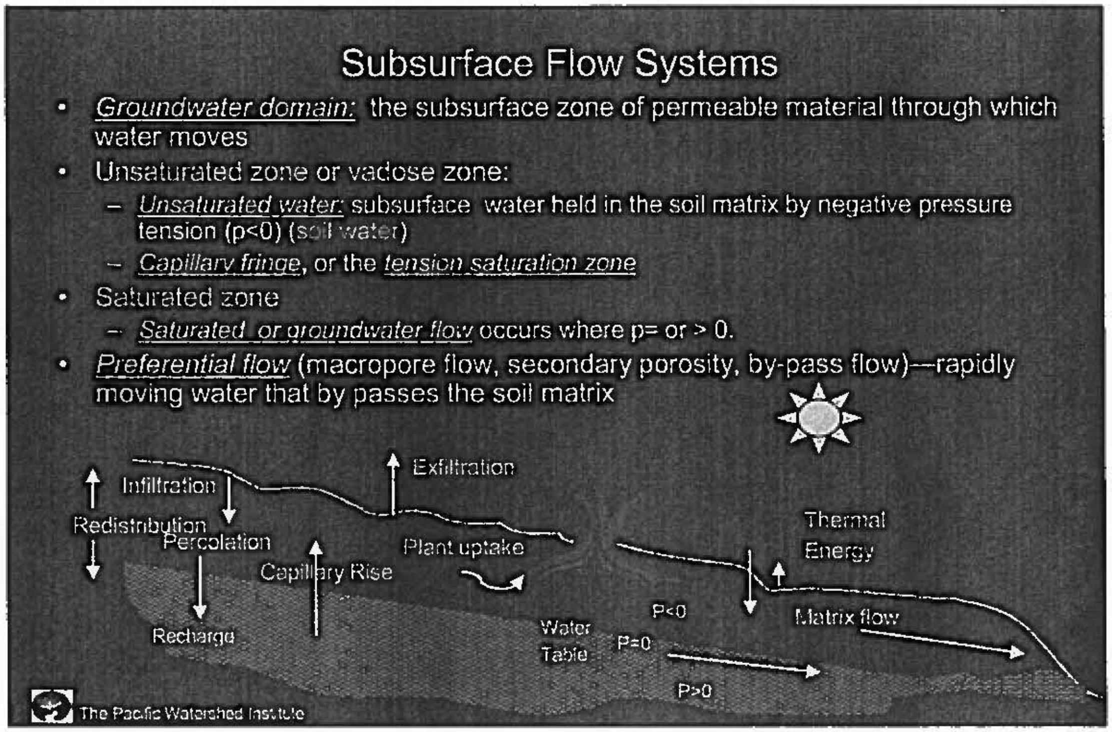

Subsurface Flow Systems

- *Groundwater domain:* the subsurface zone of permeable material through which water moves
- Unsaturated zone or vadose zone:
  - *Unsaturated water:* subsurface water held in the soil matrix by negative pressure tension ($p<0$) (soil water)
  - *Capillary fringe*, or the *tension saturation zone*
- Saturated zone
  - *Saturated or groundwater flow* occurs where p= or > 0.
- *Preferential flow* (macropore flow, secondary porosity, by-pass flow)—rapidly moving water that by passes the soil matrix

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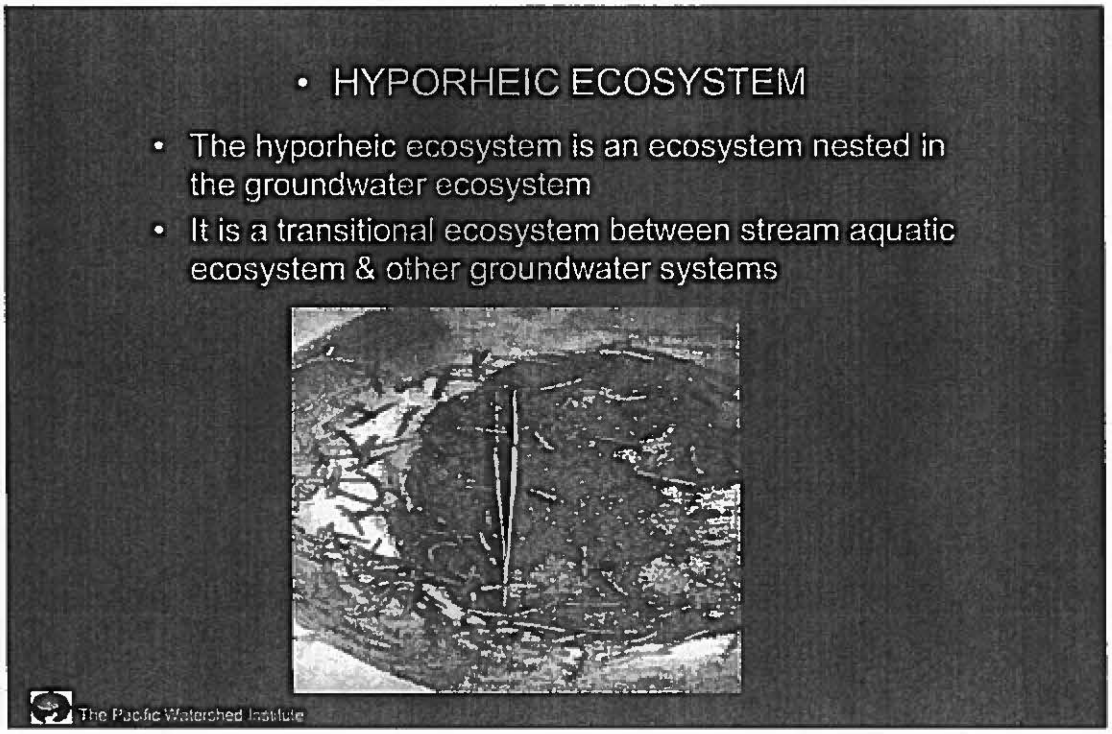

• HYPORHEIC ECOSYSTEM

- The hyporheic ecosystem is an ecosystem nested in the groundwater ecosystem
- It is a transitional ecosystem between stream aquatic ecosystem & other groundwater systems

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- The physical & chemical characteristics fluctuate:
    - –Exchanges water & other materials from the stream
    - –Exchanges water & other materials from other groundwater systems
- The size varies in time and space--within & between streams
    - –Vertical: centimeters to 10+ meters
    - –Horizontal: meters to kilometers

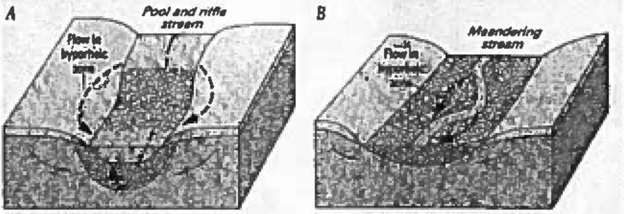
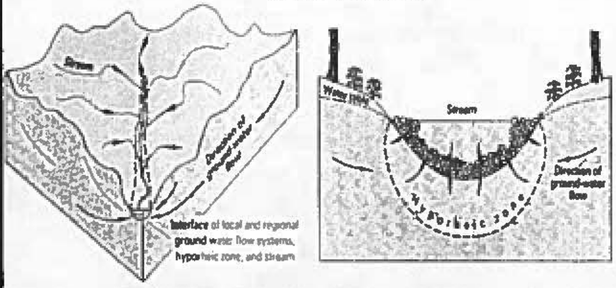


Figure 14. Surface-water exchange with ground water in the hyporheic zone is associated with abrupt changes in streambed slope (A) and with stream meanders (B).

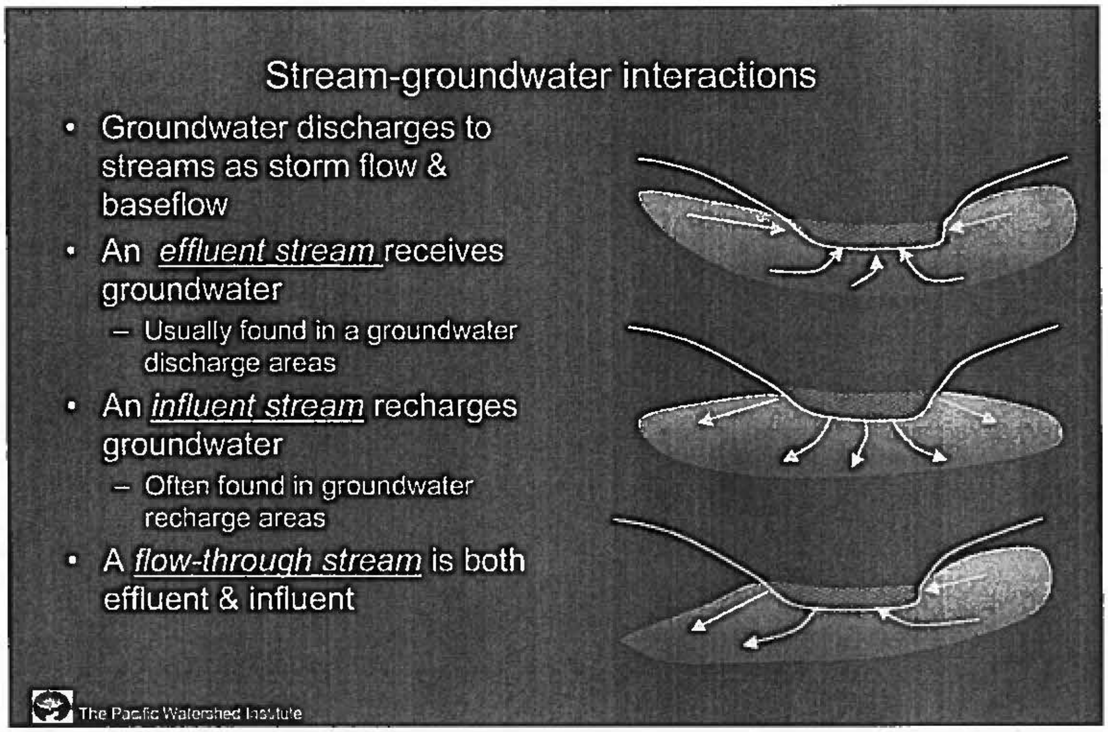
Winter et al 1998

Winter et al 1998



Key elements of subsurface flow influencing heat transport

- Flux
- Storage
- Recharge-discharge



Stream-groundwater interactions

- Groundwater discharges to streams as storm flow & baseflow
- An *effluent stream* receives groundwater
  - Usually found in a groundwater discharge areas
- An *influent stream* recharges groundwater
  - Often found in groundwater recharge areas
- A *flow-through stream* is both effluent & influent

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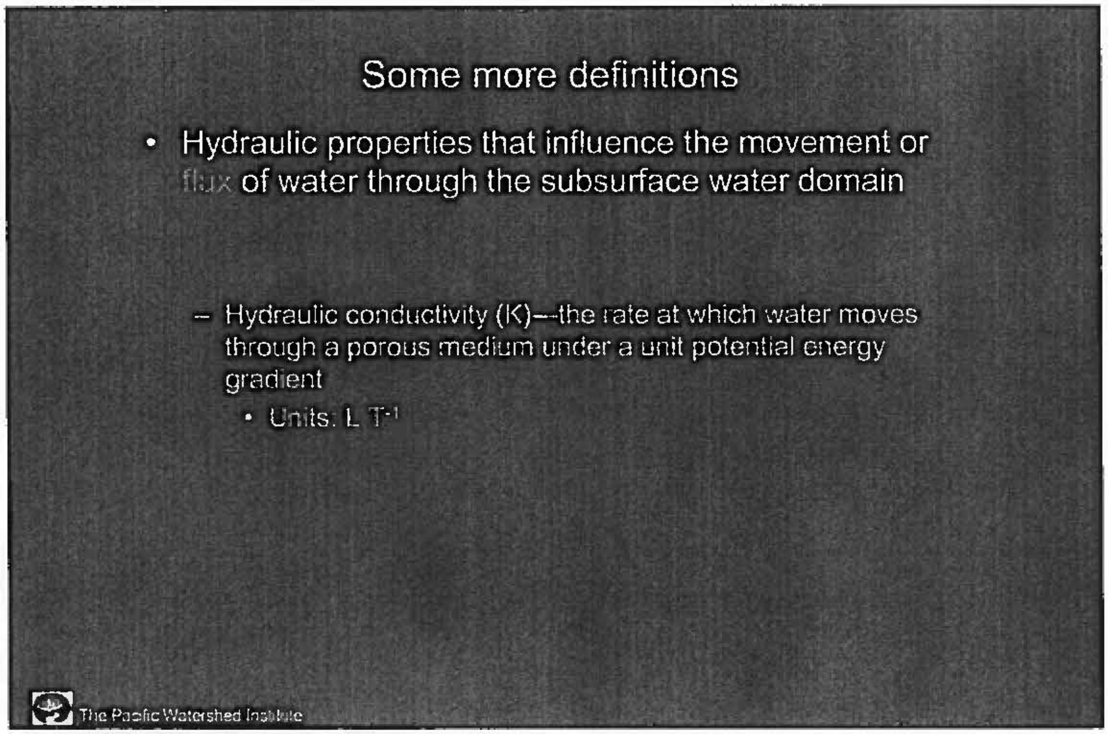

Some more definitions

- Hydraulic properties that influence the movement or flux of water through the subsurface water domain
  - Hydraulic conductivity (K)—the rate at which water moves through a porous medium under a unit potential energy gradient
    - Units: $L\ T^{-1}$

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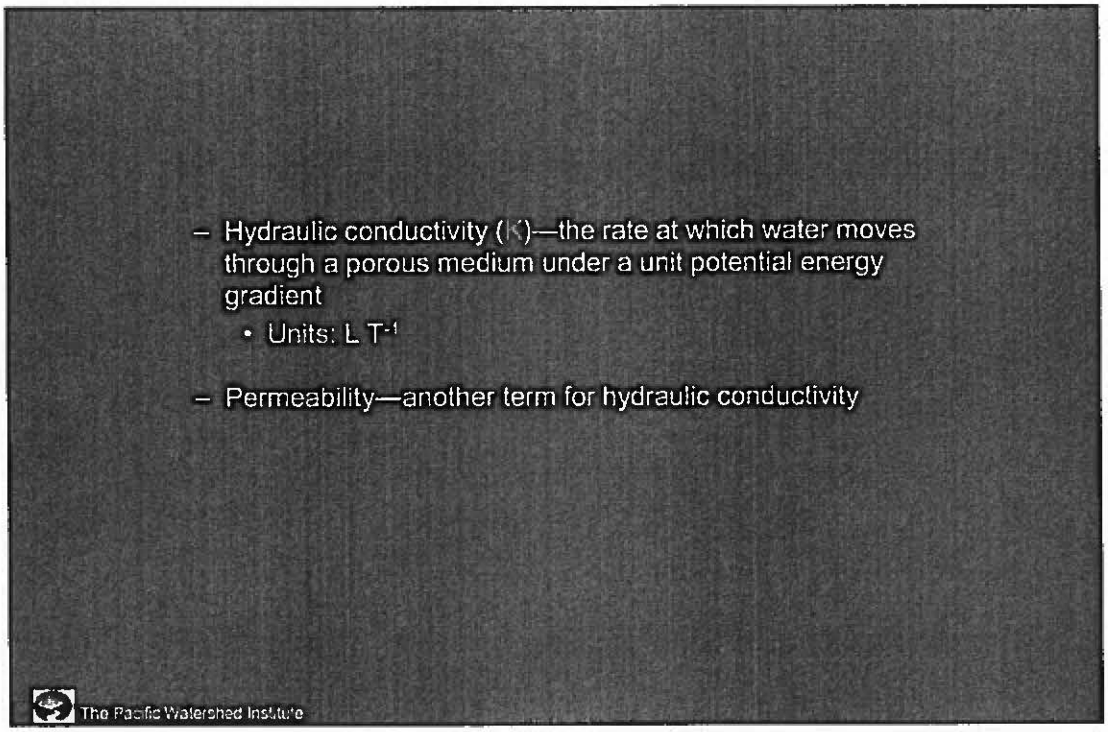

- Hydraulic conductivity (K)—the rate at which water moves through a porous medium under a unit potential energy gradient
  - Units: $L\ T^{-1}$
- Permeability—another term for hydraulic conductivity

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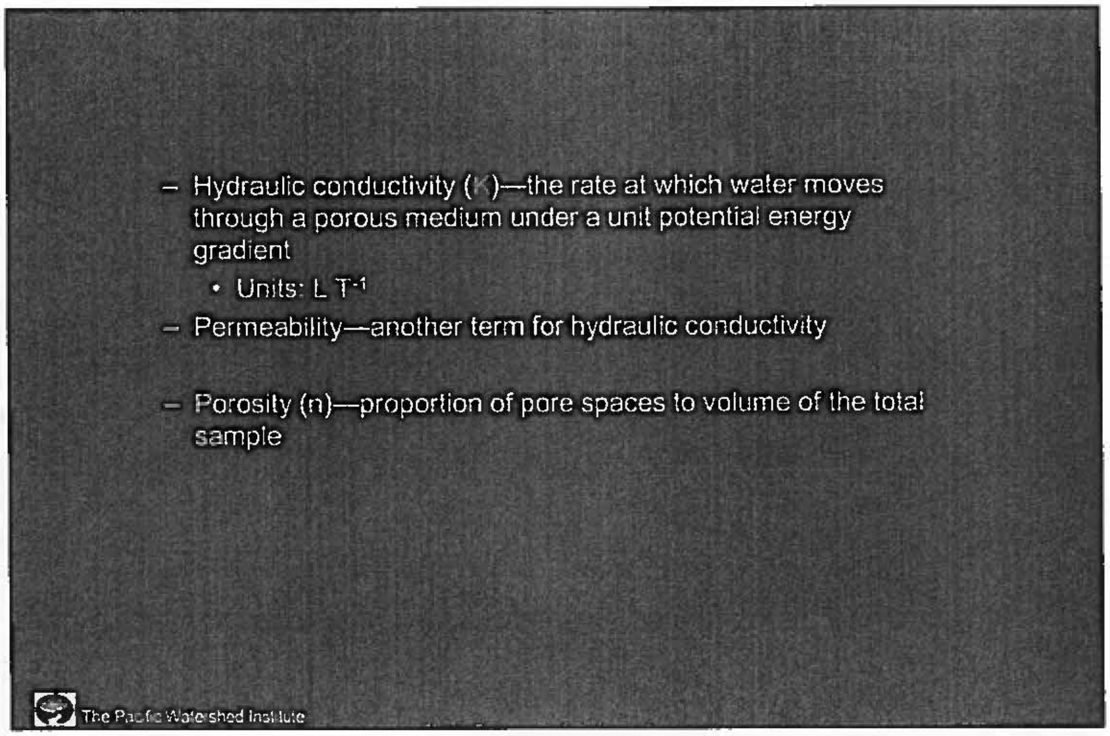

- Hydraulic conductivity (K)—the rate at which water moves through a porous medium under a unit potential energy gradient
  - Units: $L\ T^{-1}$
- Permeability—another term for hydraulic conductivity
- Porosity (n)—proportion of pore spaces to volume of the total sample

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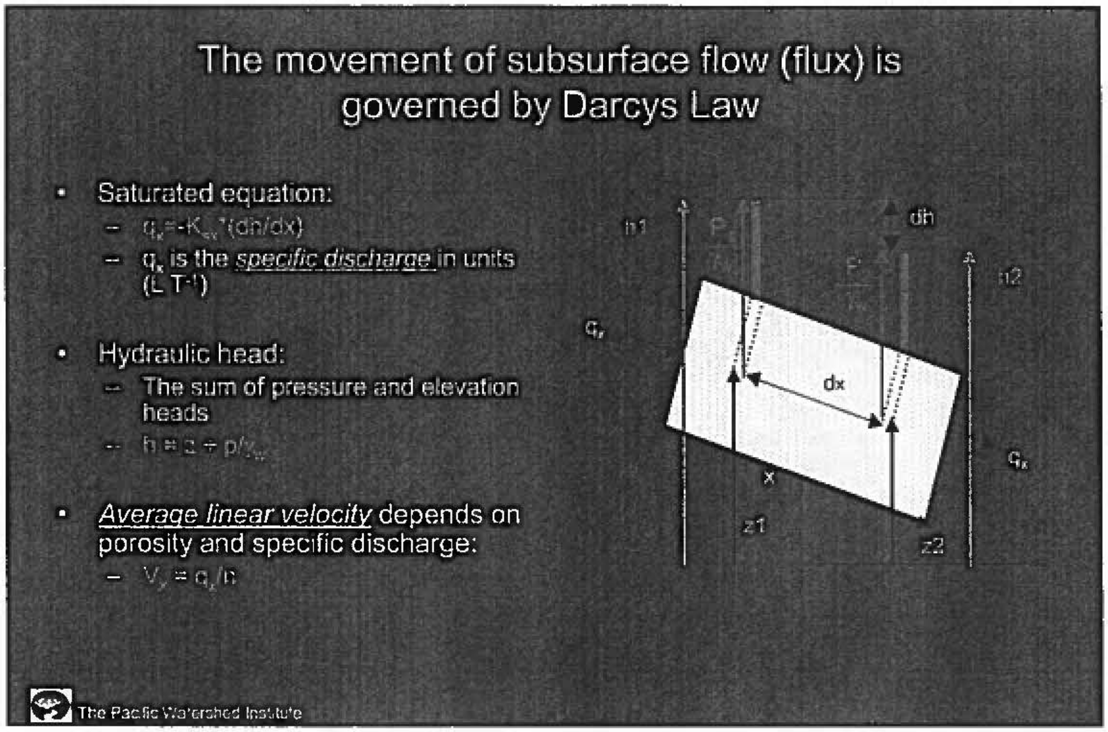

The movement of subsurface flow (flux) is governed by Darcys Law

- Saturated equation:
  - $q_x = -K_{sx} * (dh/dx)$
  - q_x is the *specific discharge* in units ($L\,T^{-1}$)
- Hydraulic head:
  - The sum of pressure and elevation heads
  - $h = z + p/\gamma_w$
- *Average linear velocity* depends on porosity and specific discharge:
  - $V_x = q_x/n$

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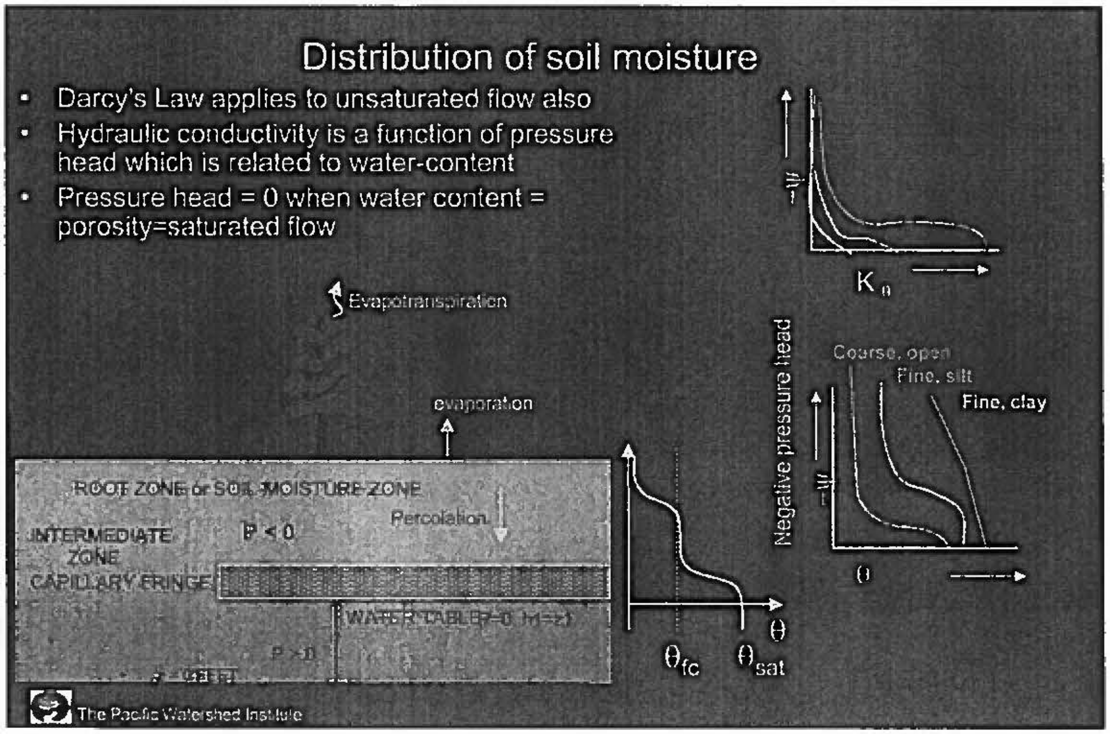

Distribution of soil moisture

- Darcy's Law applies to unsaturated flow also
- Hydraulic conductivity is a function of pressure head which is related to water-content
- Pressure head = 0 when water content = porosity=saturated flow

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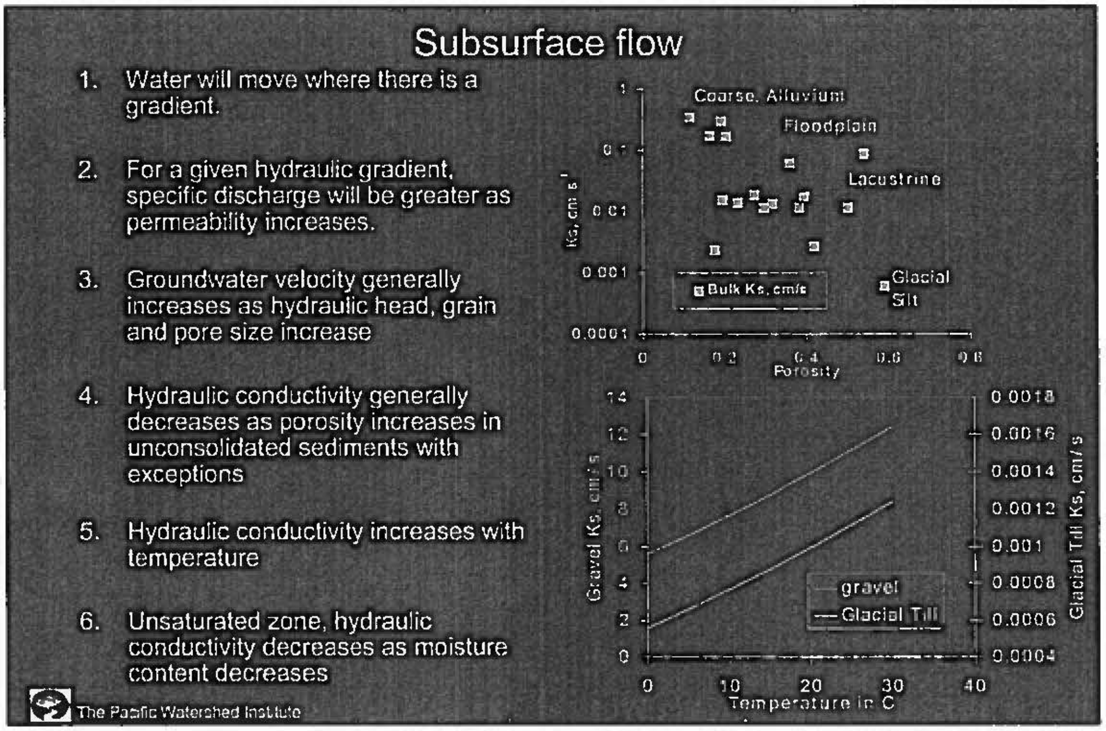

Subsurface flow

1. Water will move where there is a gradient.
2. For a given hydraulic gradient, specific discharge will be greater as permeability increases.
3. Groundwater velocity generally increases as hydraulic head, grain and pore size increase
4. Hydraulic conductivity generally decreases as porosity increases in unconsolidated sediments with exceptions
5. Hydraulic conductivity increases with temperature
6. Unsaturated zone, hydraulic conductivity decreases as moisture content decreases

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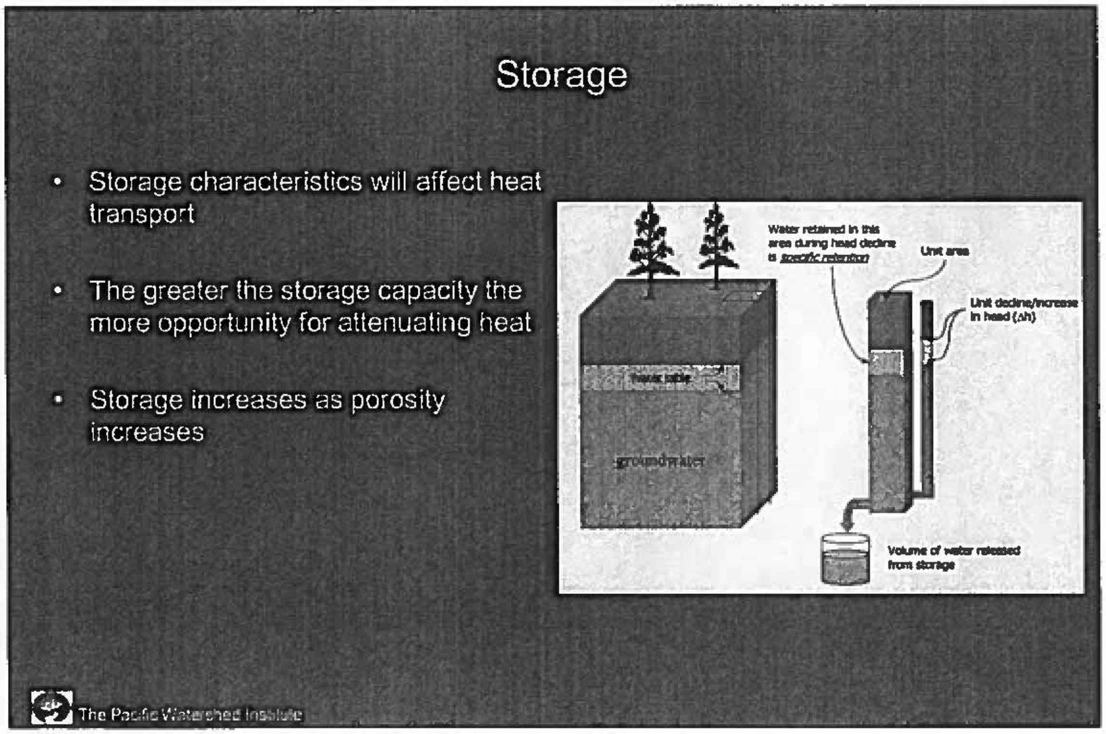

Storage

- Storage characteristics will affect heat transport
- The greater the storage capacity the more opportunity for attenuating heat
- Storage increases as porosity increases

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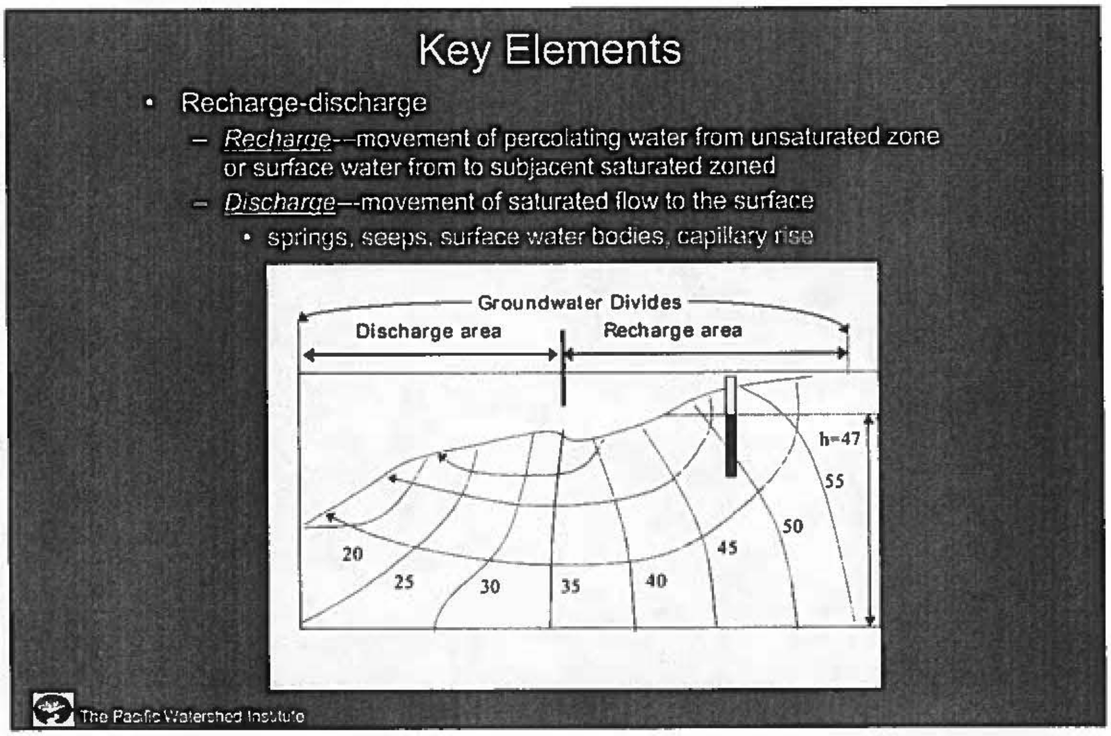

Key Elements

- Recharge-discharge
  - *Recharge*--movement of percolating water from unsaturated zone or surface water from to subjacent saturated zoned
  - *Discharge*--movement of saturated flow to the surface
    - springs, seeps, surface water bodies, capillary rise

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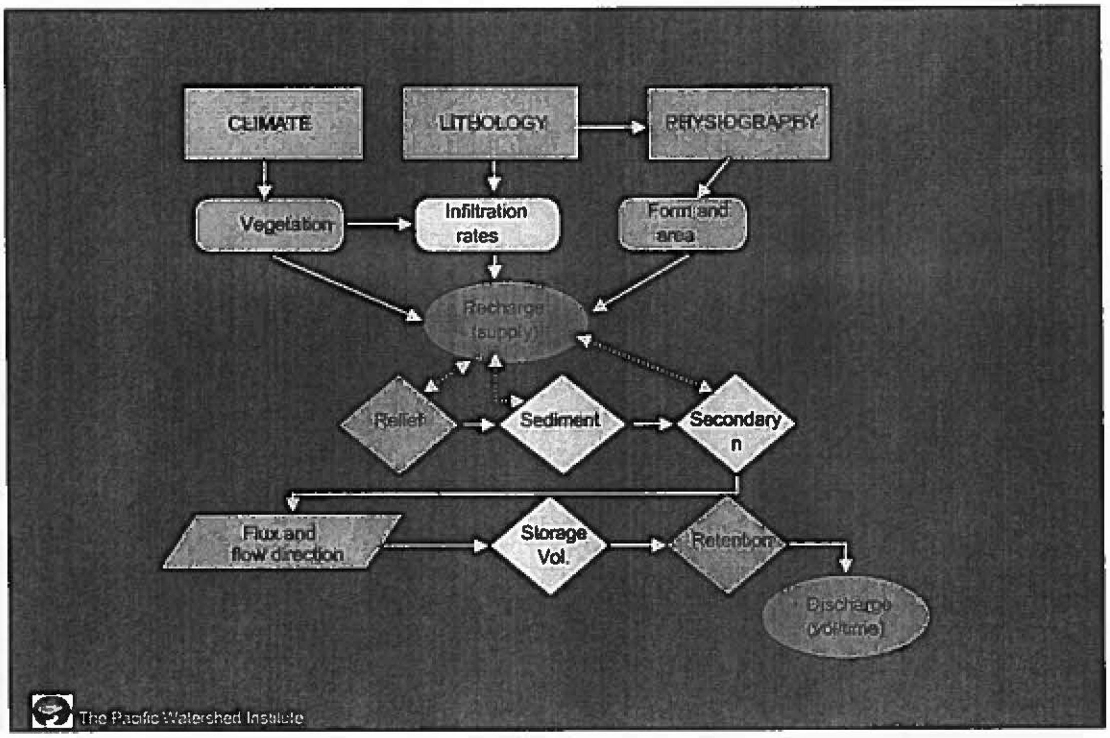

CLIMATE
LITHOLOGY
PHYSIOGRAPHY
Vegetation
Infiltration rates
Form and area
Recharge (supply)
Relief
Sediment
Secondary n
Flux and flow direction
Storage Vol.
Retention
Discharge (volume)

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Key Elements:Recharge

- Small differences in local conditions can cause large differences in recharge
- Recharge more likely to occur quickly:
  - Soils with high hydraulic conductivity
  - Water table is at a shallow depth
  - The soil is relatively wet when recharge event begins
  - Water-input rate is low & the event is of long duration

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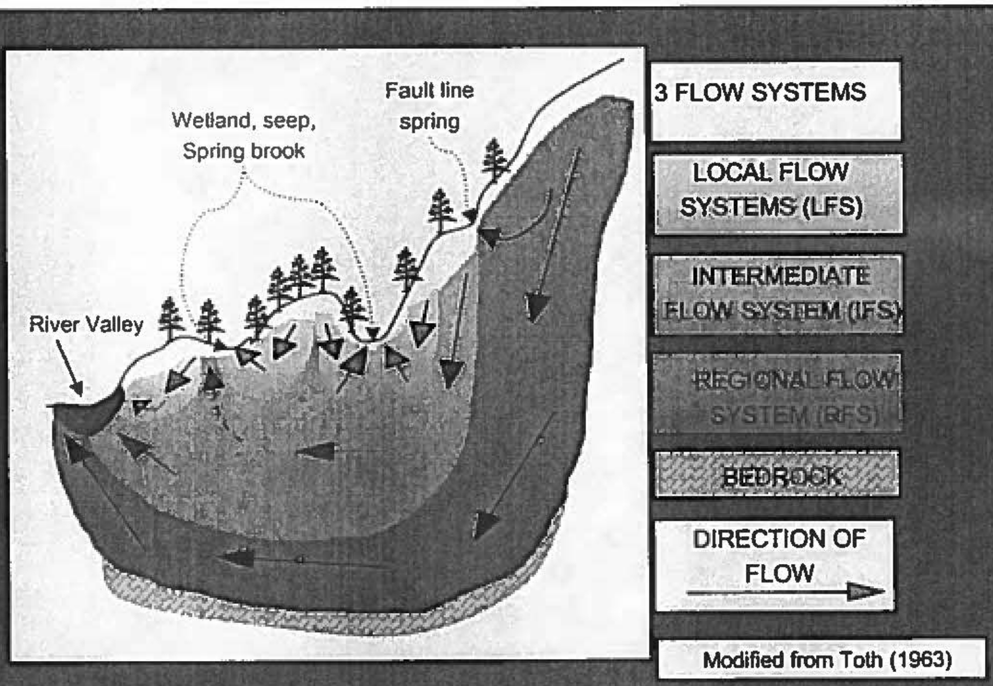

Modified from Toth (1963)

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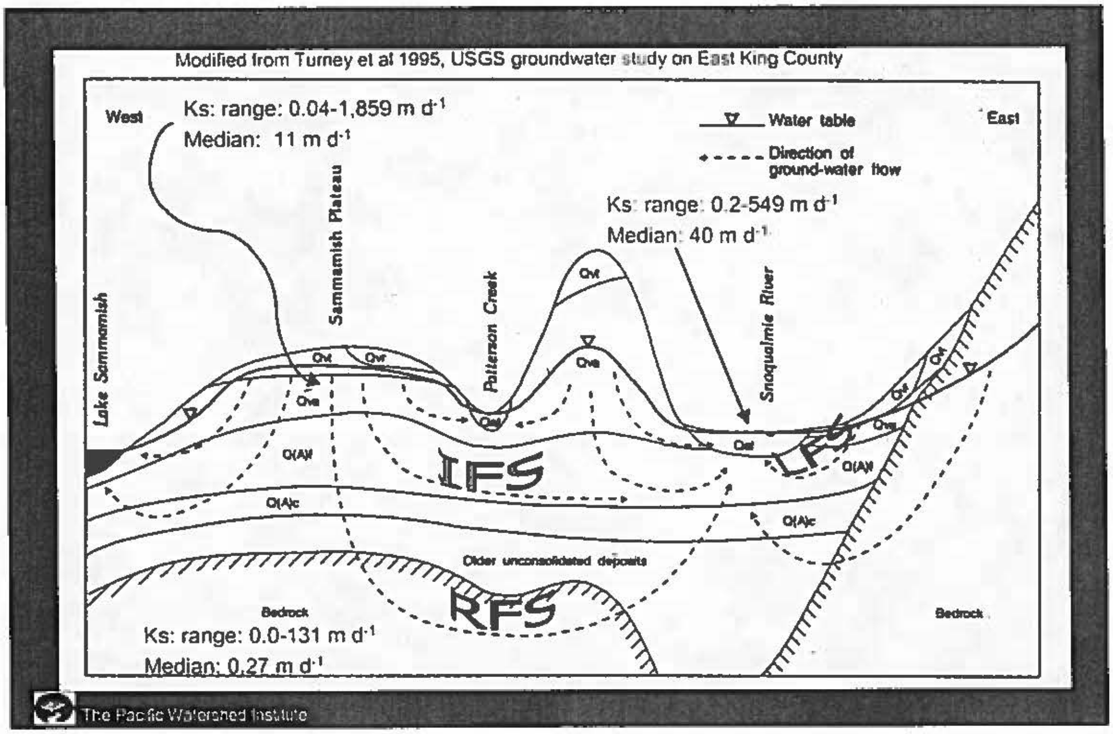

Modified from Turney et al 1995, USGS groundwater study on East King County

Ks: range: 0.04-1,859 m d^{-1}
Median: 11 m d^{-1}

Ks: range: 0.2-549 m d^{-1}
Median: 40 m d^{-1}

Ks: range: 0.0-131 m d^{-1}
Median: 0.27 m d^{-1}

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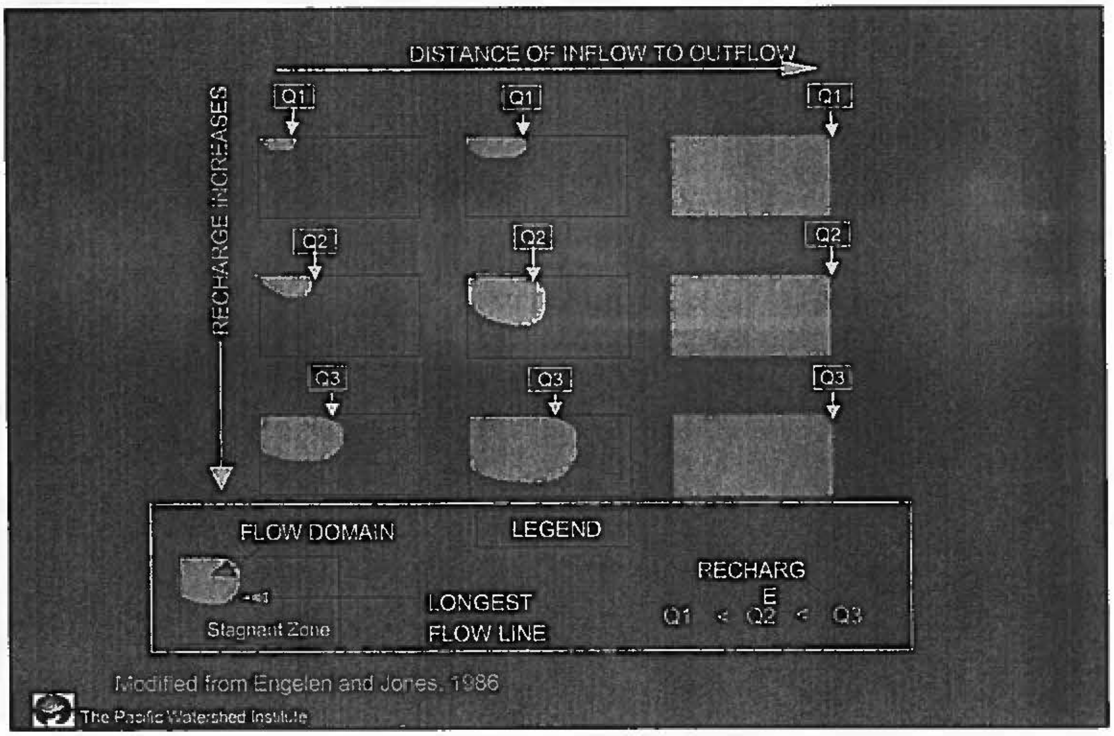

Modified from Engelen and Jones, 1986

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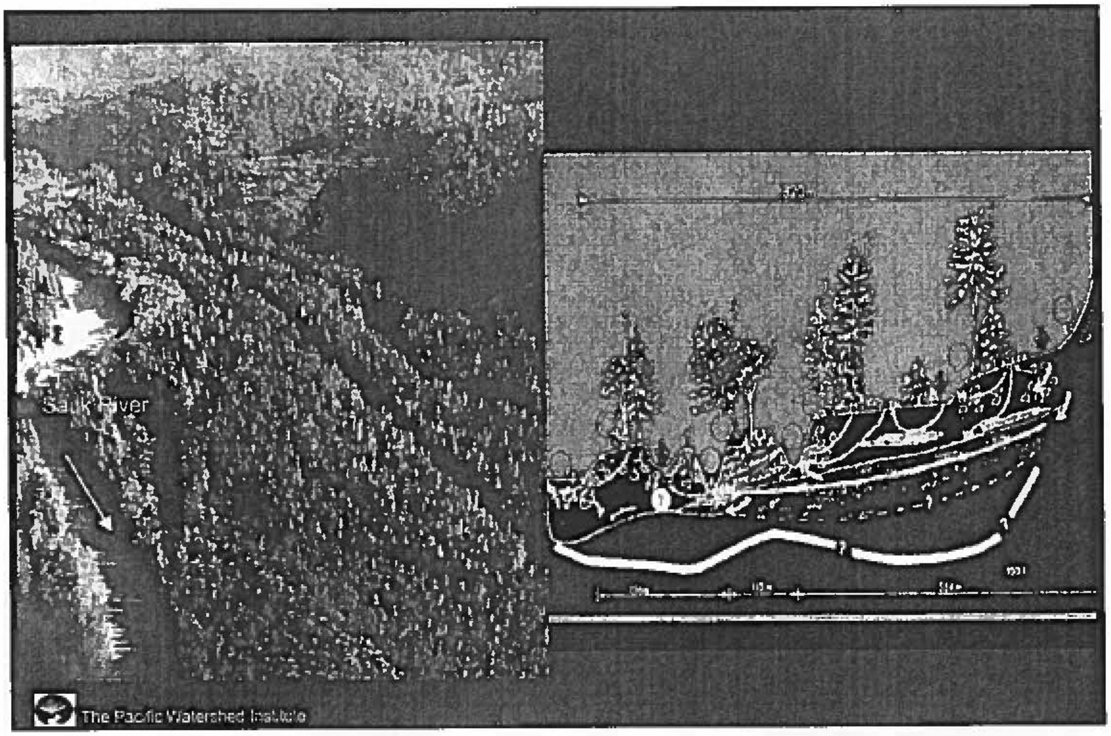

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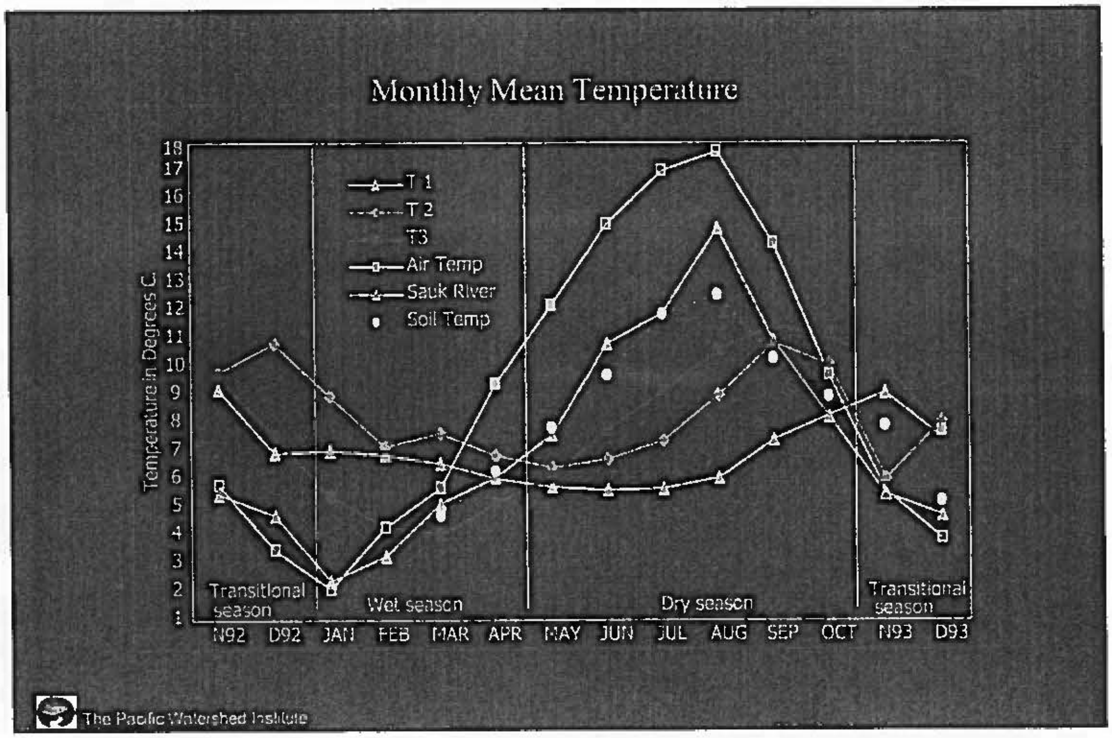

Monthly Mean Temperature

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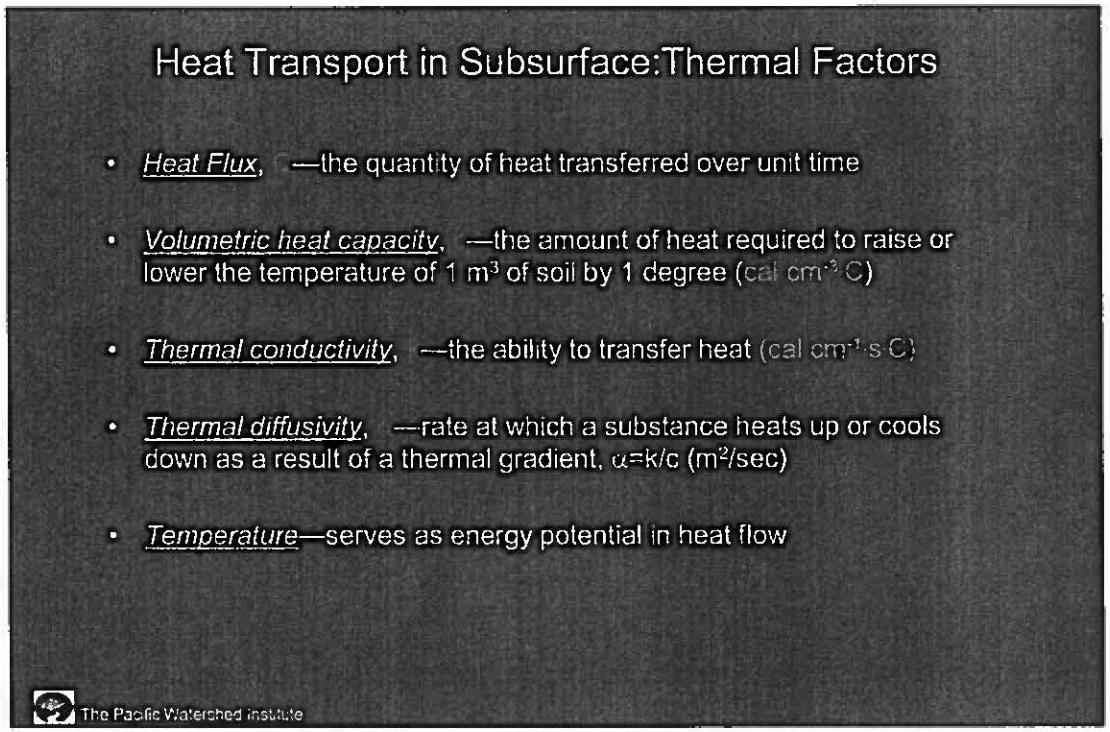

Heat Transport in Subsurface:Thermal Factors

- *Heat Flux*, —the quantity of heat transferred over unit time
- *Volumetric heat capacity*, —the amount of heat required to raise or lower the temperature of 1 m^3 of soil by 1 degree (cal cm^{-3} C)
- *Thermal conductivity*, —the ability to transfer heat (cal cm^{-1} s C)
- *Thermal diffusivity*, —rate at which a substance heats up or cools down as a result of a thermal gradient, $\alpha=k/c$ (m^2/sec)
- *Temperature*—serves as energy potential in heat flow

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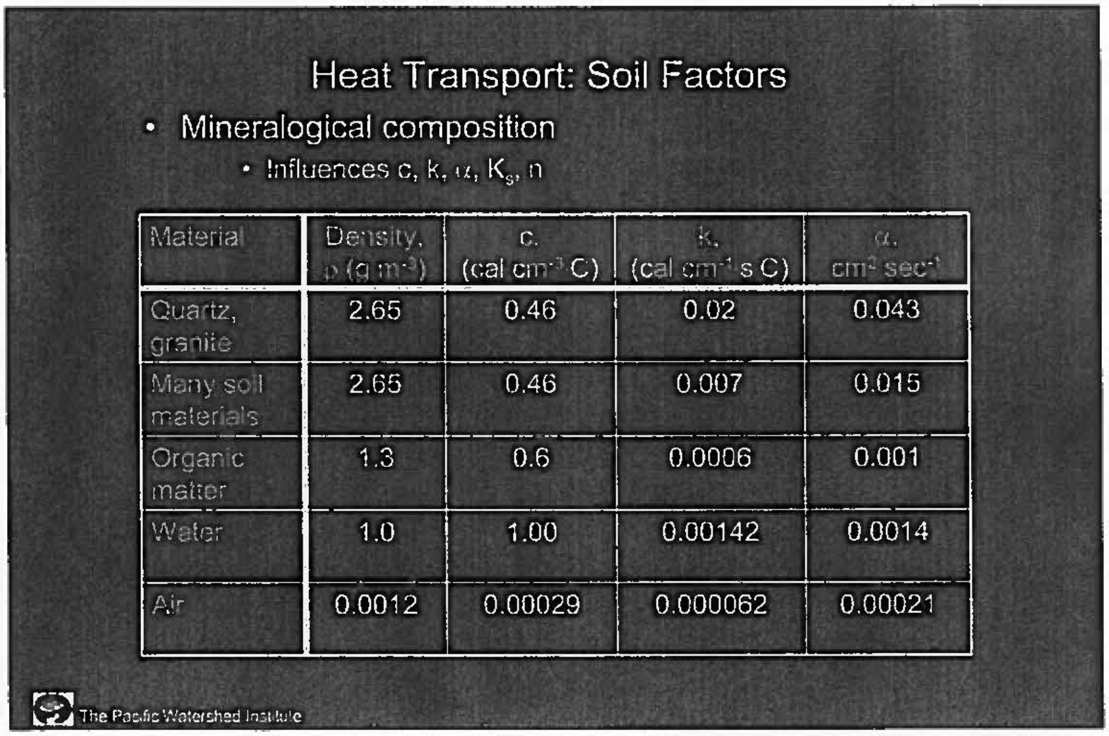

Heat Transport: Soil Factors

- Mineralogical composition
  - Influences c, k, α, K_s, n

Material	Density, ρ (g m^{-3})	c, (cal cm^{-3} C)	k, (cal cm^{-1} s C)	α, cm^2 sec^{-1}
Quartz, granite	2.65	0.46	0.02	0.043
Many soil materials	2.65	0.46	0.007	0.015
Organic matter	1.3	0.6	0.0006	0.001
Water	1.0	1.00	0.00142	0.0014
Air	0.0012	0.00029	0.000062	0.00021

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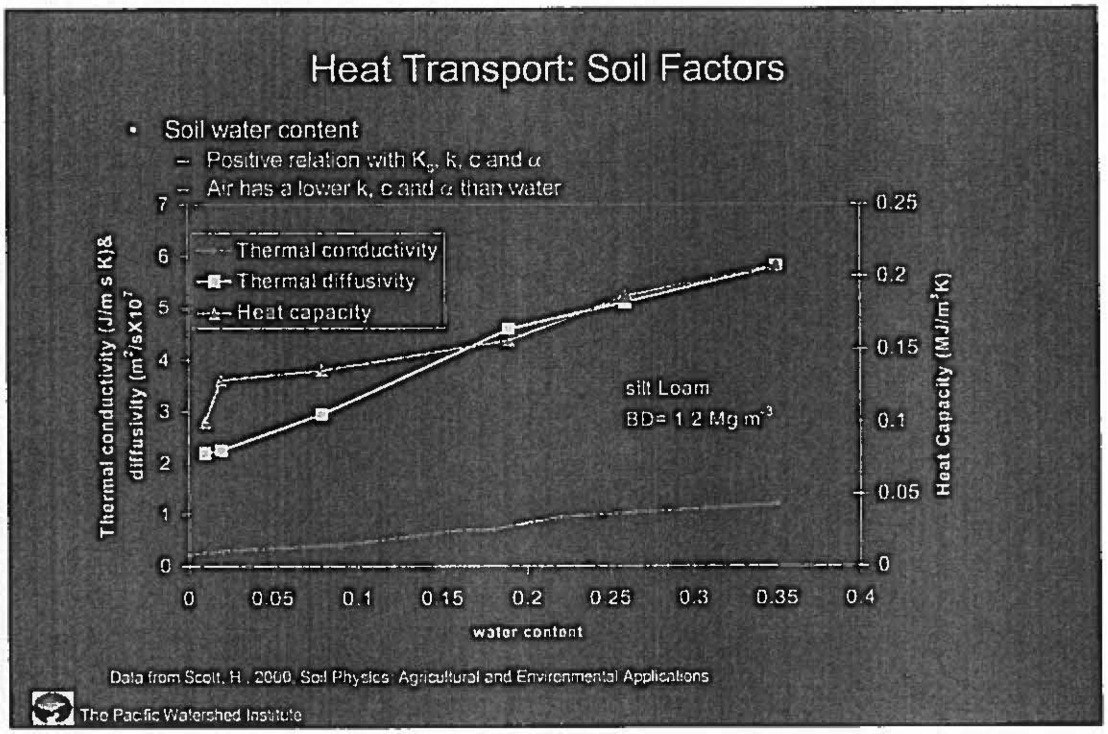

Heat Transport: Soil Factors

- Soil water content
  - Positive relation with K_s, k, c and α
  - Air has a lower k, c and α than water

Data from Scott, H , 2000, Soil Physics: Agricultural and Environmental Applications

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Subsurface Heat Transport

- Heat can be transported in a porous medium by:
  - Conduction—linear law relating heat flux to temperature gradient

    $$H= -k\Delta T/\Delta z$$

    - Heat flux is a function of thermal conductivity & temperature gradient over depth
    - The greater the temperature differentials the higher the heat flow
    - When heat flow density is negative, then heat going into soil (heat flows from warmer temperatures to cooler temperatures)
  - Radiation—emitted because of temperature of a body
  - Convection—movement of heat by moving water (forced convection—no density gradients)
    - A function of the transient velocity field

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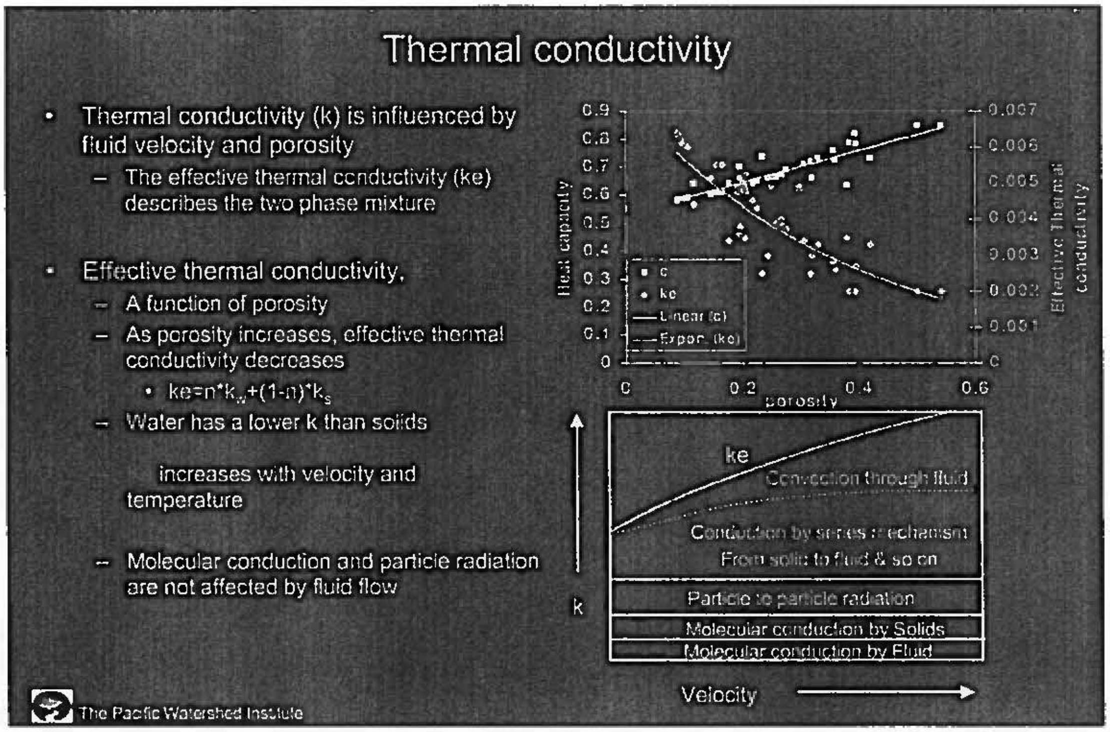


Thermal conductivity

- Thermal conductivity (k) is influenced by fluid velocity and porosity
  - The effective thermal conductivity (ke) describes the two phase mixture
- Effective thermal conductivity,
  - A function of porosity
  - As porosity increases, effective thermal conductivity decreases
    - $ke=n^*k_w+(1-n)^*k_s$
  - Water has a lower k than solids

    increases with velocity and temperature

  - Molecular conduction and particle radiation are not affected by fluid flow

ke

Convection through fluid

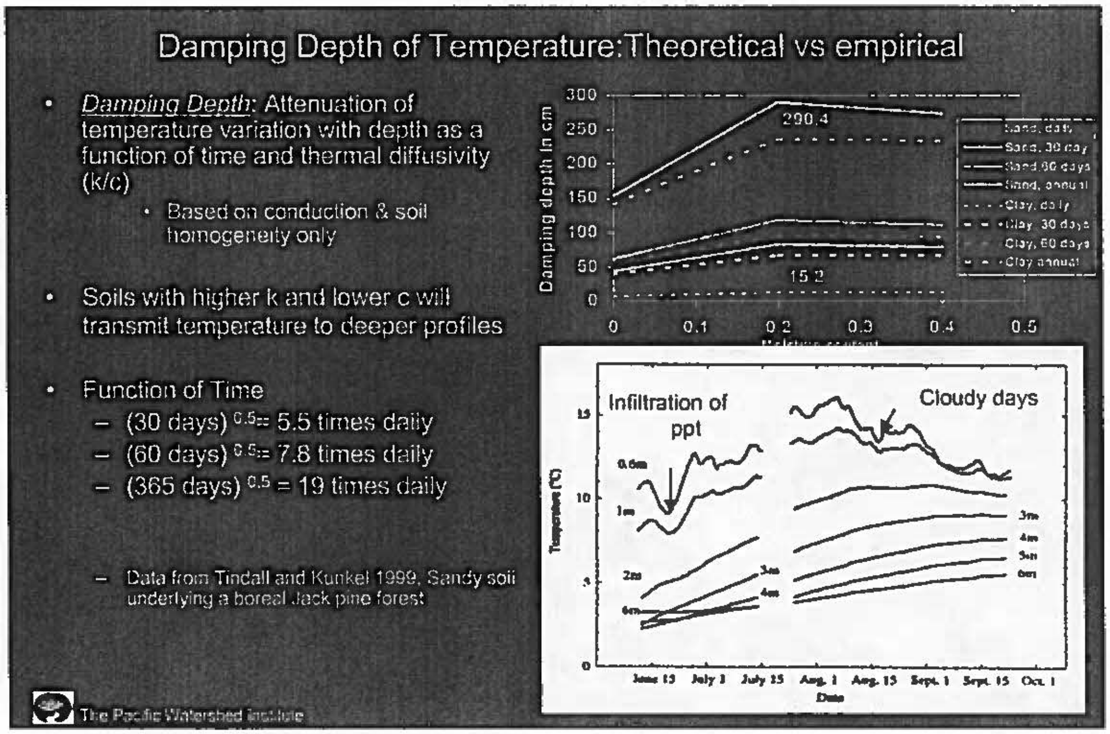
Conduction by series mechanism

From solid to fluid & so on

Particle to particle radiation

Molecular conduction by Solids

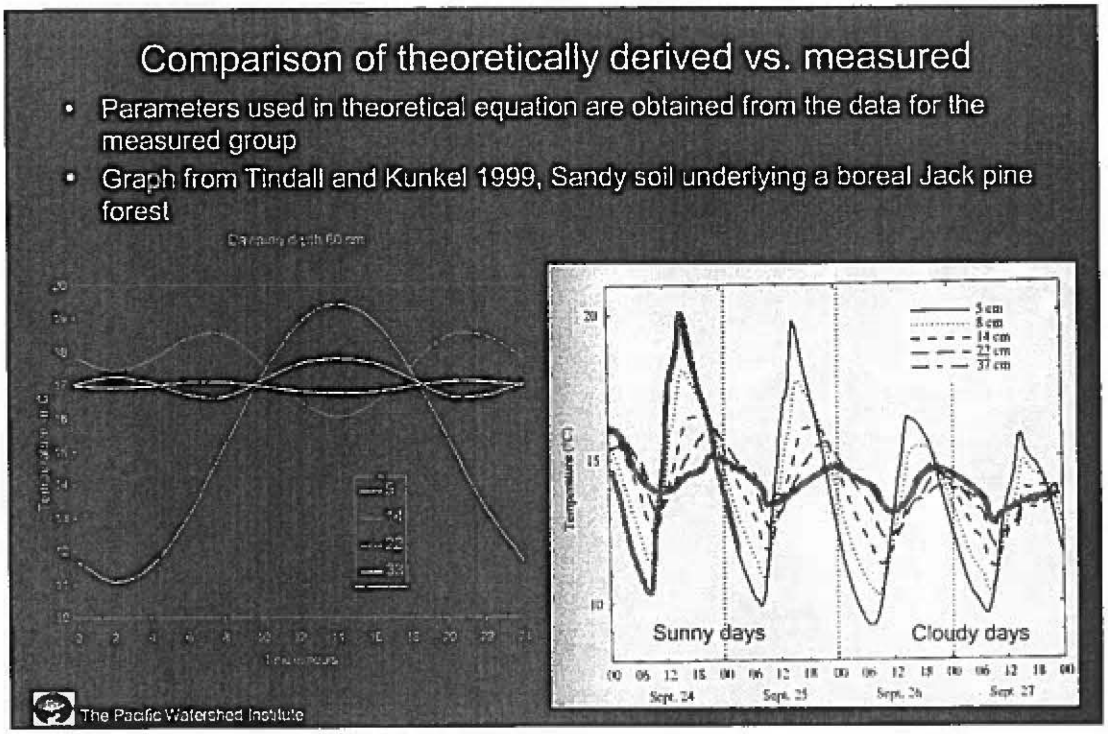
Molecular conduction by Fluid



Damping Depth of Temperature:Theoretical vs empirical

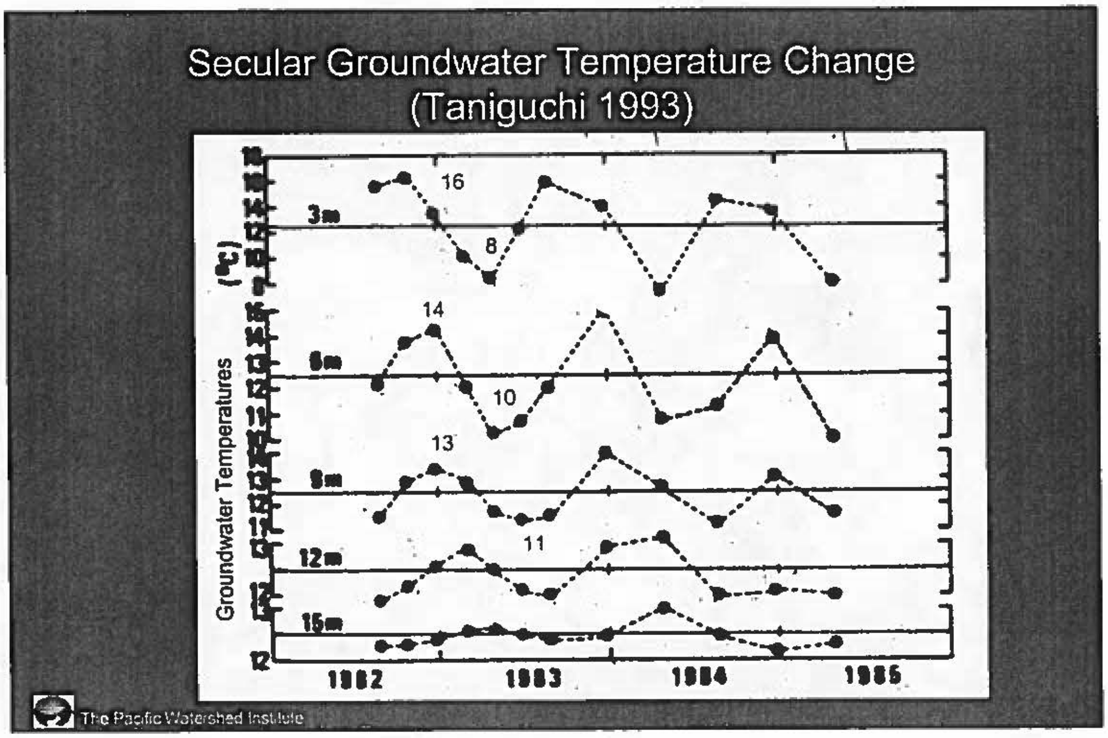
- *Damping Depth*: Attenuation of temperature variation with depth as a function of time and thermal diffusivity (k/c)
  - Based on conduction & soil homogeneity only
- Soils with higher k and lower c will transmit temperature to deeper profiles
- Function of Time
  - $(30\ \text{days})^{0.5}$= 5.5 times daily
  - $(60\ \text{days})^{0.5}$= 7.8 times daily
  - $(365\ \text{days})^{0.5}$ = 19 times daily

  - Data from Tindall and Kunkel 1999, Sandy soil underlying a boreal Jack pine forest

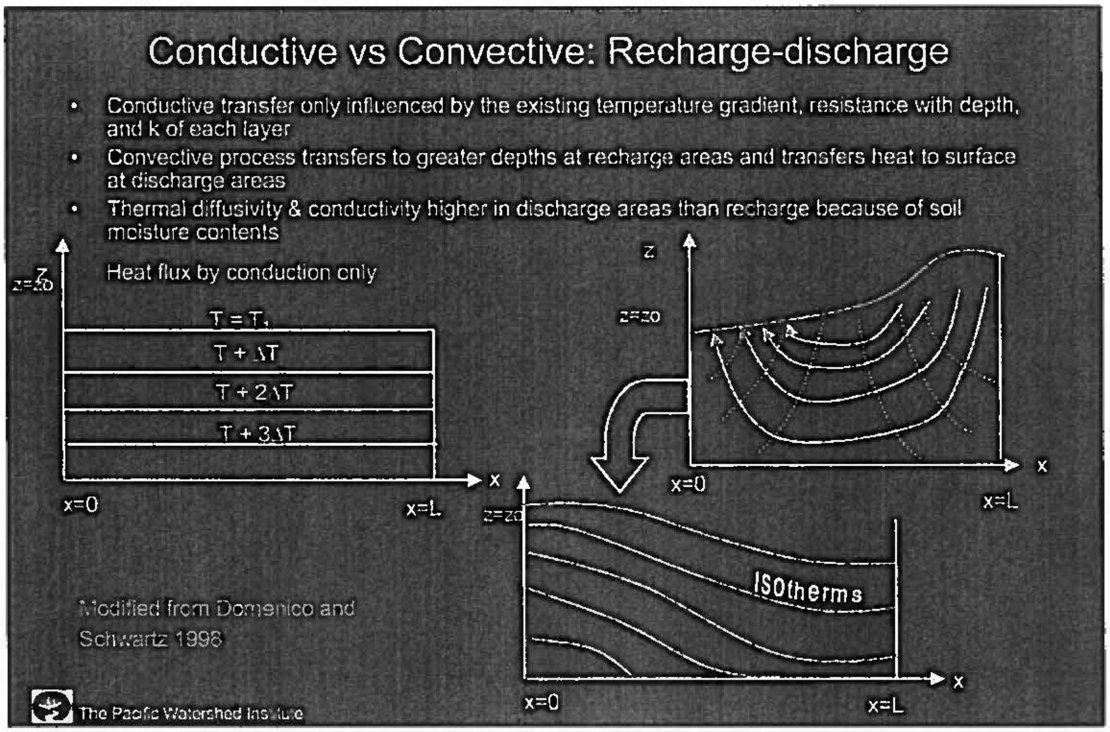


Comparison of theoretically derived vs. measured

- Parameters used in theoretical equation are obtained from the data for the measured group
- Graph from Tindall and Kunkel 1999, Sandy soil underlying a boreal Jack pine forest



Secular Groundwater Temperature Change (Taniguchi 1993)



Conductive vs Convective: Recharge-discharge

- Conductive transfer only influenced by the existing temperature gradient, resistance with depth, and k of each layer
- Convective process transfers to greater depths at recharge areas and transfers heat to surface at discharge areas
- Thermal diffusivity & conductivity higher in discharge areas than recharge because of soil moisture contents

Heat flux by conduction only

Modified from Domenico and Schwartz 1998

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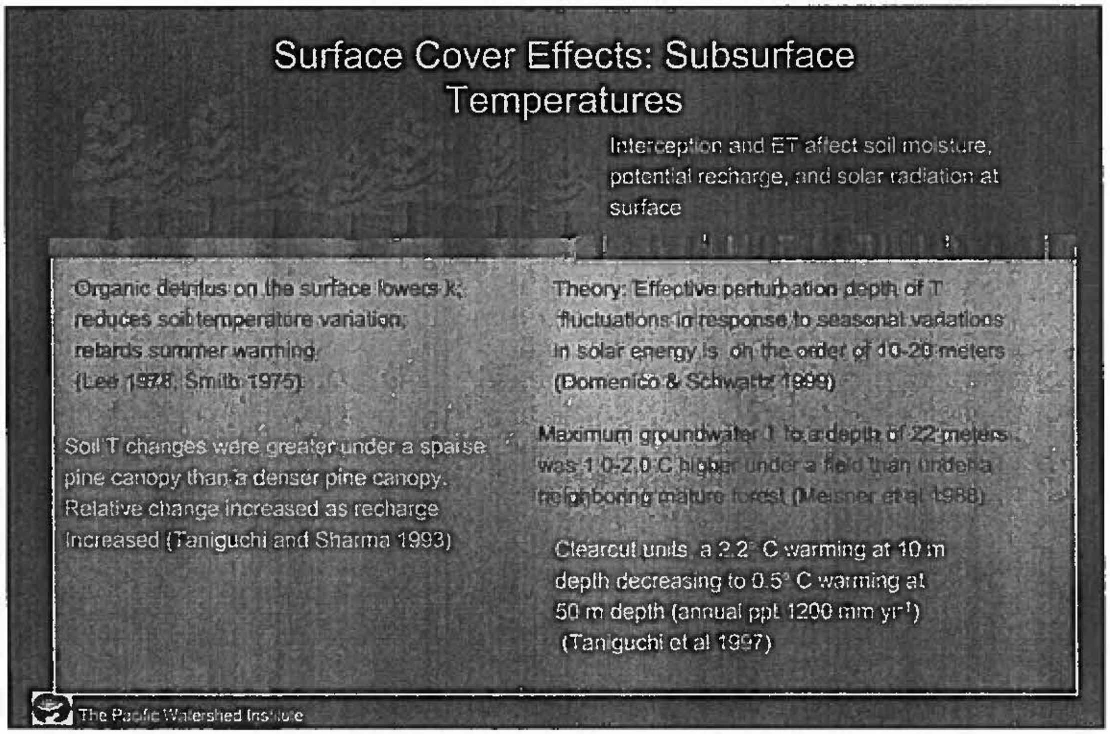

Surface Cover Effects: Subsurface Temperatures

Interception and ET affect soil moisture, potential recharge, and solar radiation at surface

Organic detritus on the surface lowers k; reduces soil temperature variation; retards summer warming (Lee 1978, Smith 1975)

Soil T changes were greater under a sparse pine canopy than a denser pine canopy. Relative change increased as recharge increased (Taniguchi and Sharma 1993)

Theory: Effective perturbation depth of T fluctuations in response to seasonal variations in solar energy is on the order of 10-20 meters (Domenico & Schwartz 1999)

Maximum groundwater T to a depth of 22 meters was 1.0-2.0 C higher under a field than under a neighboring mature forest (Meisner et al 1988)

Clearcut units a 2.2° C warming at 10 m depth decreasing to 0.5° C warming at 50 m depth (annual ppt 1200 mm yr^{-1}) (Taniguchi et al 1997)

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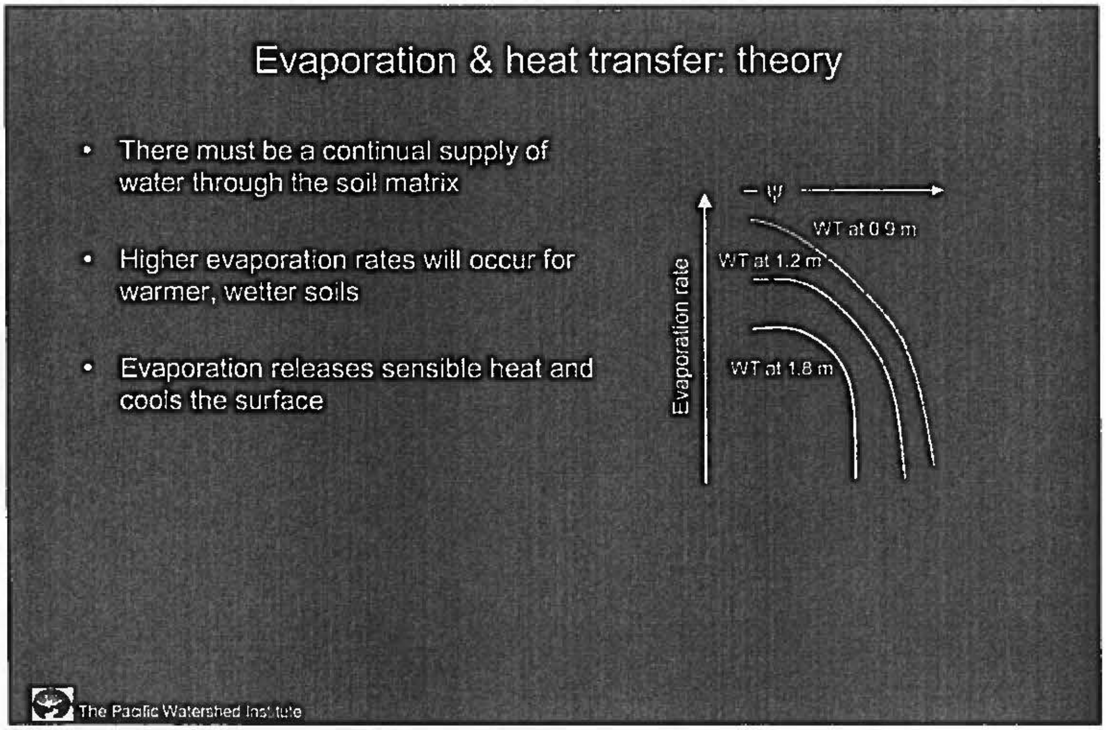
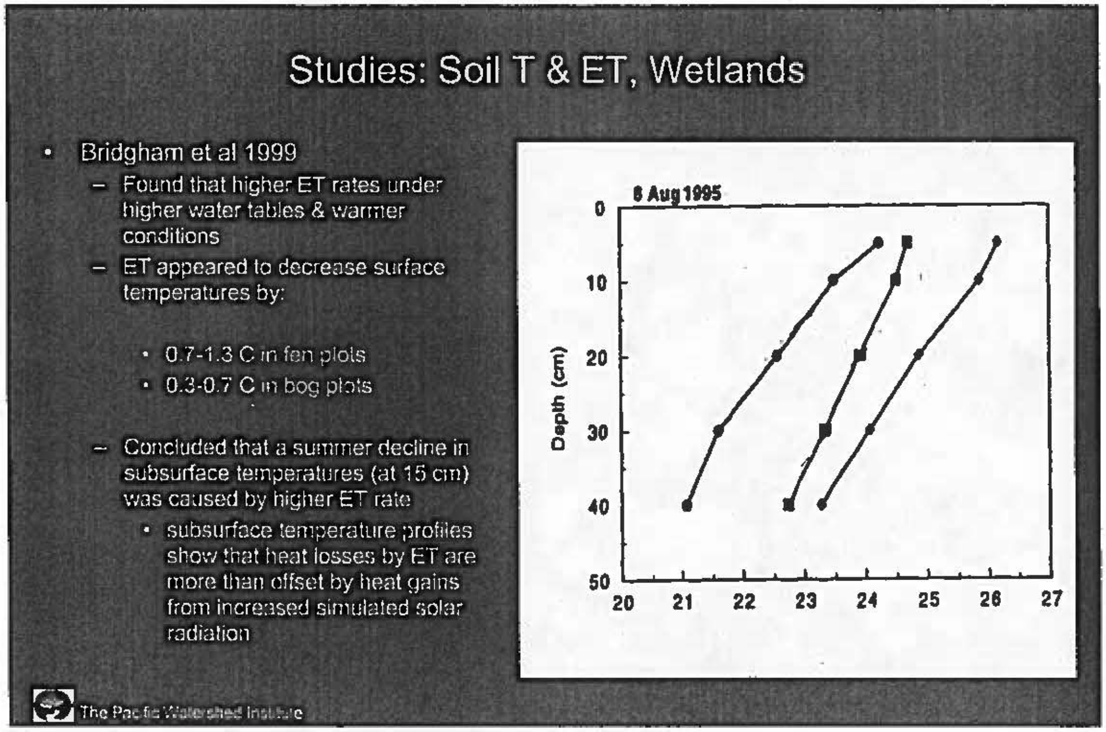


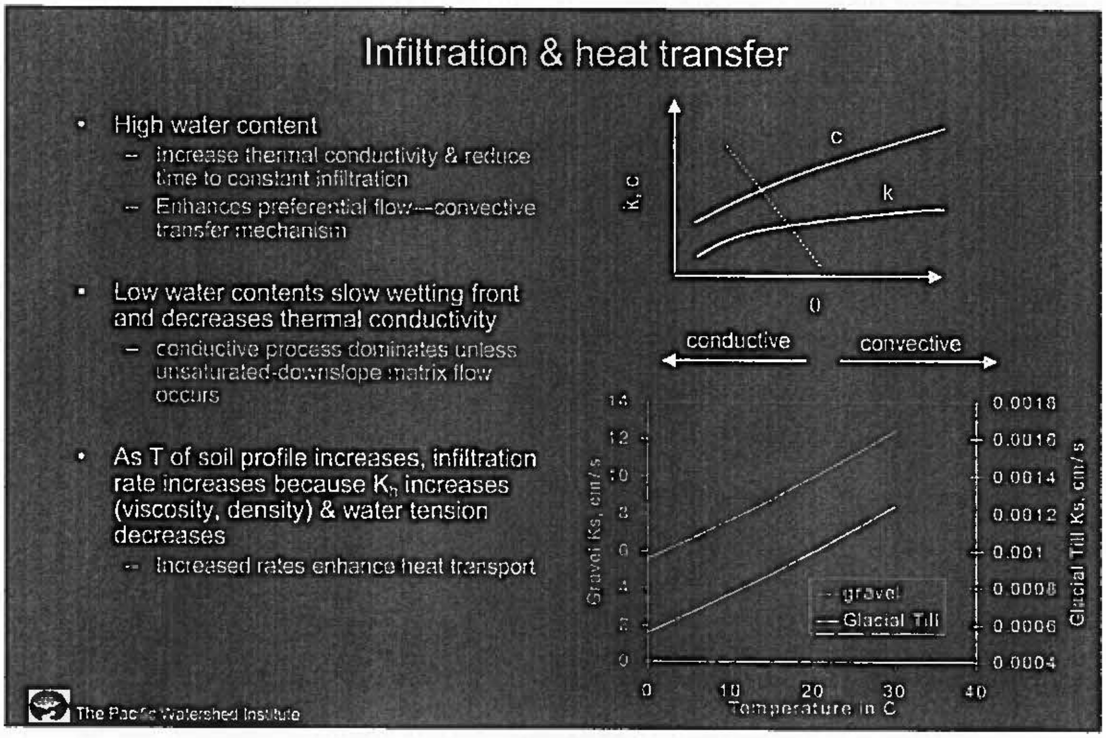
Evaporation & heat transfer: theory

- There must be a continual supply of water through the soil matrix
- Higher evaporation rates will occur for warmer, wetter soils
- Evaporation releases sensible heat and cools the surface



Studies: Soil T & ET, Wetlands

- Bridgham et al 1999
  - Found that higher ET rates under higher water tables & warmer conditions
  - ET appeared to decrease surface temperatures by:
    - 0.7-1.3 C in fen plots
    - 0.3-0.7 C in bog plots
  - Concluded that a summer decline in subsurface temperatures (at 15 cm) was caused by higher ET rate
    - subsurface temperature profiles show that heat losses by ET are more than offset by heat gains from increased simulated solar radiation



Infiltration & heat transfer

- High water content
  - increase thermal conductivity & reduce time to constant infiltration
  - Enhances preferential flow—convective transfer mechanism
- Low water contents slow wetting front and decreases thermal conductivity
  - conductive process dominates unless unsaturated-downslope matrix flow occurs
- As T of soil profile increases, infiltration rate increases because K_h increases (viscosity, density) & water tension decreases
  - Increased rates enhance heat transport

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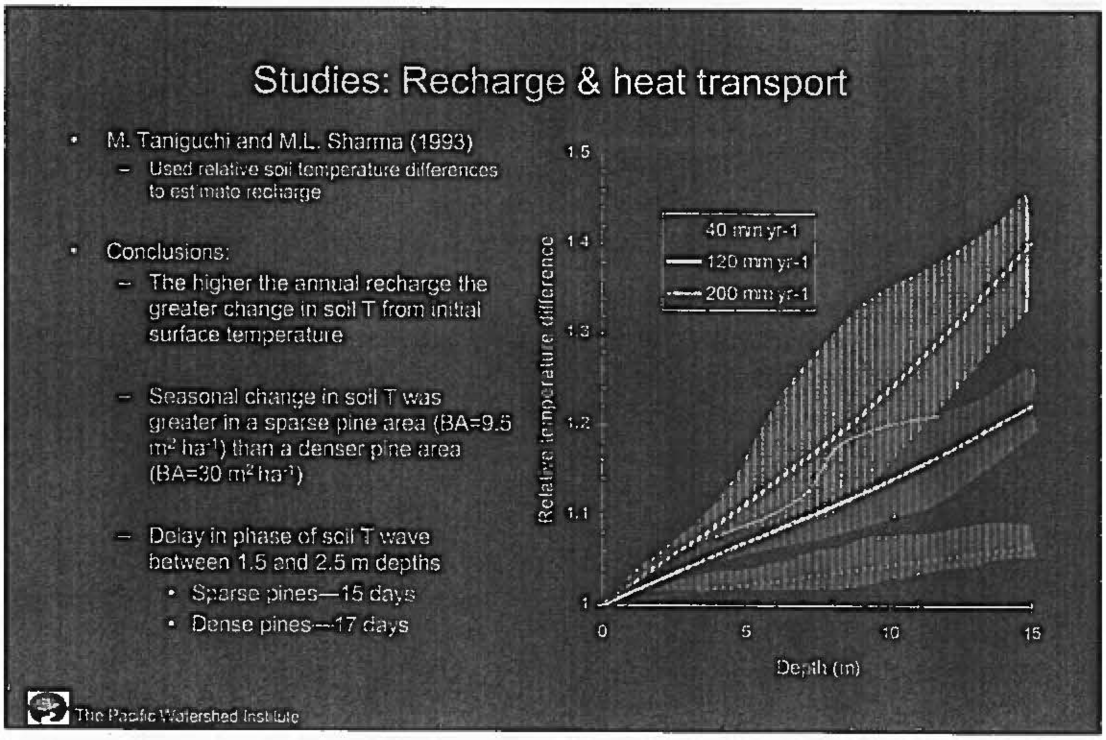

Studies: Recharge & heat transport

- M. Taniguchi and M.L. Sharma (1993)
  - Used relative soil temperature differences to estimate recharge
- Conclusions:
  - The higher the annual recharge the greater change in soil T from initial surface temperature
  - Seasonal change in soil T was greater in a sparse pine area (BA=9.5 $m^2 ha^{-1}$) than a denser pine area (BA=30 $m^2 ha^{-1}$)
  - Delay in phase of soil T wave between 1.5 and 2.5 m depths
    - Sparse pines—15 days
    - Dense pines—17 days

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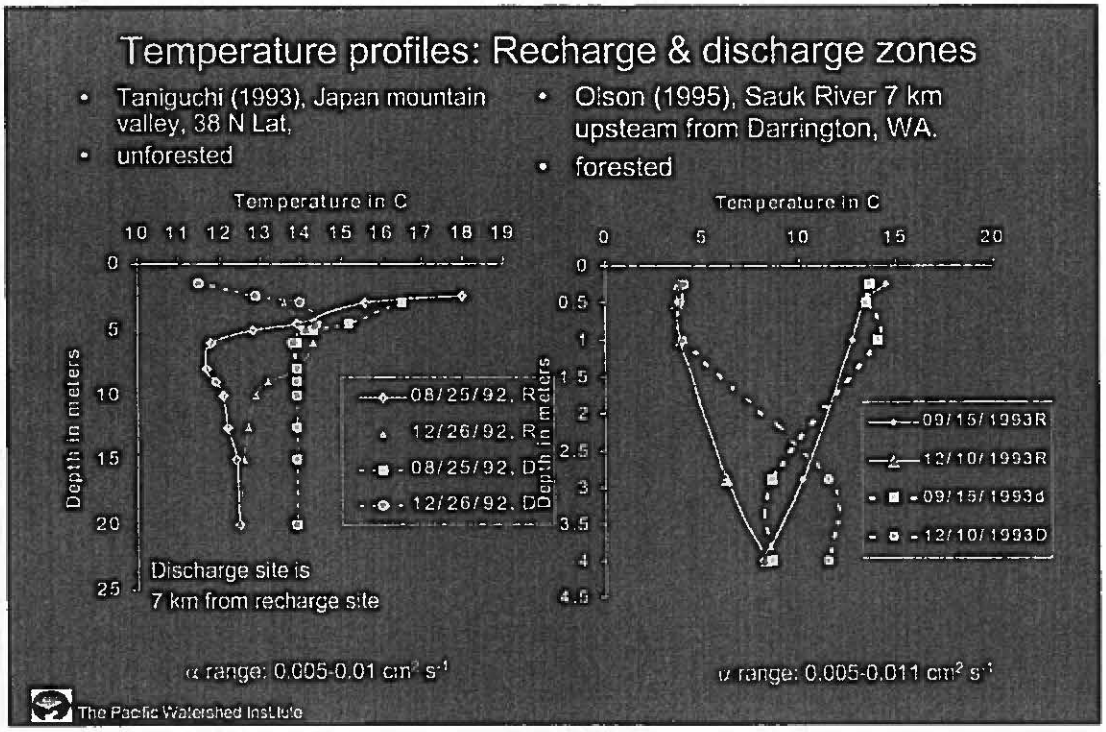

Temperature profiles: Recharge & discharge zones

- Taniguchi (1993), Japan mountain valley, 38 N Lat,
- unforested

- Olson (1995), Sauk River 7 km upsteam from Darrington, WA.
- forested

α range: 0.005-0.01 cm² s⁻¹

α range: 0.005-0.011 cm² s⁻¹

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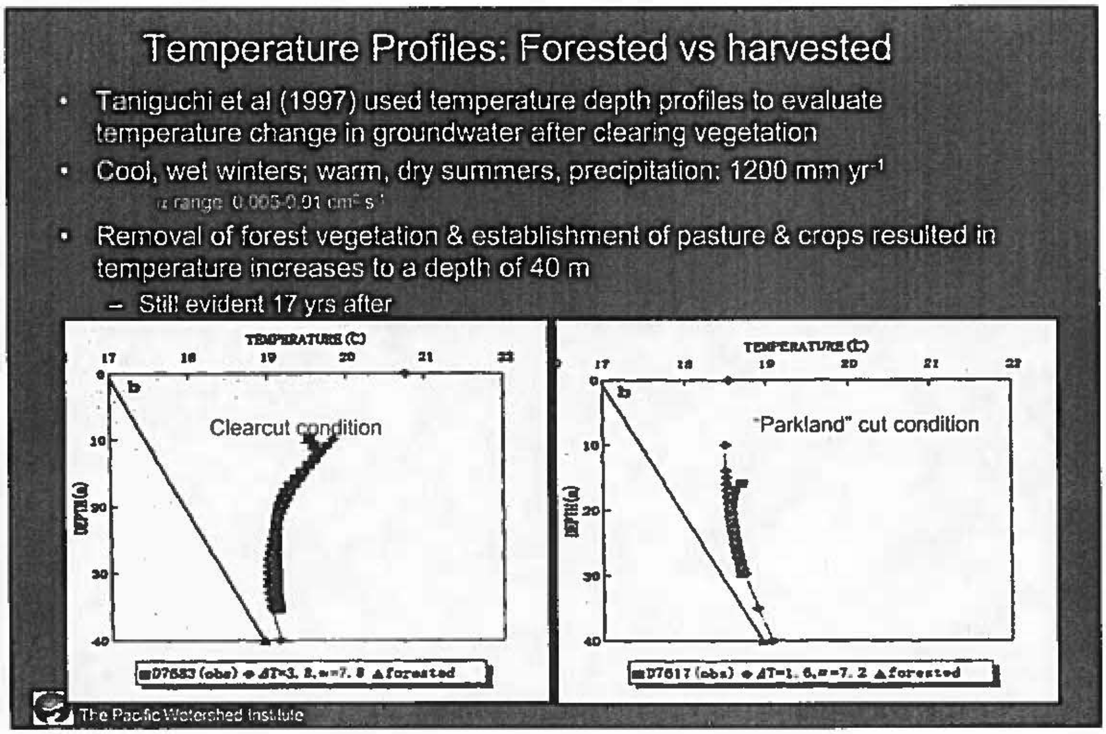

Temperature Profiles: Forested vs harvested

- Taniguchi et al (1997) used temperature depth profiles to evaluate temperature change in groundwater after clearing vegetation
- Cool, wet winters; warm, dry summers, precipitation: 1200 mm yr⁻¹
  α range: 0.005-0.01 cm² s⁻¹
- Removal of forest vegetation & establishment of pasture & crops resulted in temperature increases to a depth of 40 m
  - Still evident 17 yrs after

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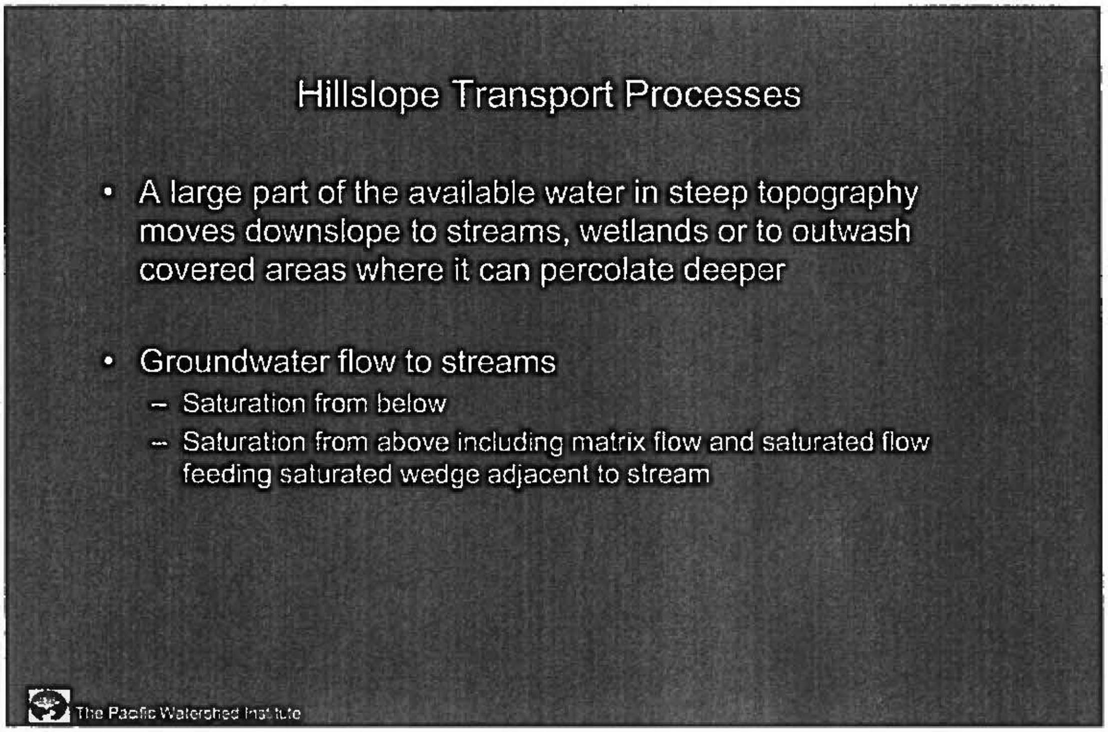

Hillslope Transport Processes

- A large part of the available water in steep topography moves downslope to streams, wetlands or to outwash covered areas where it can percolate deeper
- Groundwater flow to streams
  - Saturation from below
  - Saturation from above including matrix flow and saturated flow feeding saturated wedge adjacent to stream

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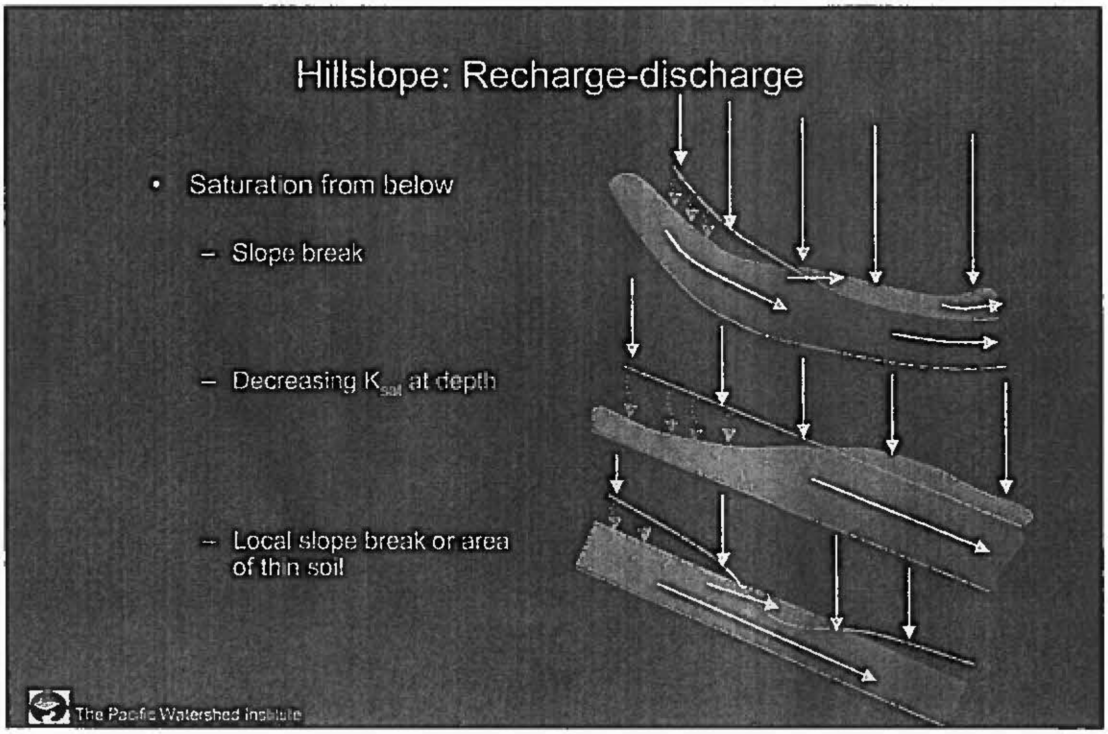

Hillslope: Recharge-discharge

- Saturation from below
  - Slope break
  - Decreasing K_{sat} at depth
  - Local slope break or area of thin soil

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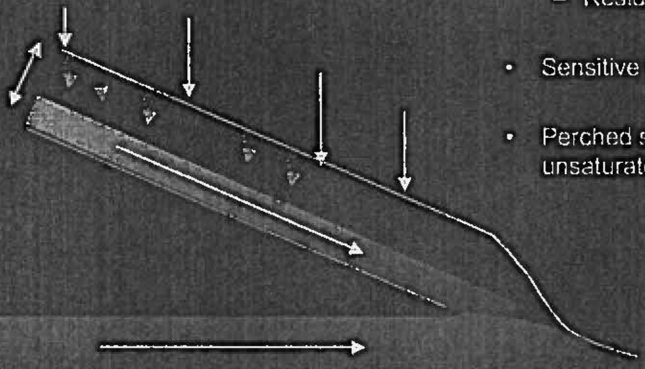
Hillslope Transport Processes

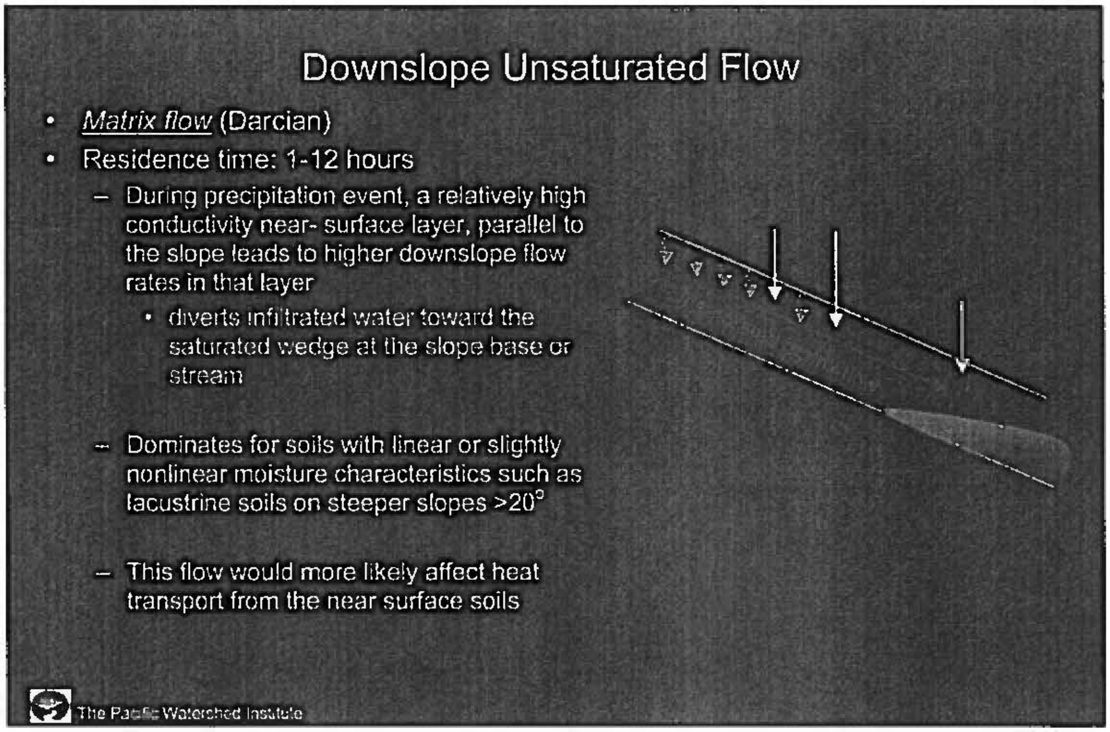
- Subsurface water flow down hillslopes caused by saturation from above:
  - *Perched saturated zones*
    - Local flow systems separated from regional systems
  - *Matrix flow (Darcian)*
    - Interflow, throughflow
    - Downslope flow occurring between the ground surface and water table
  - *Preferential flow*—rapidly moving flow, maybe non-Darcian
    - Topographic/sediment induced
    - Macropore flow

Perched saturated flow: dry conditions

Infiltrating water percolates to a less permeable layer above the groundwater table



- Formation of "perched" or local flow saturated zone on a hillslope
  - High conductivity layer over much less permeable layer
  - Slopes steep, straight to convex
  - Residence time, percolation:1-50 hrs
- Sensitive to initial moisture content and Ks
- Perched system will capture heat from the unsaturated matrix & transport is downslope



Downslope Unsaturated Flow

- *Matrix flow* (Darcian)
- Residence time: 1-12 hours
  - During precipitation event, a relatively high conductivity near- surface layer, parallel to the slope leads to higher downslope flow rates in that layer
    - diverts infiltrated water toward the saturated wedge at the slope base or stream
  - Dominates for soils with linear or slightly nonlinear moisture characteristics such as lacustrine soils on steeper slopes >20°
  - This flow would more likely affect heat transport from the near surface soils

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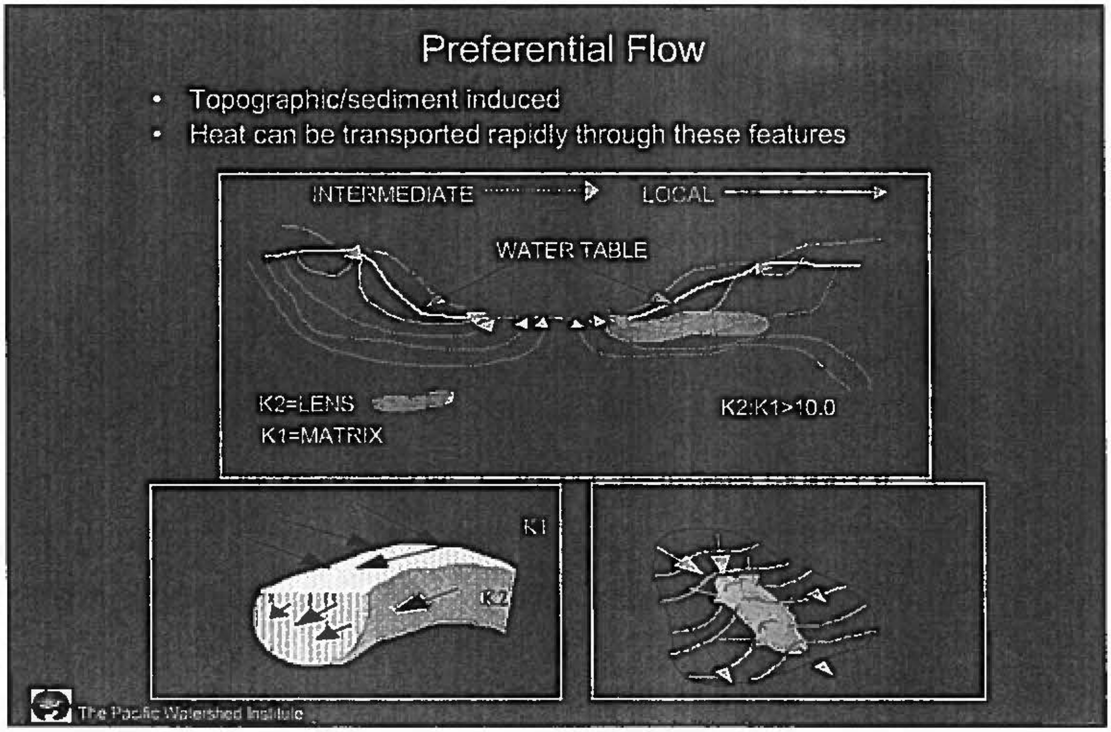

Preferential Flow

- Topographic/sediment induced
- Heat can be transported rapidly through these features

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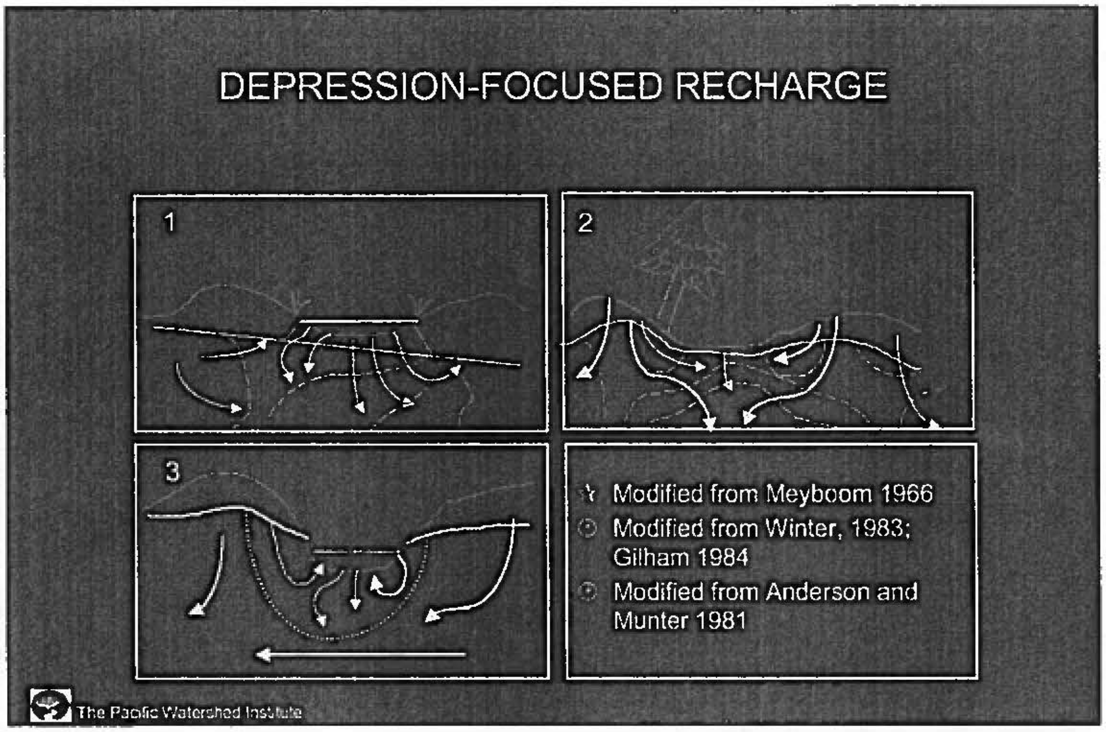

DEPRESSION-FOCUSED RECHARGE

- Modified from Meyboom 1966
- Modified from Winter, 1983; Gilham 1984
- Modified from Anderson and Munter 1981

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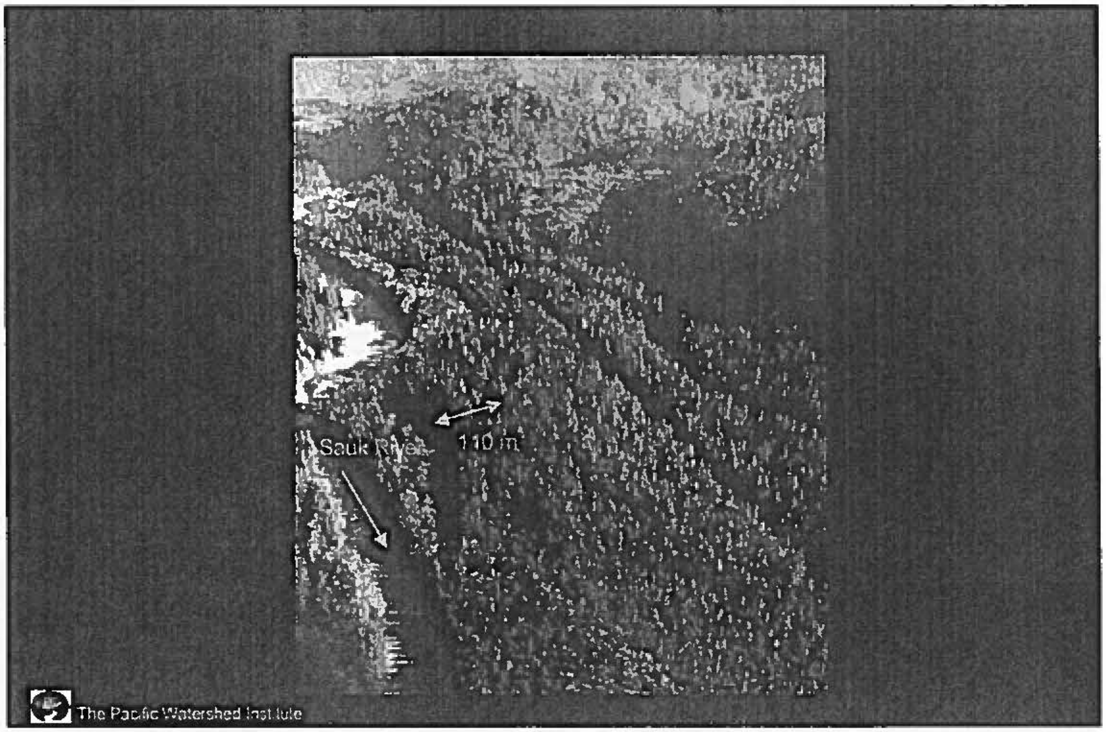

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Examples on the landscape

Buried channel feature on a terrace

Incised ephmeral channel at terrace base

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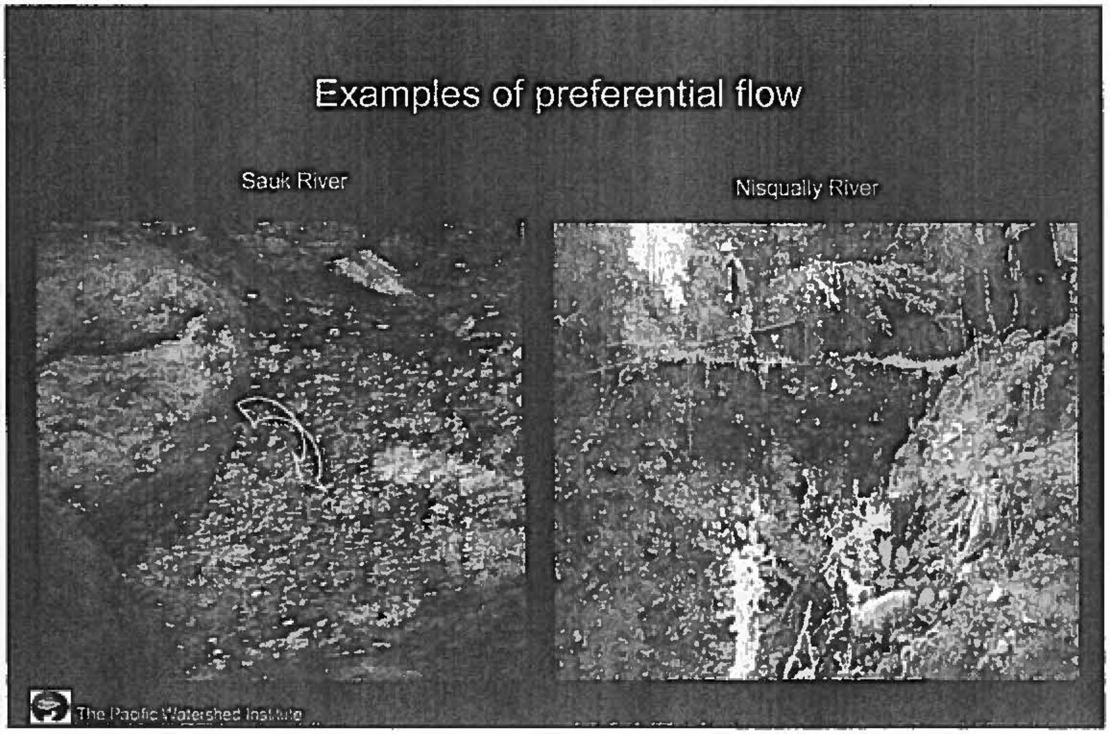

Examples of preferential flow

Sauk River

Nisqually River

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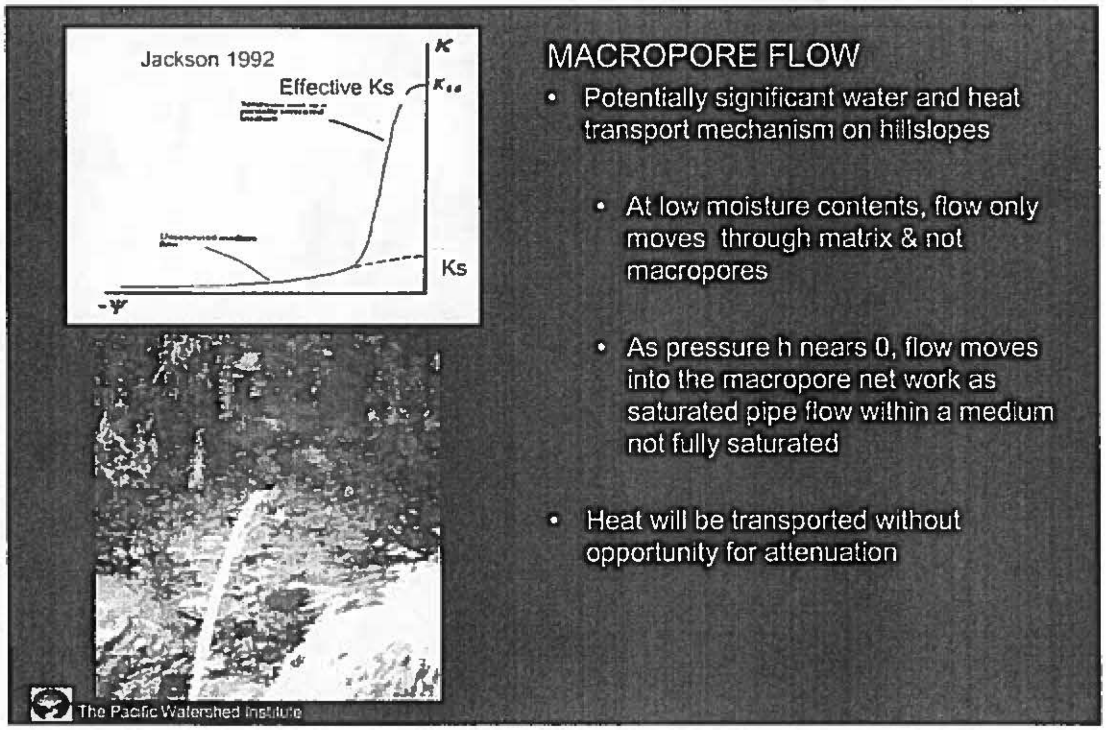

MACROPORE FLOW

- Potentially significant water and heat transport mechanism on hillslopes
  - At low moisture contents, flow only moves through matrix & not macropores
  - As pressure h nears 0, flow moves into the macropore net work as saturated pipe flow within a medium not fully saturated
- Heat will be transported without opportunity for attenuation

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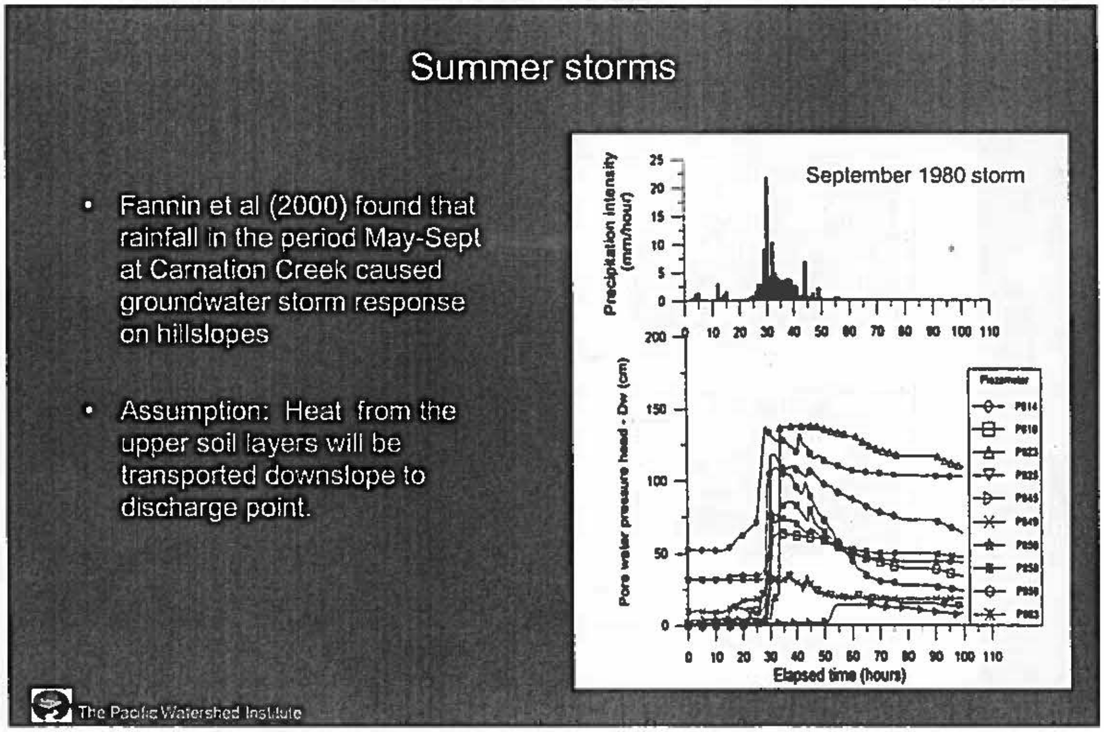

Summer storms

- Fannin et al (2000) found that rainfall in the period May-Sept at Carnation Creek caused groundwater storm response on hillslopes
- Assumption: Heat from the upper soil layers will be transported downslope to discharge point.

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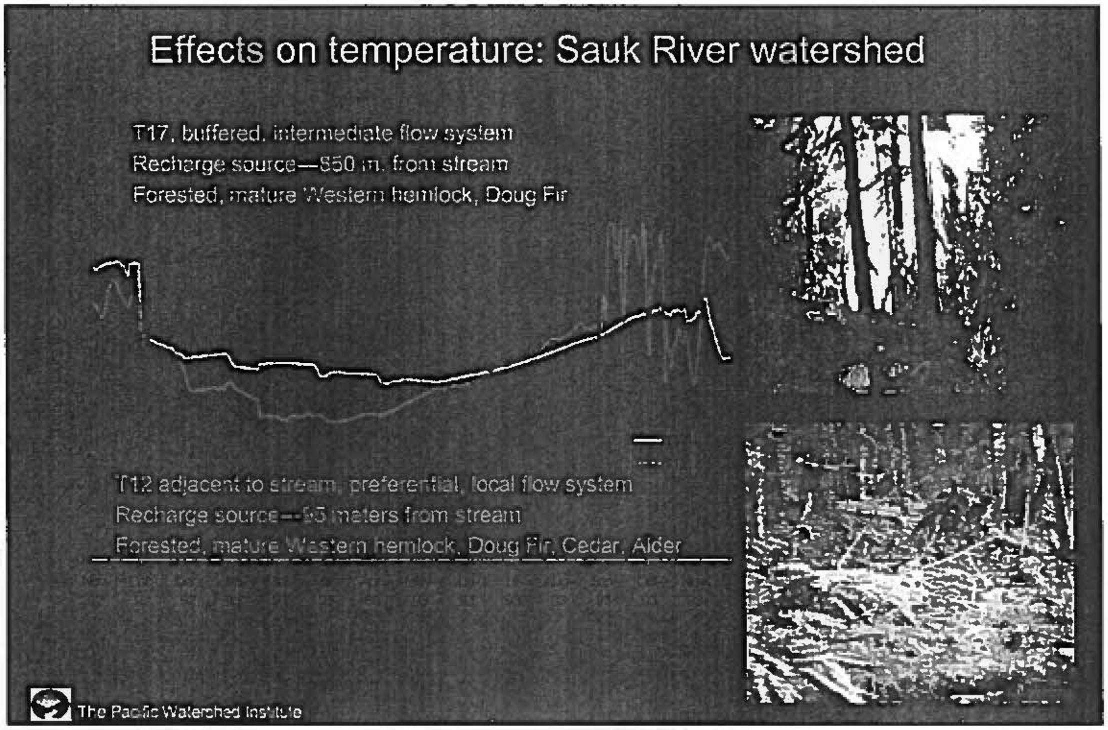

Effects on temperature: Sauk River watershed

T17, buffered, intermediate flow system
Recharge source—850 m. from stream
Forested, mature Western hemlock, Doug Fir

T12 adjacent to stream, preferential, local flow system
Recharge source—65 meters from stream
Forested, mature Western hemlock, Doug Fir, Cedar, Alder

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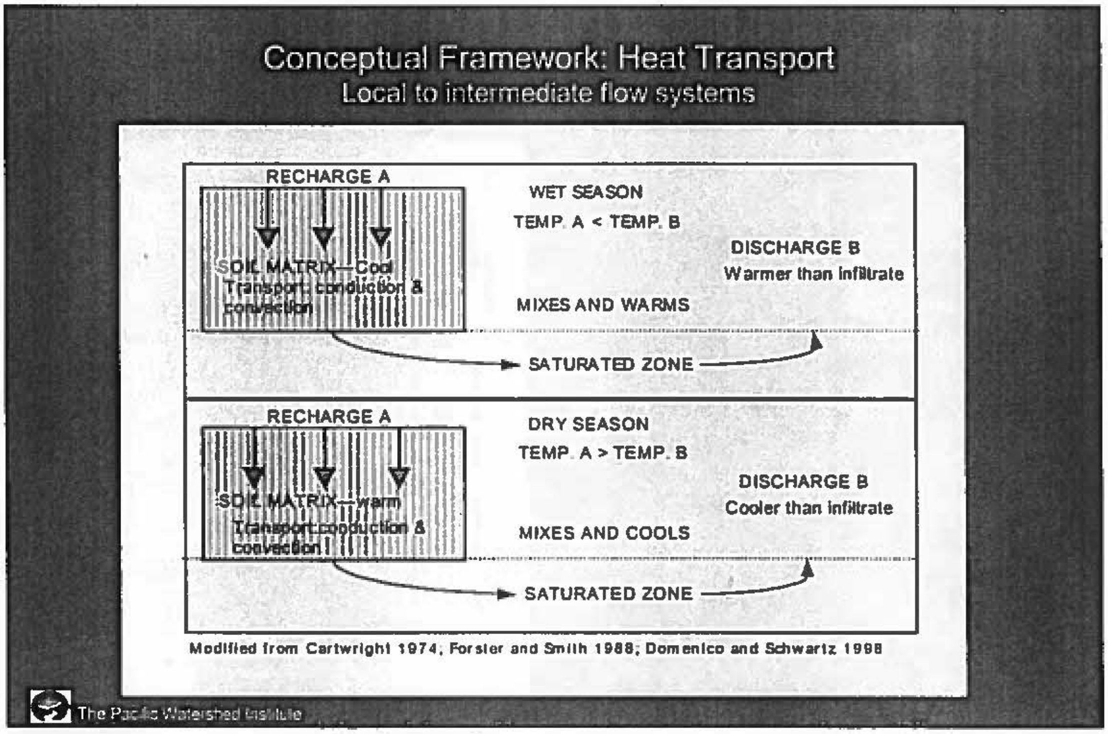

Conceptual Framework: Heat Transport

Local to intermediate flow systems

RECHARGE A
SOIL MATRIX—Cool
Transport: conduction & convection
WET SEASON
TEMP. A < TEMP. B
DISCHARGE B
Warmer than infiltrate
MIXES AND WARMS
SATURATED ZONE

RECHARGE A
SOIL MATRIX—warm
Transport: conduction & convection
DRY SEASON
TEMP. A > TEMP. B
DISCHARGE B
Cooler than infiltrate
MIXES AND COOLS
SATURATED ZONE

Modified from Cartwright 1974; Forster and Smith 1988; Domenico and Schwartz 1998

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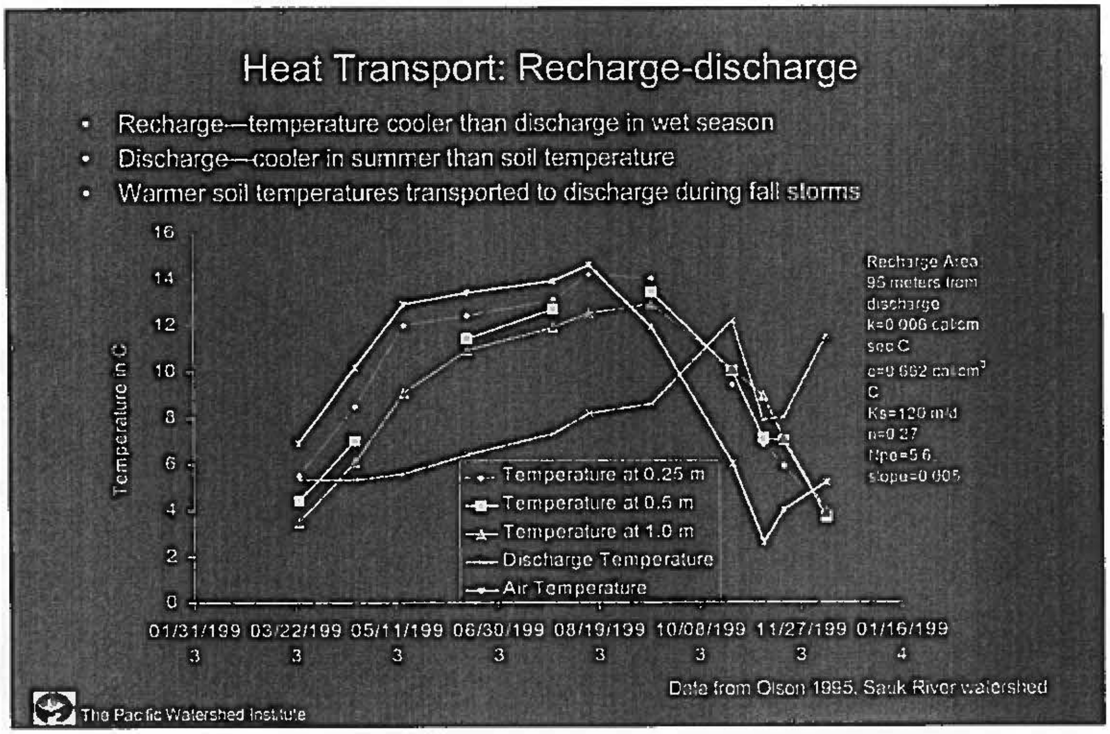

Heat Transport: Recharge-discharge

- Recharge—temperature cooler than discharge in wet season
- Discharge—cooler in summer than soil temperature
- Warmer soil temperatures transported to discharge during fall storms

Data from Olson 1995, Sauk River watershed

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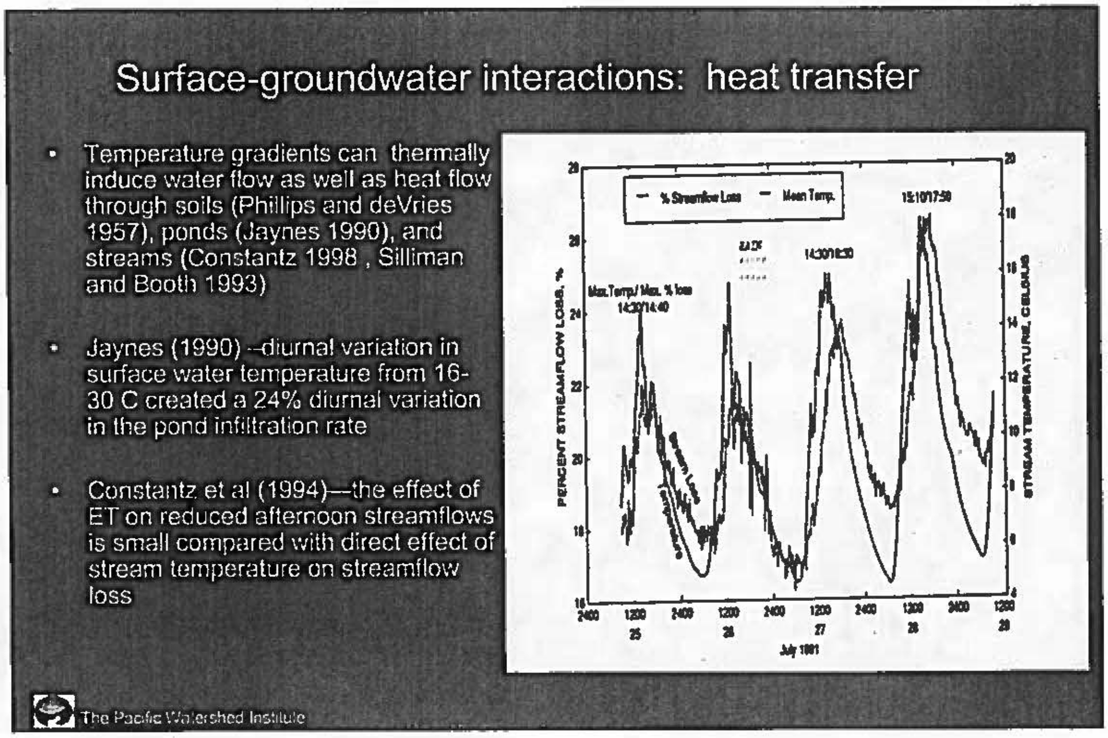

Surface-groundwater interactions: heat transfer

- Temperature gradients can thermally induce water flow as well as heat flow through soils (Phillips and deVries 1957), ponds (Jaynes 1990), and streams (Constantz 1998 , Silliman and Booth 1993)
- Jaynes (1990) --diurnal variation in surface water temperature from 16-30 C created a 24% diurnal variation in the pond infiltration rate
- Constantz et al (1994)—the effect of ET on reduced afternoon streamflows is small compared with direct effect of stream temperature on streamflow loss

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Summary: Subsurface Heat Transport

- Unsaturated zone—heat transport depends on water content, hydraulic and thermal conductivity, heat and storage capacity, porosity, runoff processes, travel time and governing equations are highly non-linear
  - Conduction dominant for dry to intermediate soil moisture conditions
  - Coupled conduction-convection for intermediate to near saturated conditions
- Saturated zone—heat transport depends on hydraulic and thermal conductivity, porosity, heat and storage capacity, travel time, and recharge-discharge dynamics
  - Convection dominates when velocities > 20 $\mathrm{m\ yr^{-1}}$ and Peclet number > 1

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Summary: Subsurface Heat Transport

- As porosity increases, hydraulic and thermal conductivity, damping depth generally decrease
- Water storage capacity and retention and heat capacity generally increase as porosity increases
- Theoretical equations for damping depth and time lag with depth apparently do not predict thermal regimes for forested areas

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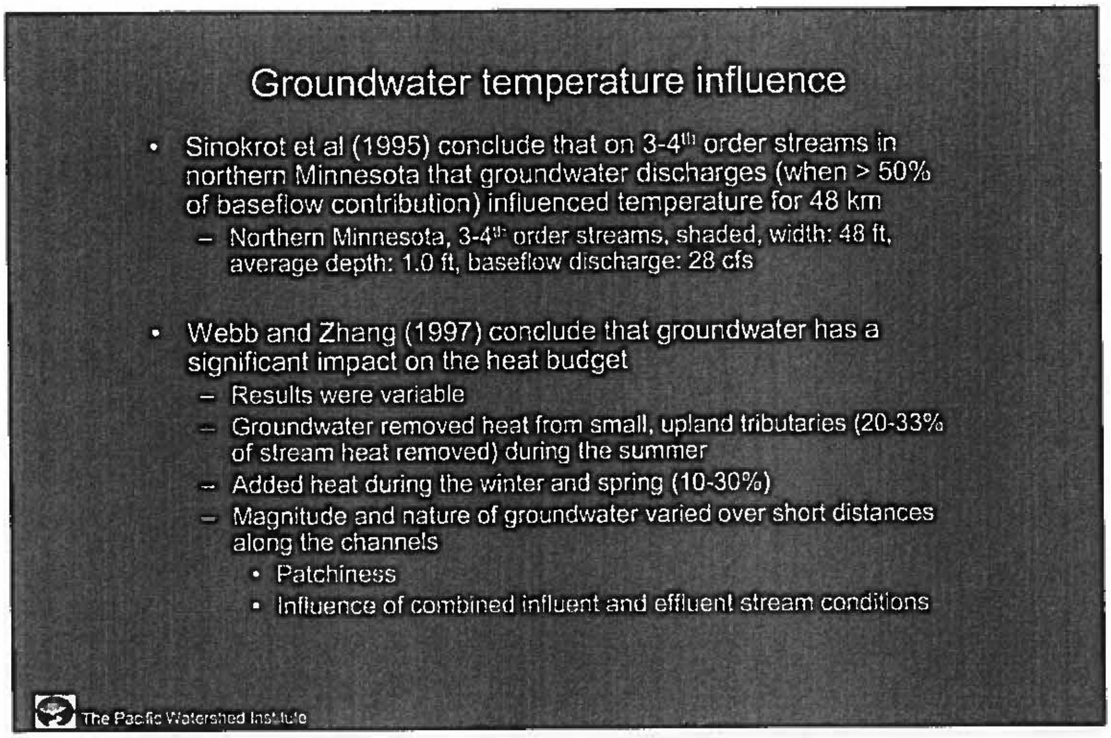

Groundwater temperature influence

- Sinokrot et al (1995) conclude that on 3-4th order streams in northern Minnesota that groundwater discharges (when > 50% of baseflow contribution) influenced temperature for 48 km
  - Northern Minnesota, 3-4th order streams, shaded, width: 48 ft, average depth: 1.0 ft, baseflow discharge: 28 cfs
- Webb and Zhang (1997) conclude that groundwater has a significant impact on the heat budget
  - Results were variable
  - Groundwater removed heat from small, upland tributaries (20-33% of stream heat removed) during the summer
  - Added heat during the winter and spring (10-30%)
  - Magnitude and nature of groundwater varied over short distances along the channels
    - Patchiness
    - Influence of combined influent and effluent stream conditions

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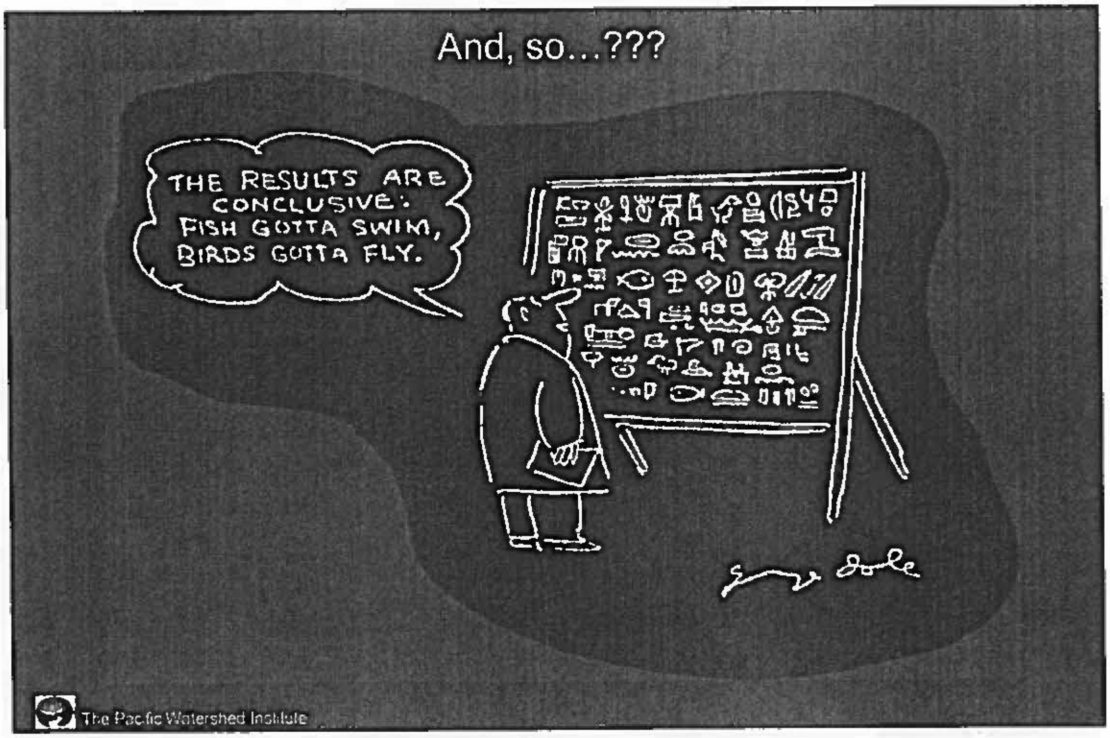

And, so...???

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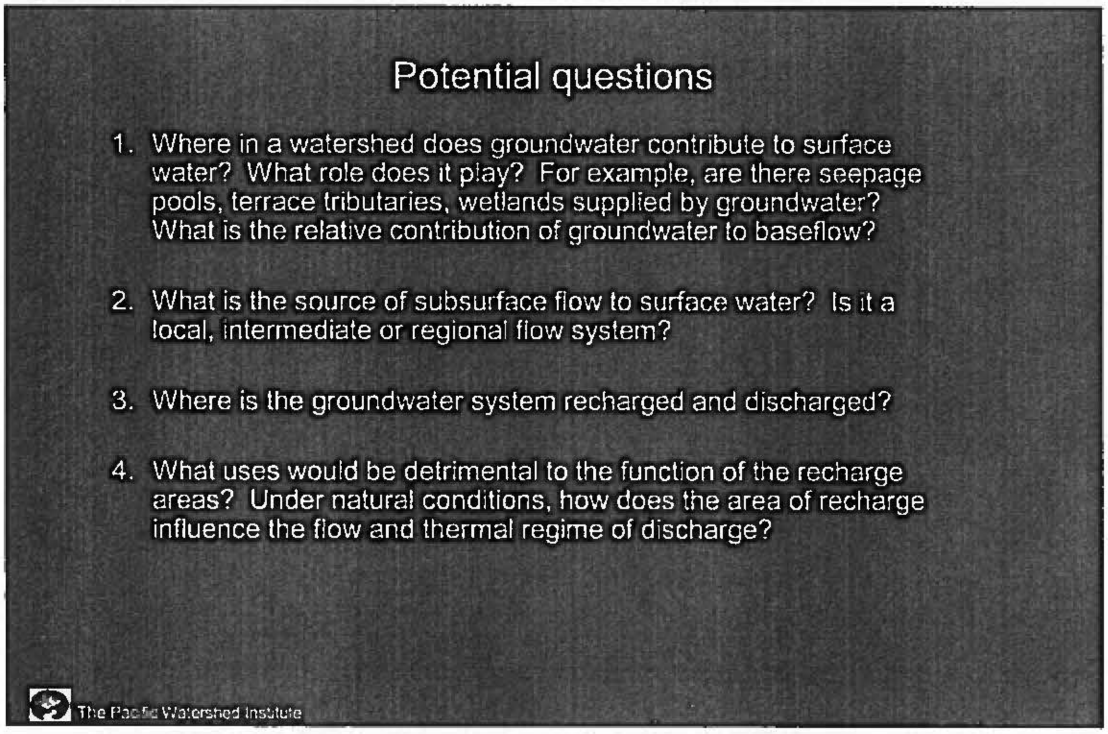

Potential questions

1. Where in a watershed does groundwater contribute to surface water? What role does it play? For example, are there seepage pools, terrace tributaries, wetlands supplied by groundwater? What is the relative contribution of groundwater to baseflow?
2. What is the source of subsurface flow to surface water? Is it a local, intermediate or regional flow system?
3. Where is the groundwater system recharged and discharged?
4. What uses would be detrimental to the function of the recharge areas? Under natural conditions, how does the area of recharge influence the flow and thermal regime of discharge?

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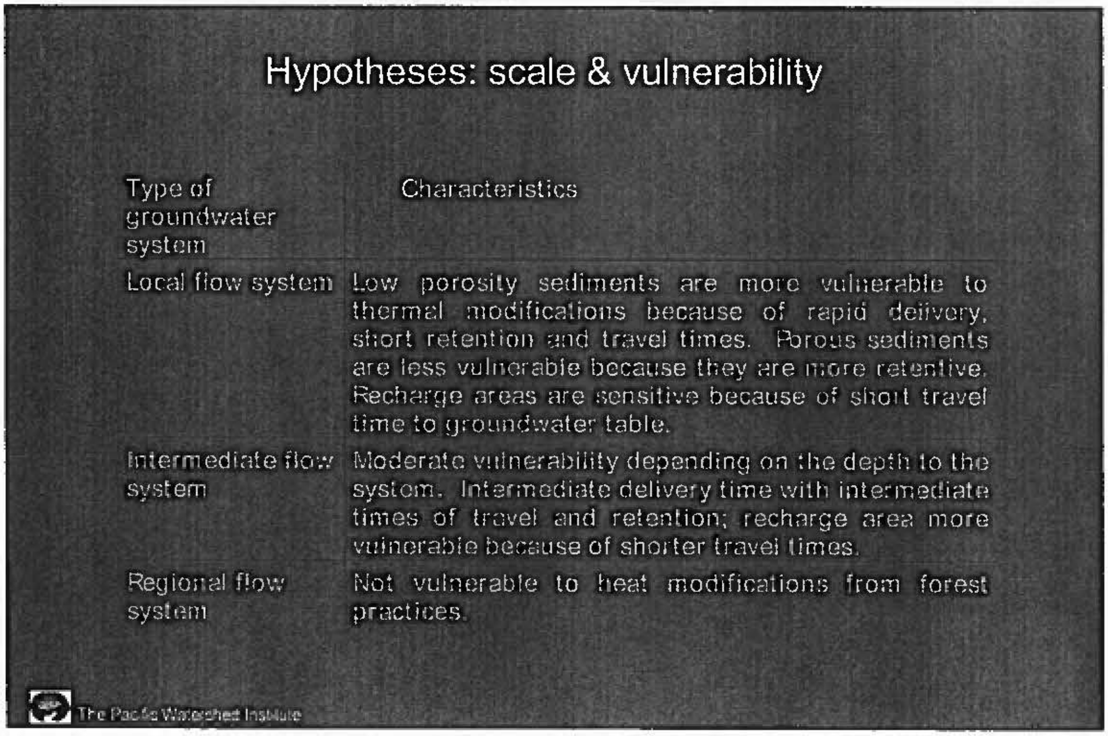

Hypotheses: scale & vulnerability

Type of groundwater system	Characteristics
Local flow system	Low porosity sediments are more vulnerable to thermal modifications because of rapid delivery, short retention and travel times. Porous sediments are less vulnerable because they are more retentive. Recharge areas are sensitive because of short travel time to groundwater table.
Intermediate flow system	Moderate vulnerability depending on the depth to the system. Intermediate delivery time with intermediate times of travel and retention; recharge area more vulnerable because of shorter travel times.
Regional flow system	Not vulnerable to heat modifications from forest practices.

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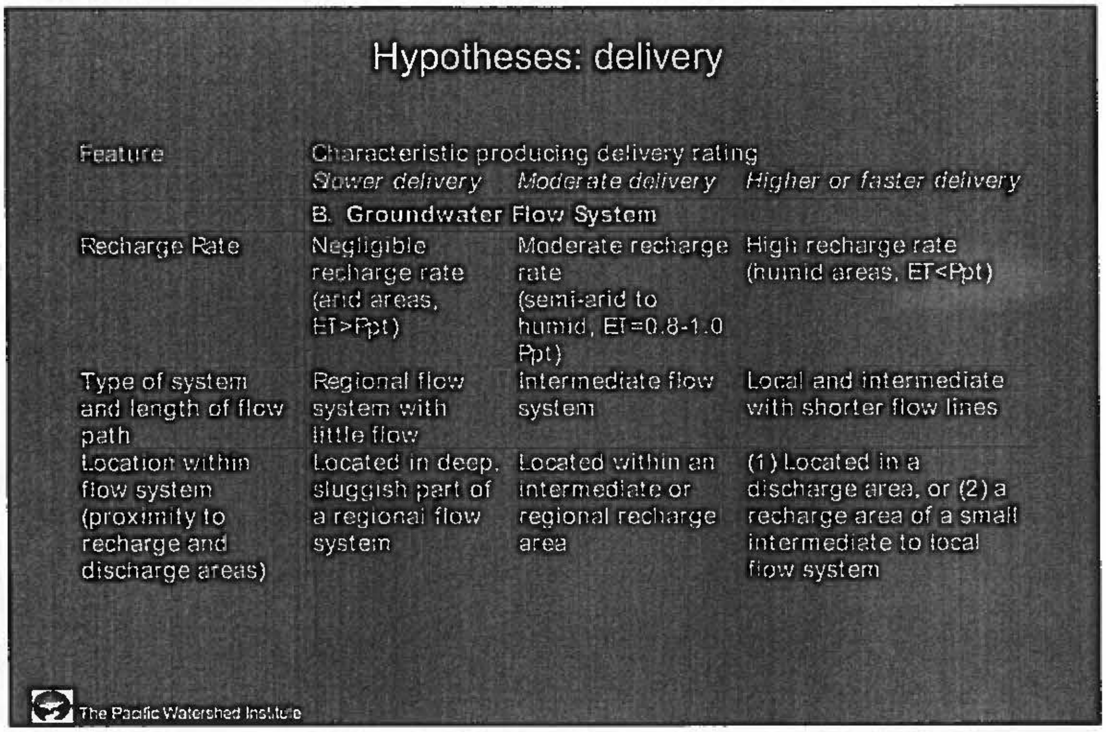

Hypotheses: delivery

Feature	Characteristic producing delivery rating		
	Slower delivery	*Moderate delivery*	*Higher or faster delivery*
	B. Groundwater Flow System		
Recharge Rate	Negligible recharge rate (arid areas, ET>Ppt)	Moderate recharge rate (semi-arid to humid, ET=0.8-1.0 Ppt)	High recharge rate (humid areas, ET<Ppt)
Type of system and length of flow path	Regional flow system with little flow	Intermediate flow system	Local and intermediate with shorter flow lines
Location within flow system (proximity to recharge and discharge areas)	Located in deep, sluggish part of a regional flow system	Located within an intermediate or regional recharge area	(1) Located in a discharge area, or (2) a recharge area of a small intermediate to local flow system

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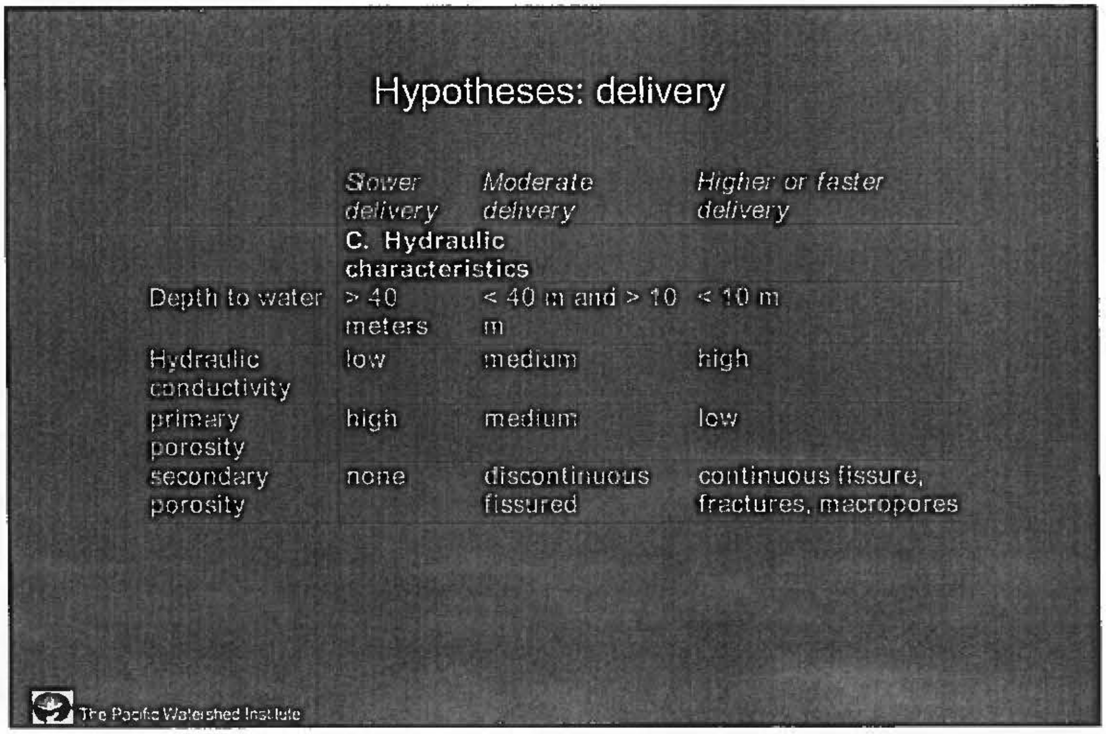

Hypotheses: delivery

	Slower delivery	*Moderate delivery*	*Higher or faster delivery*
	C. Hydraulic characteristics		
Depth to water	> 40 meters	< 40 m and > 10 m	< 10 m
Hydraulic conductivity	low	medium	high
primary porosity	high	medium	low
secondary porosity	none	discontinuous fissured	continuous fissure, fractures, macropores

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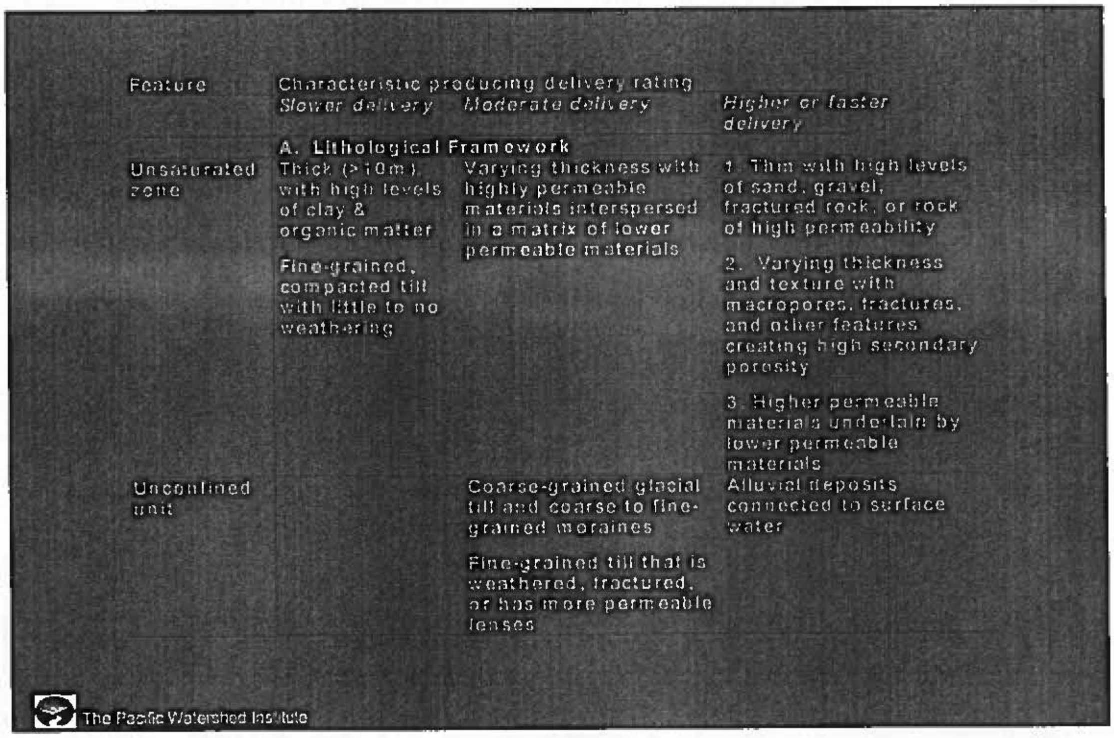

Feature	Characteristic producing delivery rating		
	Slower delivery	*Moderate delivery*	*Higher or faster delivery*
	A. Lithological Framework		
Unsaturated zone	Thick (>10m), with high levels of clay & organic matter Fine-grained, compacted till with little to no weathering	Varying thickness with highly permeable materials interspersed in a matrix of lower permeable materials	1. Thin with high levels of sand, gravel, fractured rock, or rock of high permeability 2. Varying thickness and texture with macropores, fractures, and other features creating high secondary porosity 3. Higher permeable materials underlain by lower permeable materials
Unconfined unit		Coarse-grained glacial till and coarse to fine-grained moraines Fine-grained till that is weathered, fractured, or has more permeable lenses	Alluvial deposits connected to surface water

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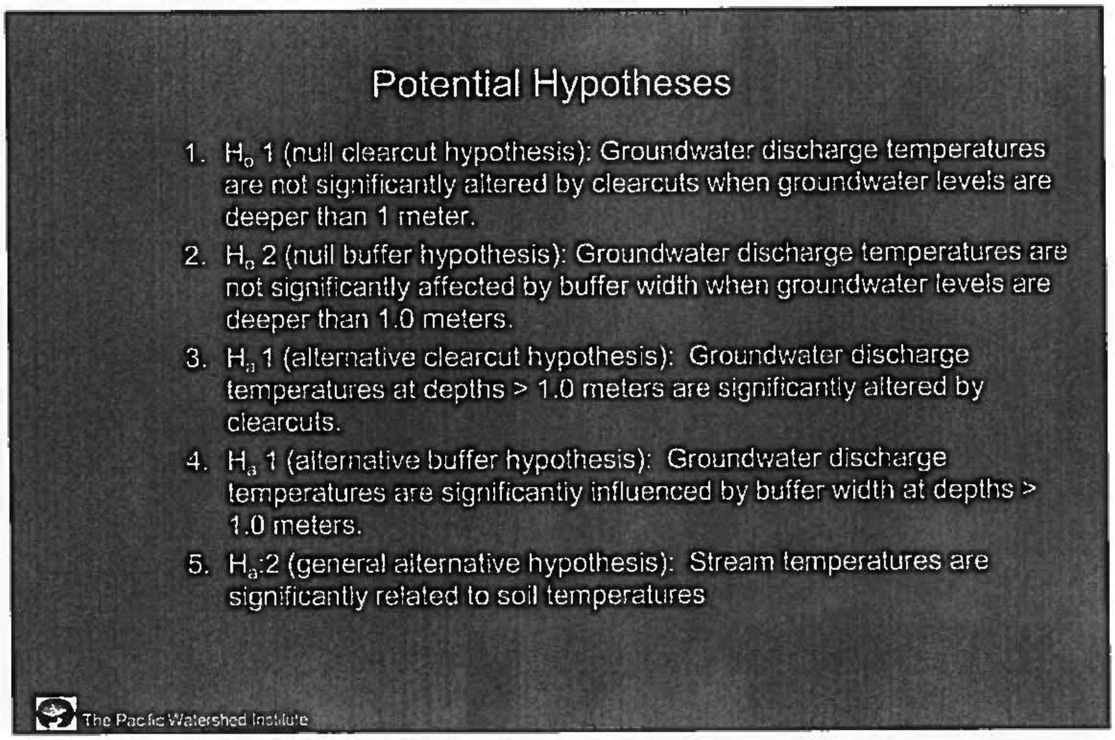

Potential Hypotheses

1. H_o 1 (null clearcut hypothesis): Groundwater discharge temperatures are not significantly altered by clearcuts when groundwater levels are deeper than 1 meter.
2. H_o 2 (null buffer hypothesis): Groundwater discharge temperatures are not significantly affected by buffer width when groundwater levels are deeper than 1.0 meters.
3. H_a 1 (alternative clearcut hypothesis): Groundwater discharge temperatures at depths > 1.0 meters are significantly altered by clearcuts.
4. H_a 1 (alternative buffer hypothesis): Groundwater discharge temperatures are significantly influenced by buffer width at depths > 1.0 meters.
5. H_a:2 (general alternative hypothesis): Stream temperatures are significantly related to soil temperatures

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Appendix E
Additional Material – Microclimate and Riparian Conditions

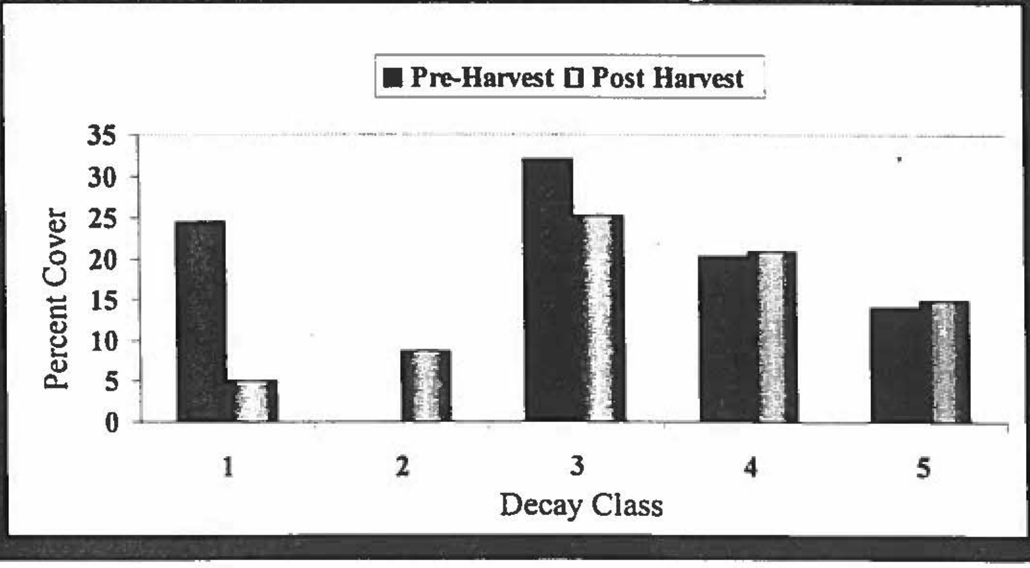
①

Environmental Characteristics of Riparian Buffers and Upslope Forests in Relation to Functions, Processes, and Management

Samuel Chan
PNW Research Station
USDA Forest Service
Corvallis, OR

②

Percent Cover of Coarse Woody Debris Greater Than (30 cm) by Decay Class at the Keel Mtn. Site in the Western Cascades of Oregon



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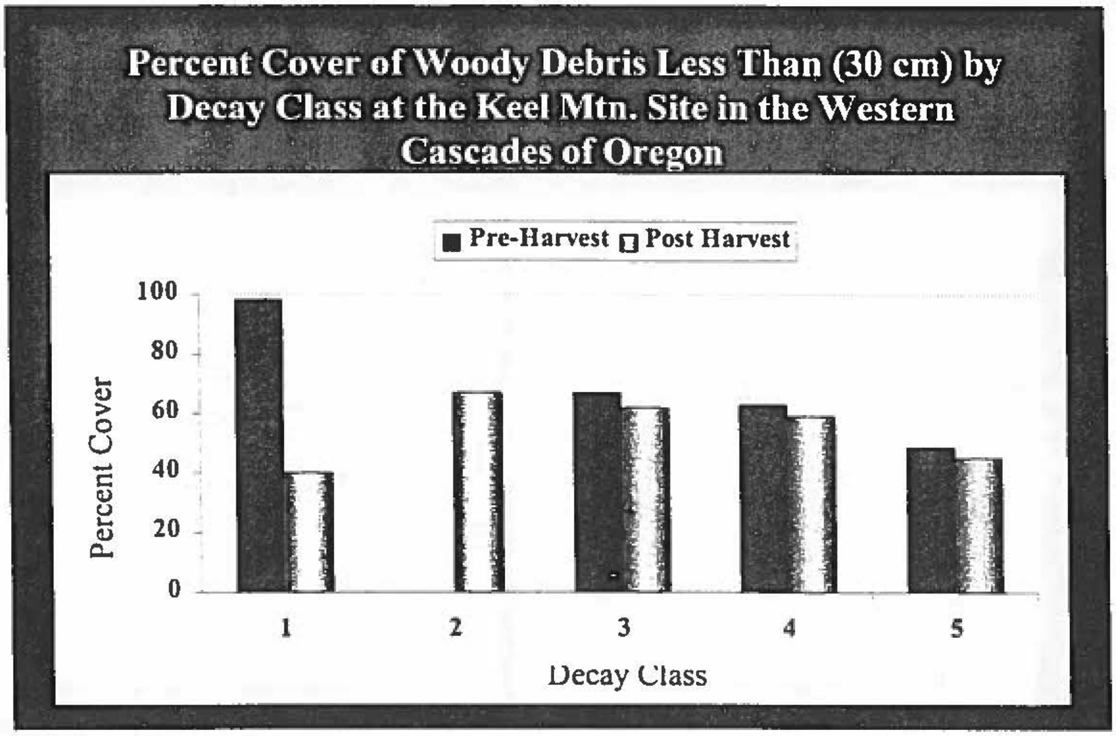

Percent Cover of Woody Debris Less Than (30 cm) by Decay Class at the Keel Mtn. Site in the Western Cascades of Oregon

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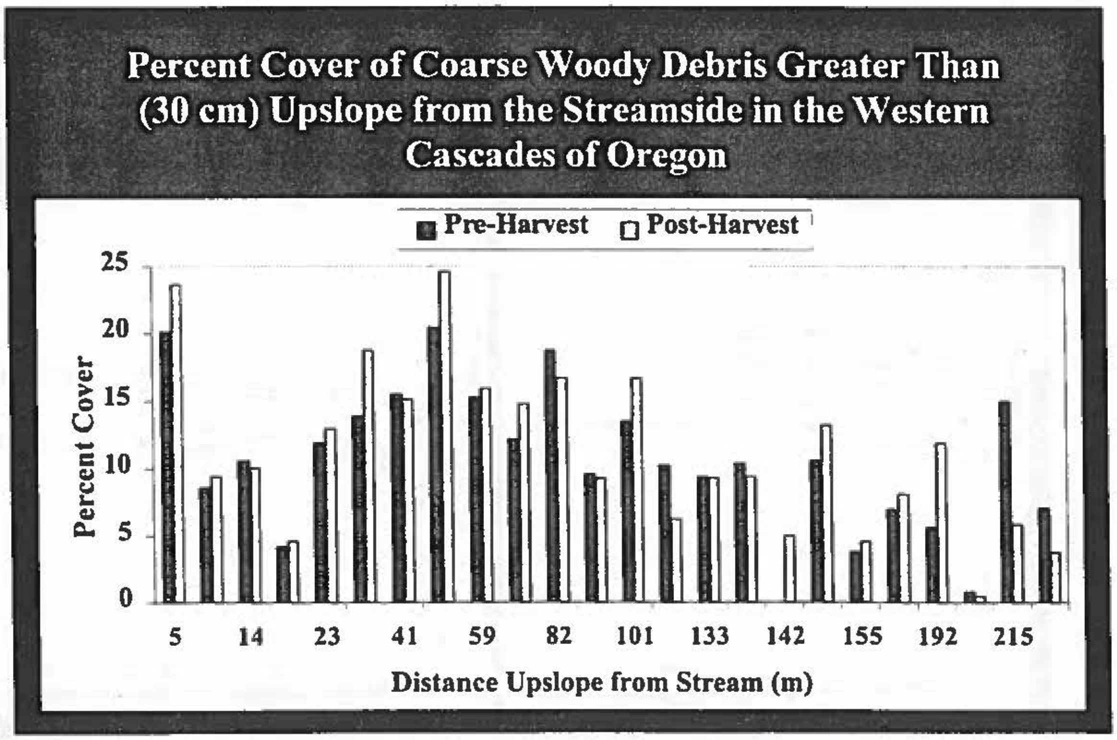
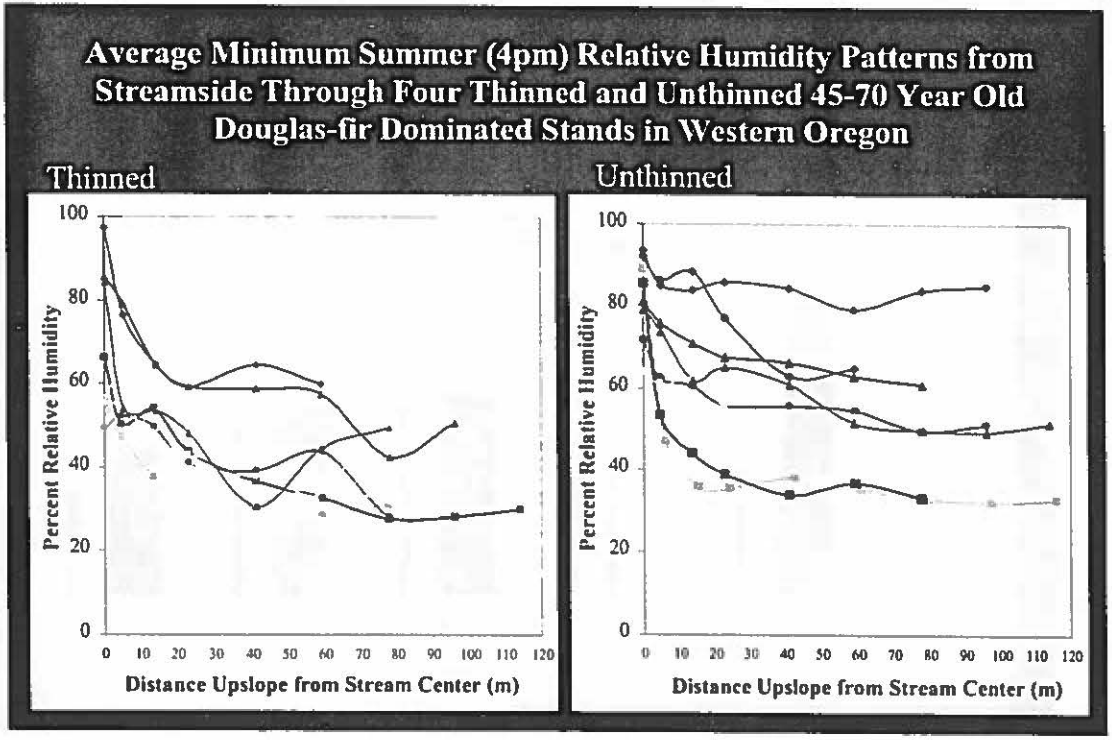


Percent Cover of Coarse Woody Debris Greater Than (30 cm) Upslope from the Streamside in the Western Cascades of Oregon

⑤

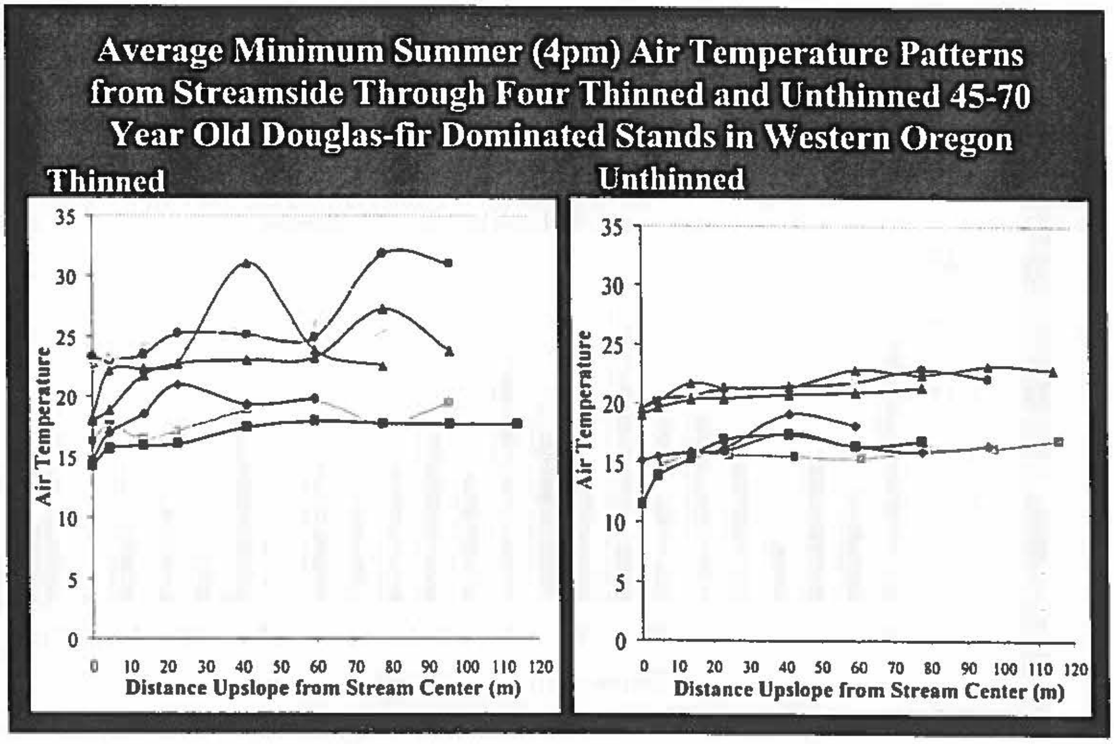


Average Minimum Summer (4pm) Relative Humidity Patterns from Streamside Through Four Thinned and Unthinned 45-70 Year Old Douglas-fir Dominated Stands in Western Oregon

Thinned

Unthinned

⑥

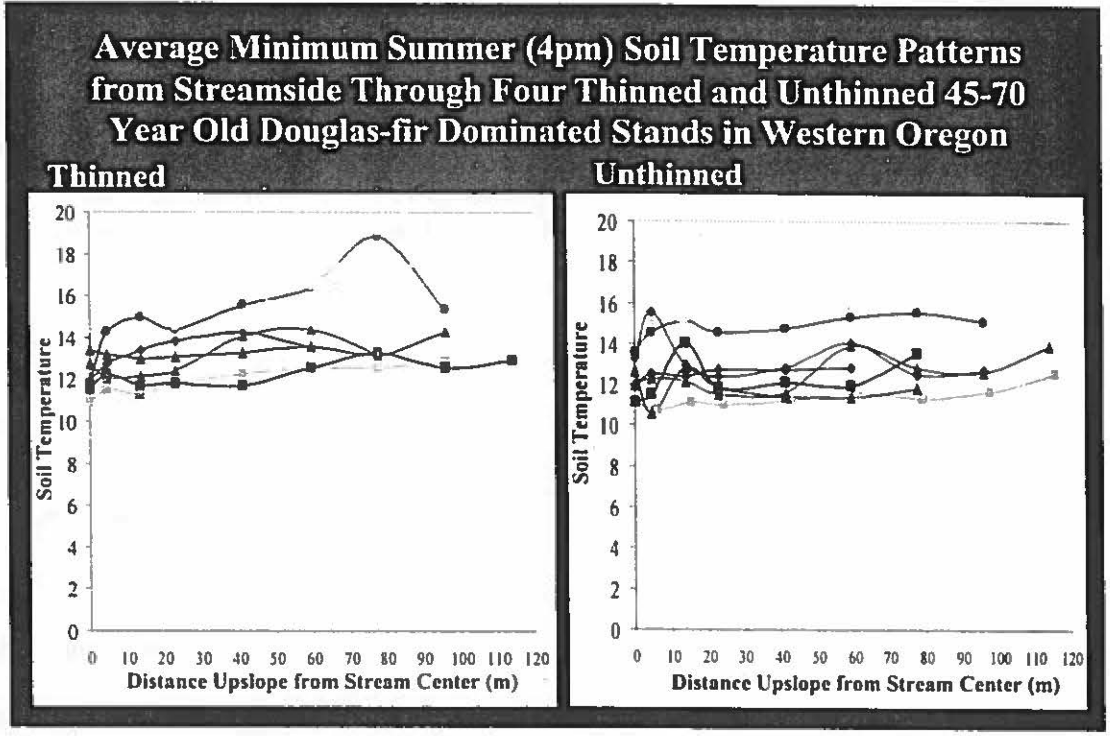


Average Minimum Summer (4pm) Air Temperature Patterns from Streamside Through Four Thinned and Unthinned 45-70 Year Old Douglas-fir Dominated Stands in Western Oregon

Thinned

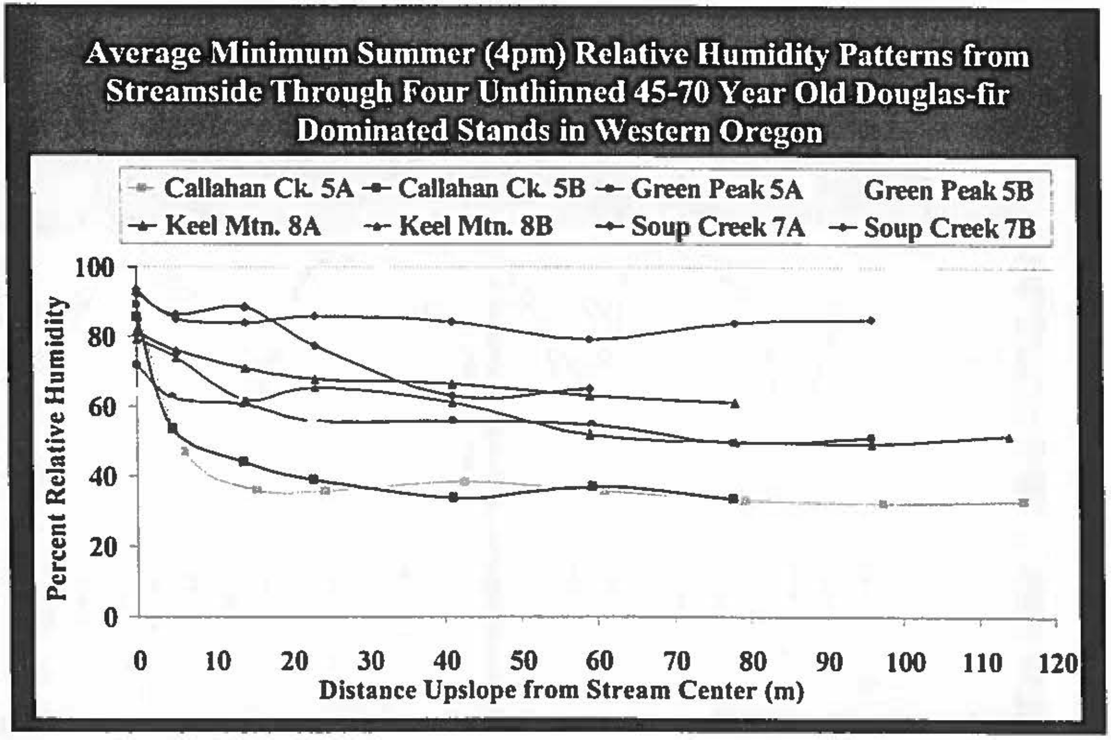
Unthinned

⑦



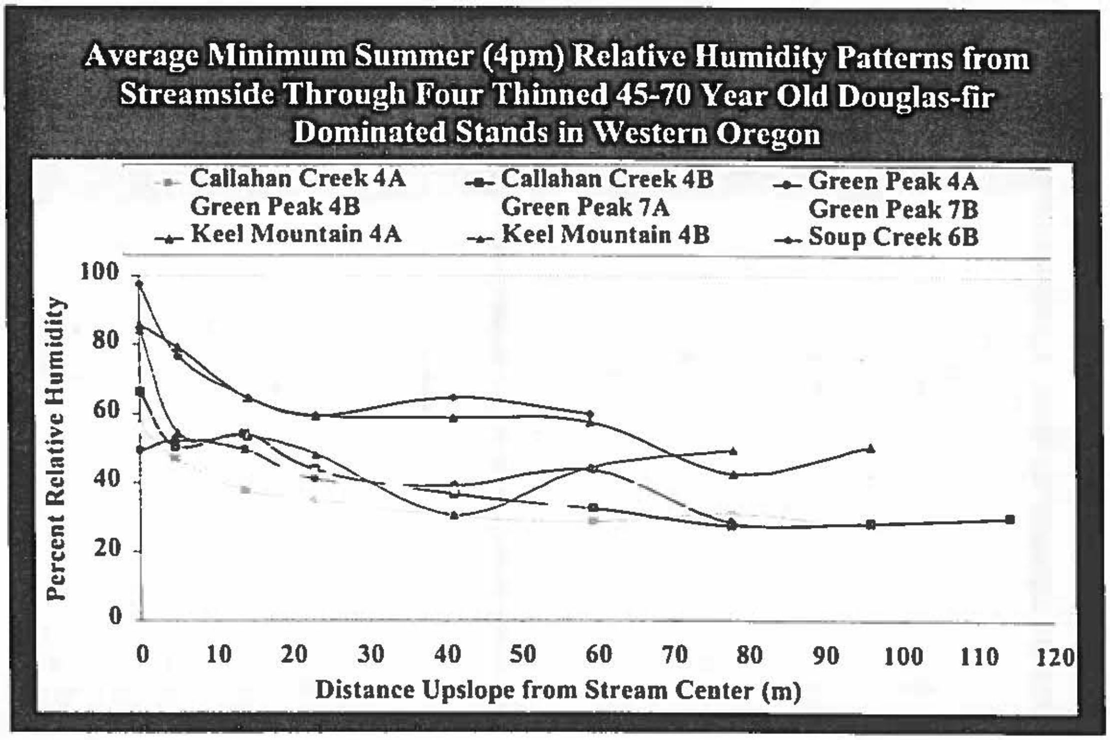
Average Minimum Summer (4pm) Soil Temperature Patterns from Streamside Through Four Thinned and Unthinned 45-70 Year Old Douglas-fir Dominated Stands in Western Oregon

⑧



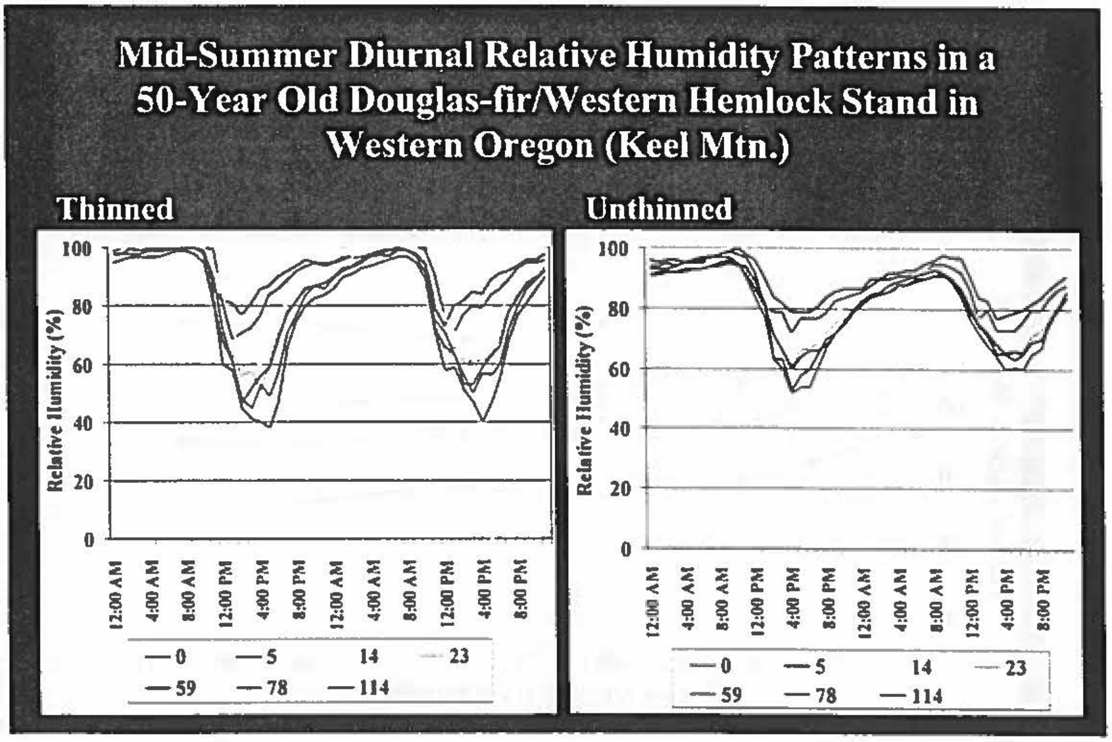
Average Minimum Summer (4pm) Relative Humidity Patterns from Streamside Through Four Unthinned 45-70 Year Old Douglas-fir Dominated Stands in Western Oregon

(9)



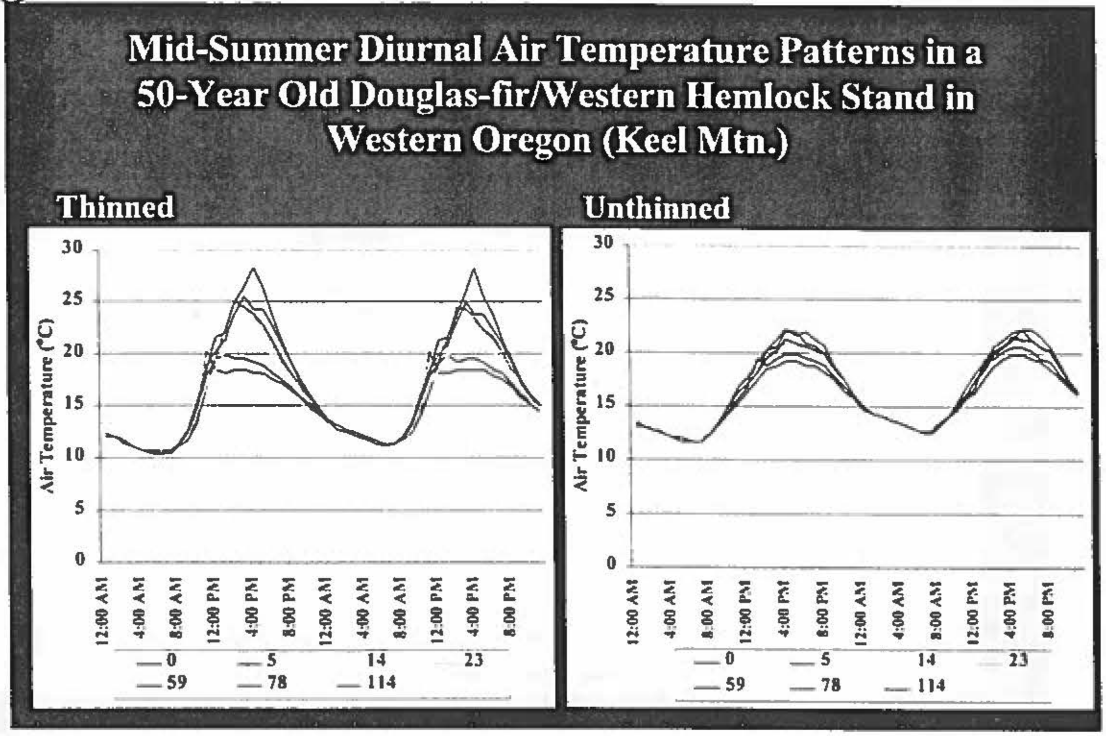
Average Minimum Summer (4pm) Relative Humidity Patterns from Streamside Through Four Thinned 45-70 Year Old Douglas-fir Dominated Stands in Western Oregon

(10)



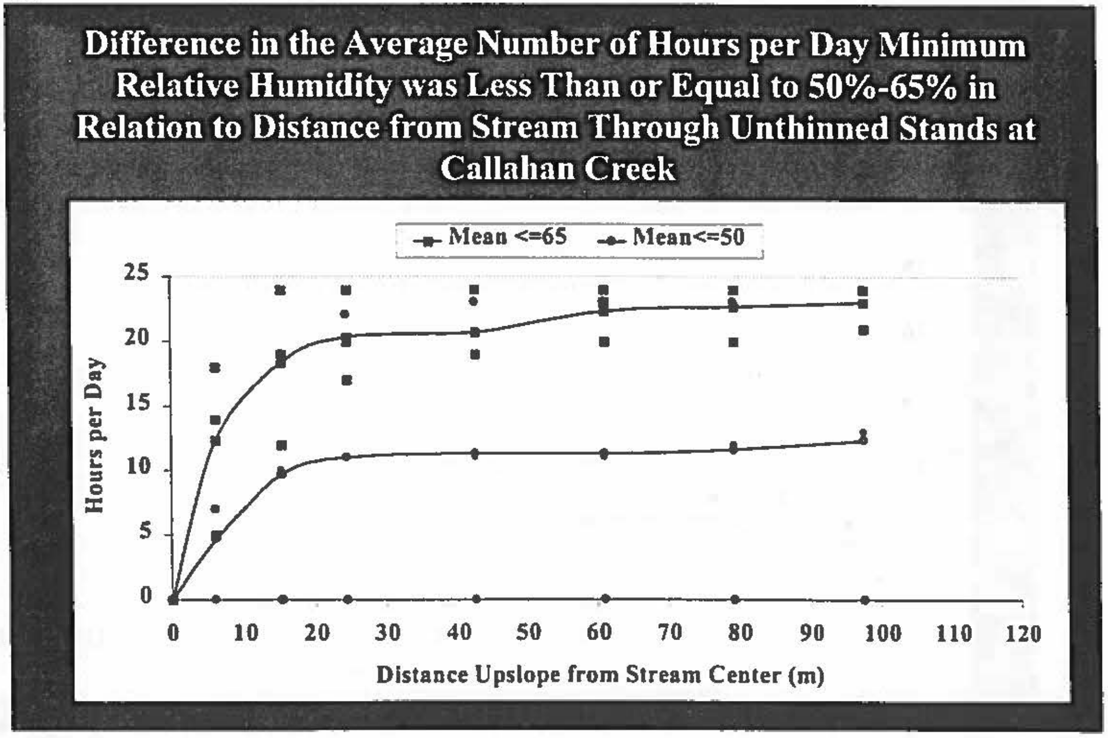
Mid-Summer Diurnal Relative Humidity Patterns in a 50-Year Old Douglas-fir/Western Hemlock Stand in Western Oregon (Keel Mtn.)

⑪



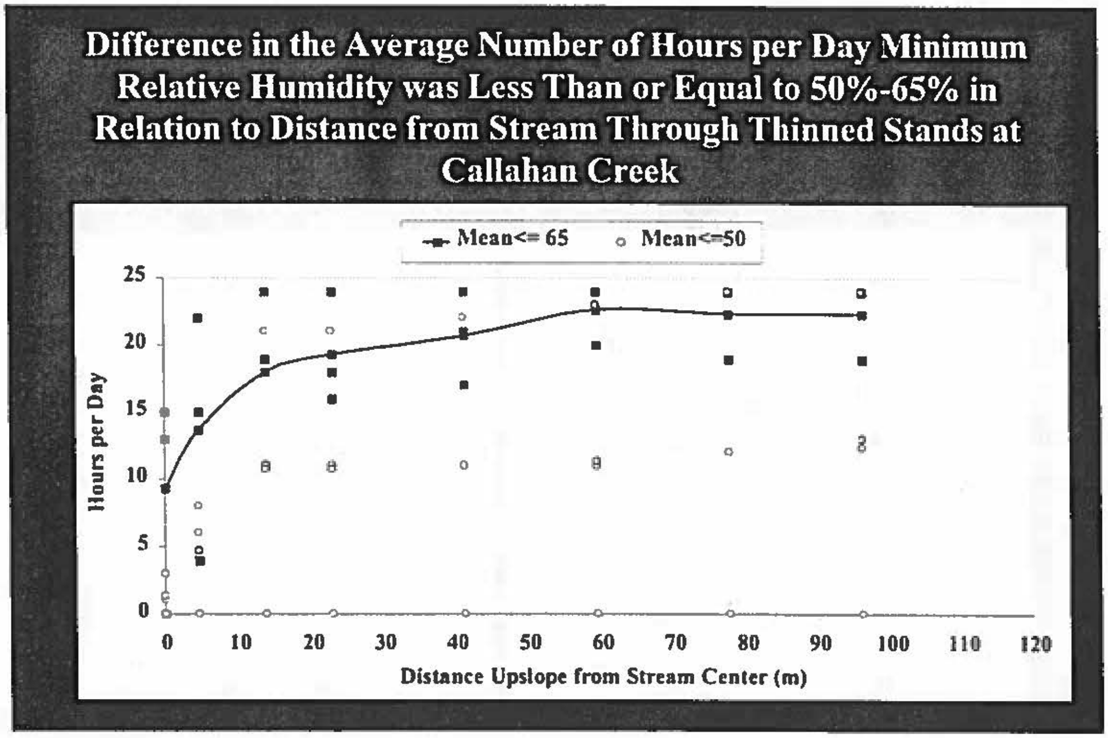
Mid-Summer Diurnal Air Temperature Patterns in a 50-Year Old Douglas-fir/Western Hemlock Stand in Western Oregon (Keel Mtn.)

⑫



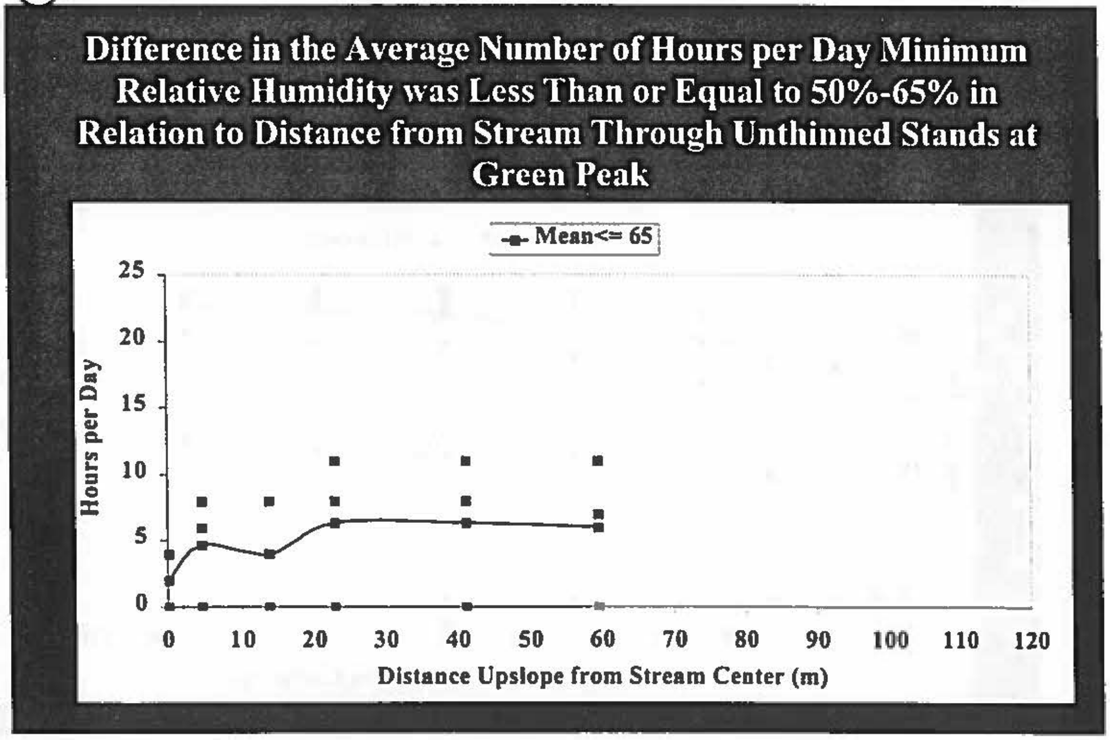
Difference in the Average Number of Hours per Day Minimum Relative Humidity was Less Than or Equal to 50%-65% in Relation to Distance from Stream Through Unthinned Stands at Callahan Creek

⑬



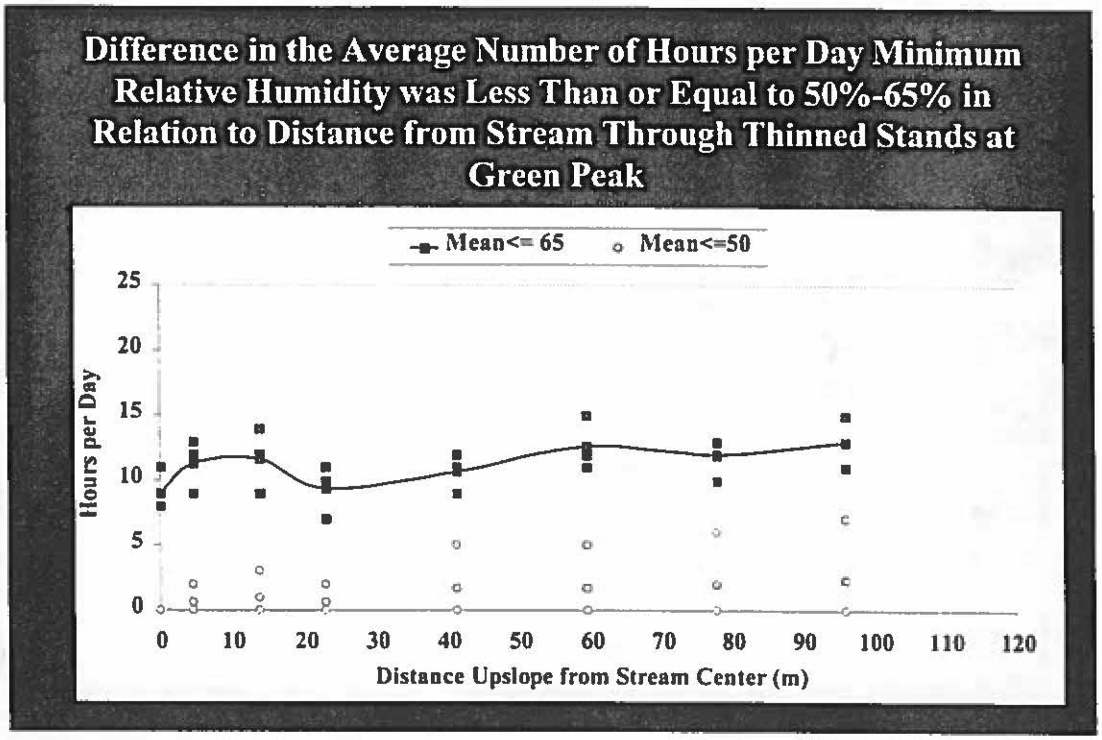
Difference in the Average Number of Hours per Day Minimum Relative Humidity was Less Than or Equal to 50%-65% in Relation to Distance from Stream Through Thinned Stands at Callahan Creek

⑭



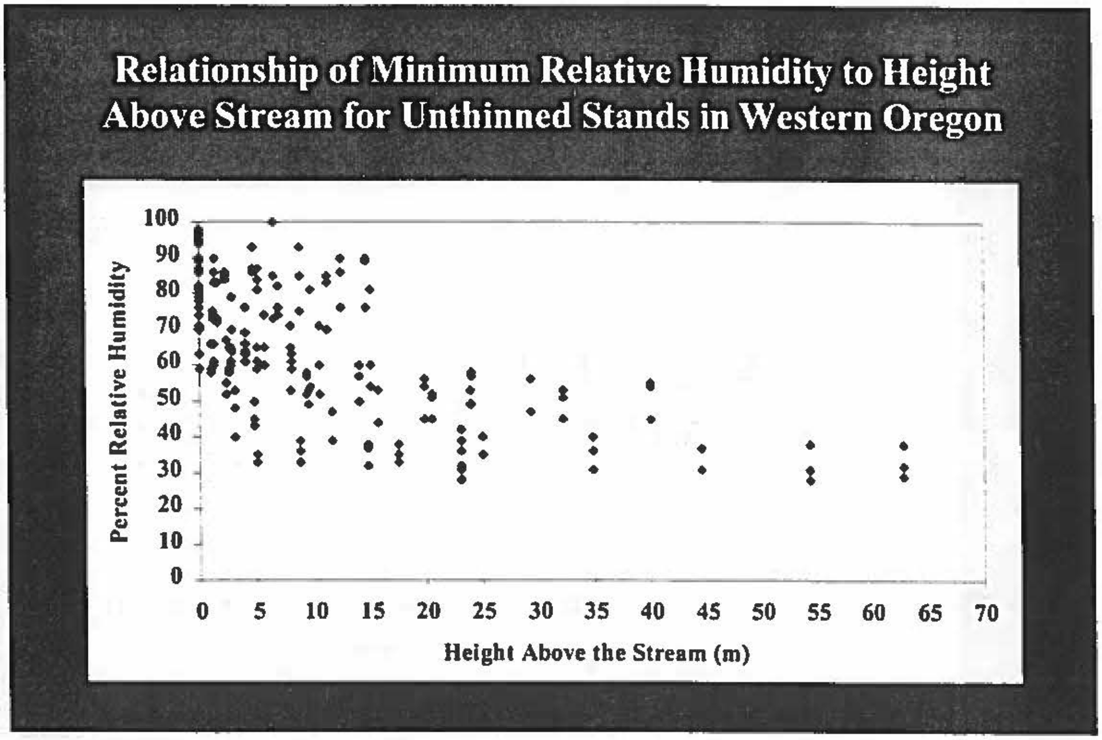
Difference in the Average Number of Hours per Day Minimum Relative Humidity was Less Than or Equal to 50%-65% in Relation to Distance from Stream Through Unthinned Stands at Green Peak

⑮



Difference in the Average Number of Hours per Day Minimum Relative Humidity was Less Than or Equal to 50%-65% in Relation to Distance from Stream Through Thinned Stands at Green Peak

⑯



Relationship of Minimum Relative Humidity to Height Above Stream for Unthinned Stands in Western Oregon

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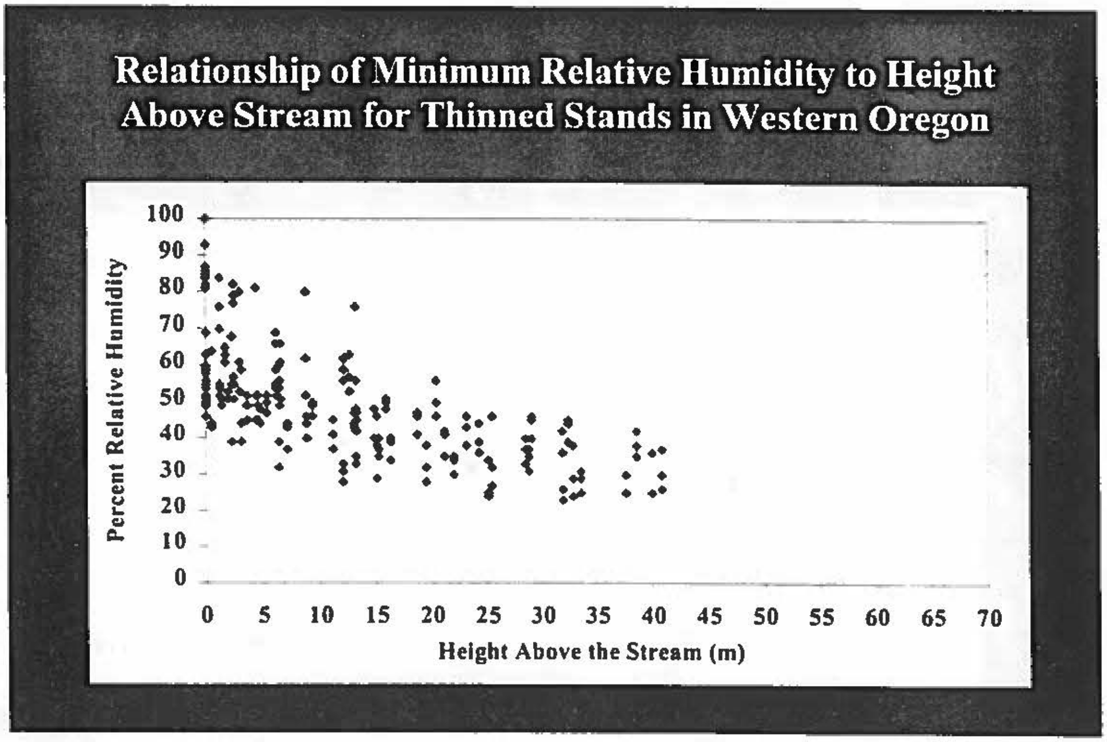
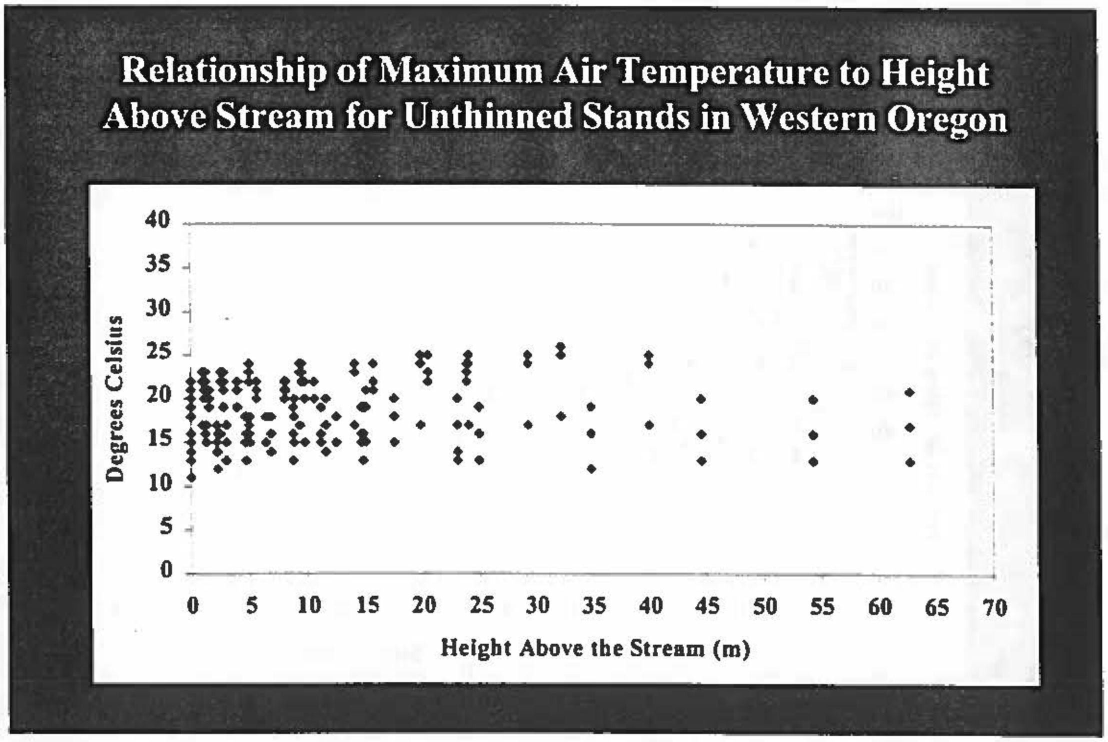


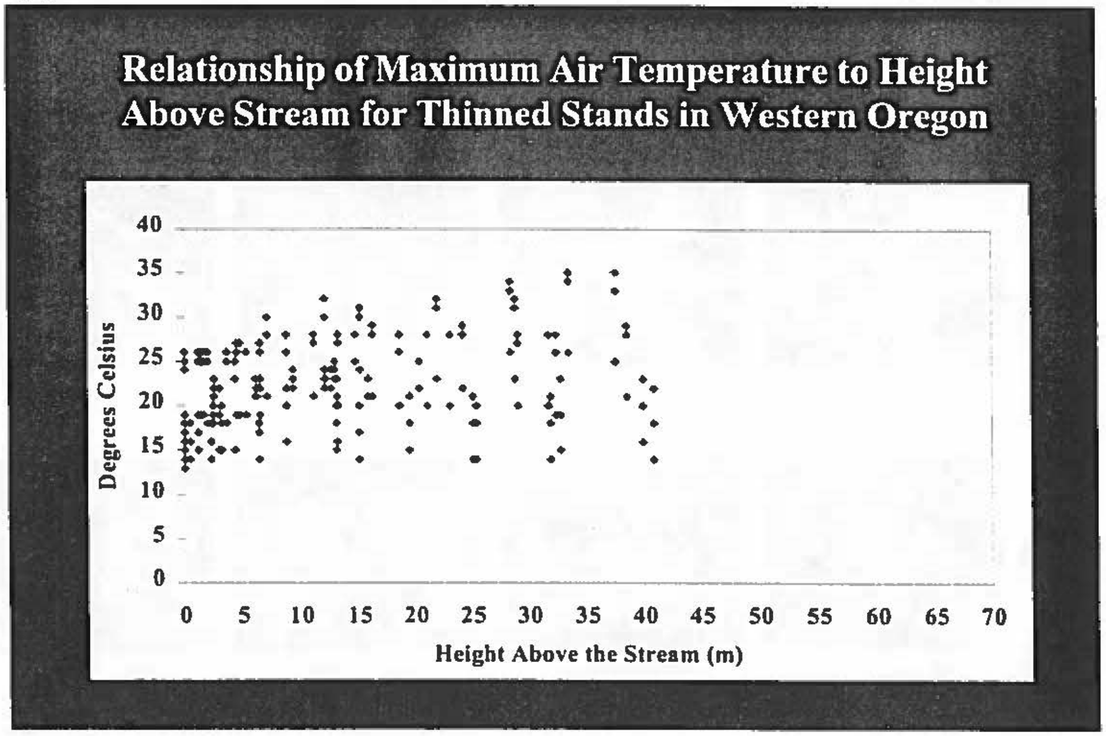
Relationship of Minimum Relative Humidity to Height Above Stream for Thinned Stands in Western Oregon

⑱



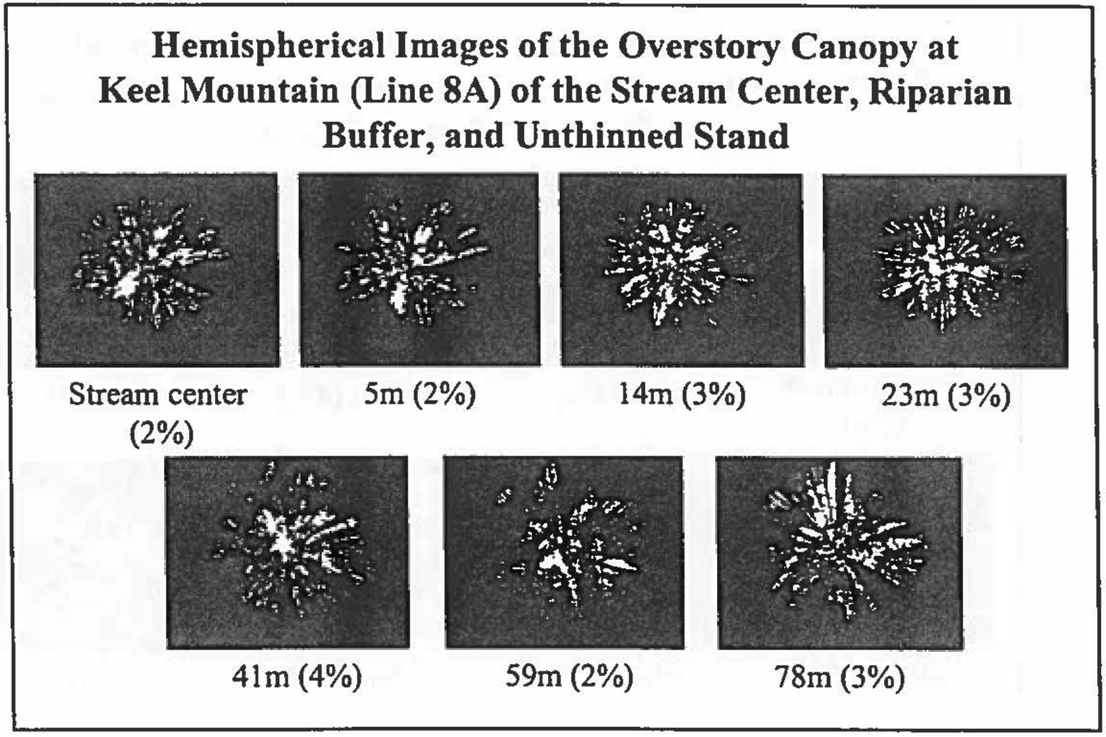
Relationship of Maximum Air Temperature to Height Above Stream for Unthinned Stands in Western Oregon

⑲



Relationship of Maximum Air Temperature to Height Above Stream for Thinned Stands in Western Oregon

⑳



Hemispherical Images of the Overstory Canopy at Keel Mountain (Line 8A) of the Stream Center, Riparian Buffer, and Unthinned Stand

Stream center (2%)

5m (2%)

14m (3%)

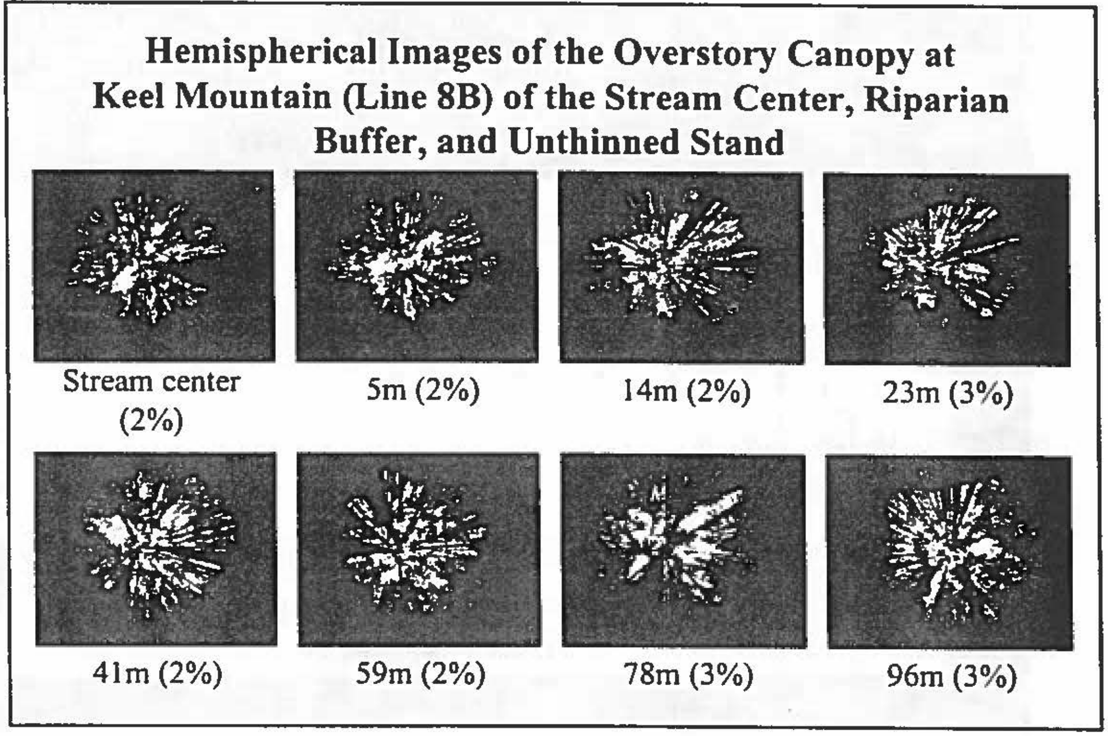
23m (3%)

41m (4%)

59m (2%)

78m (3%)

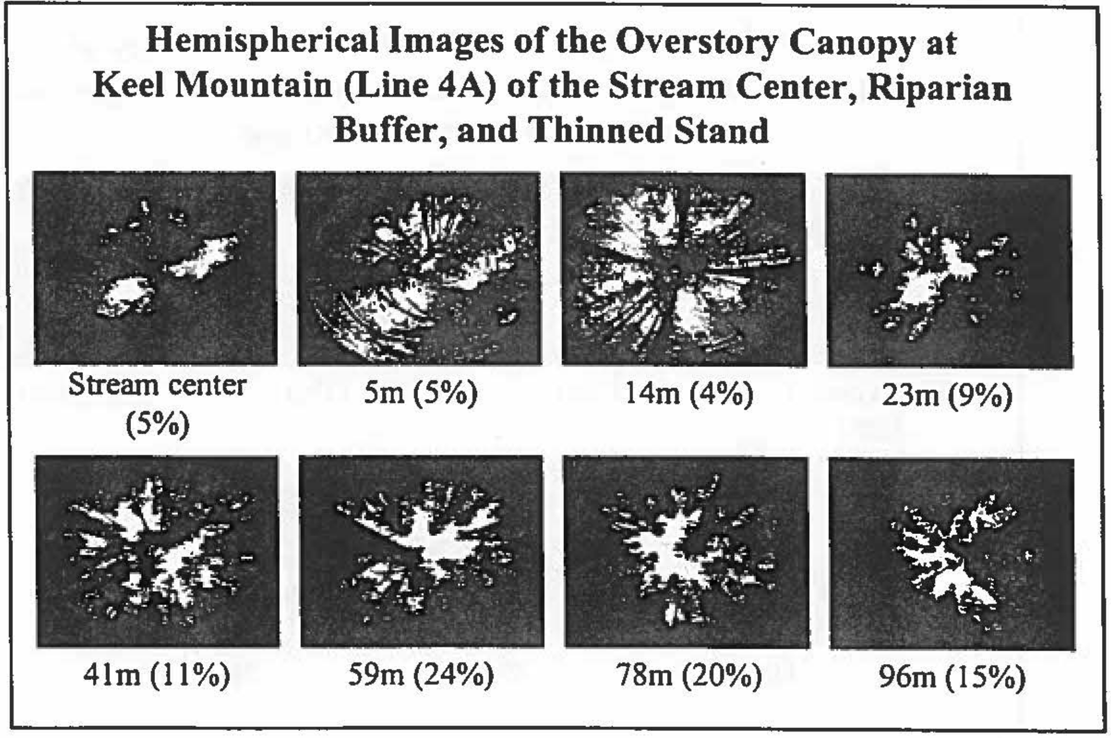
㉑



Hemispherical Images of the Overstory Canopy at Keel Mountain (Line 8B) of the Stream Center, Riparian Buffer, and Unthinned Stand

Stream center (2%)
5m (2%)
14m (2%)
23m (3%)
41m (2%)
59m (2%)
78m (3%)
96m (3%)

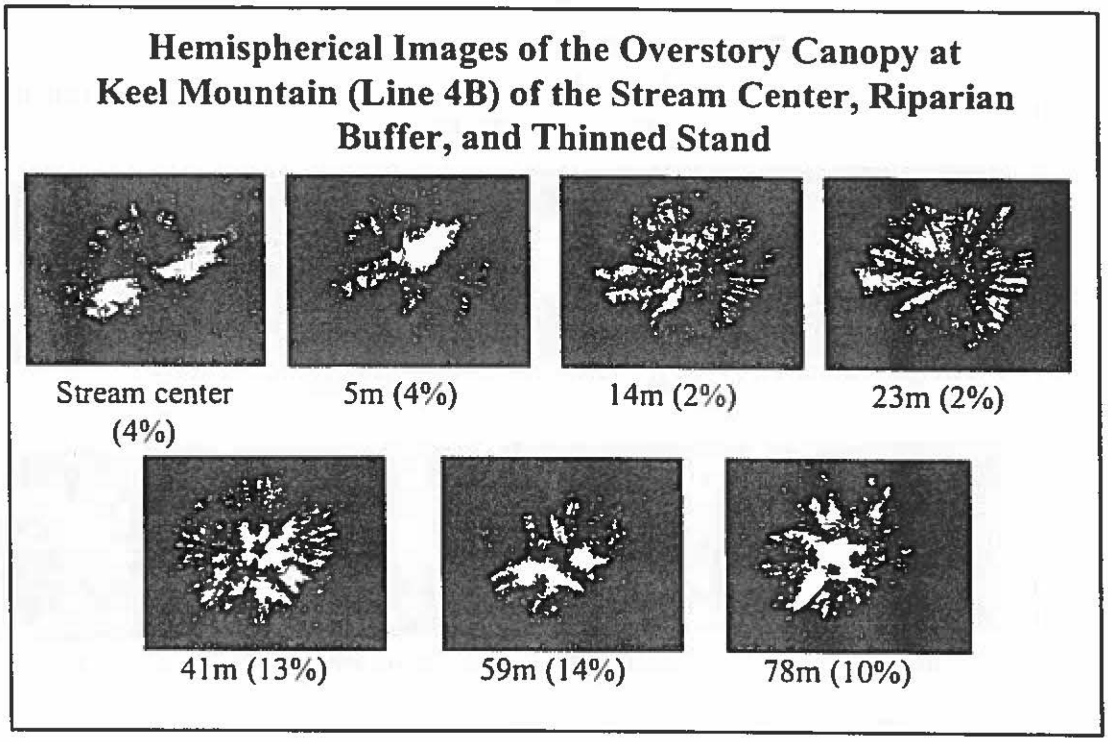
㉒



Hemispherical Images of the Overstory Canopy at Keel Mountain (Line 4A) of the Stream Center, Riparian Buffer, and Thinned Stand

Stream center (5%)
5m (5%)
14m (4%)
23m (9%)
41m (11%)
59m (24%)
78m (20%)
96m (15%)

㉓



Hemispherical Images of the Overstory Canopy at Keel Mountain (Line 4B) of the Stream Center, Riparian Buffer, and Thinned Stand

Stream center (4%)

5m (4%)

14m (2%)

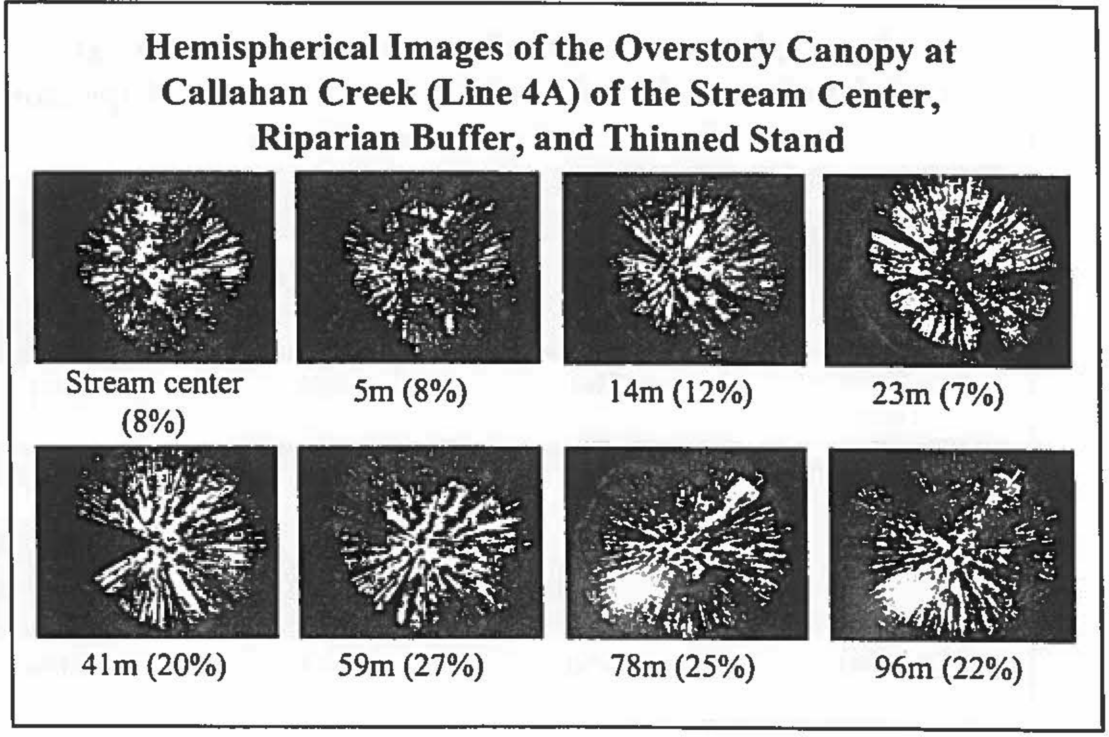
23m (2%)

41m (13%)

59m (14%)

78m (10%)

㉔



Hemispherical Images of the Overstory Canopy at Callahan Creek (Line 4A) of the Stream Center, Riparian Buffer, and Thinned Stand

Stream center (8%)

5m (8%)

14m (12%)

23m (7%)

41m (20%)

59m (27%)

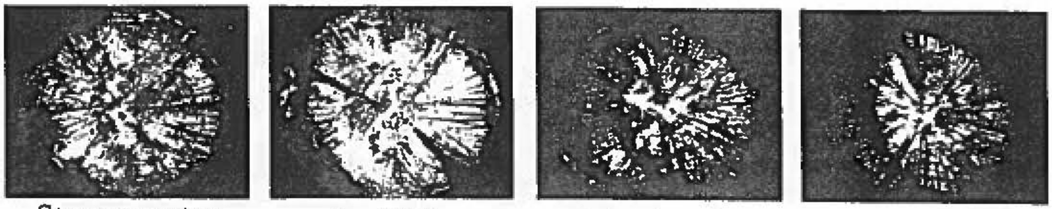
78m (25%)

96m (22%)

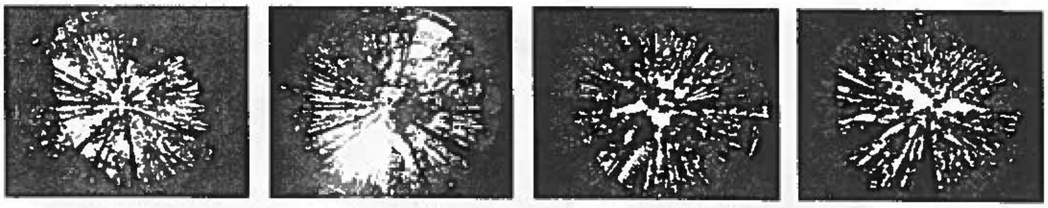
12

㉕

Hemispherical Images of the Overstory Canopy at Callahan Creek (Line 4B) of the Stream Center, Riparian Buffer, and Thinned Stand



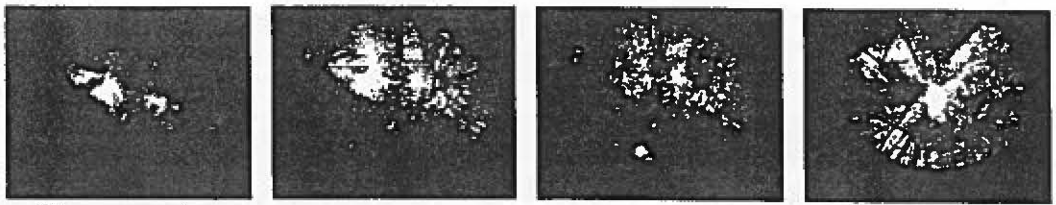
Stream center (6%) | 5m (6%) | 14m (10%) | 23m (11%)



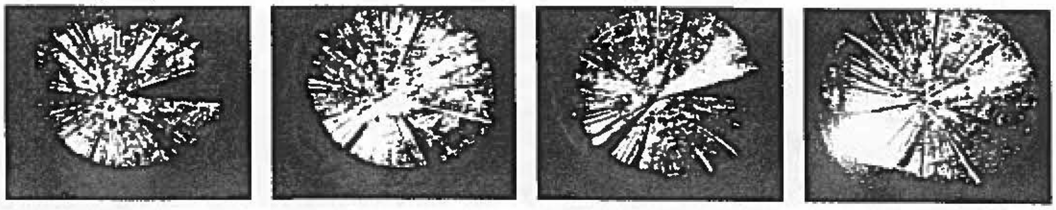
41m (13%) | 59m (9%) | 78m (15%) | 96m (23%)

㉖

Hemispherical Images of the Overstory Canopy at Callahan Creek (Line 5A) of the Stream Center, Riparian Buffer, and Unthinned Stand

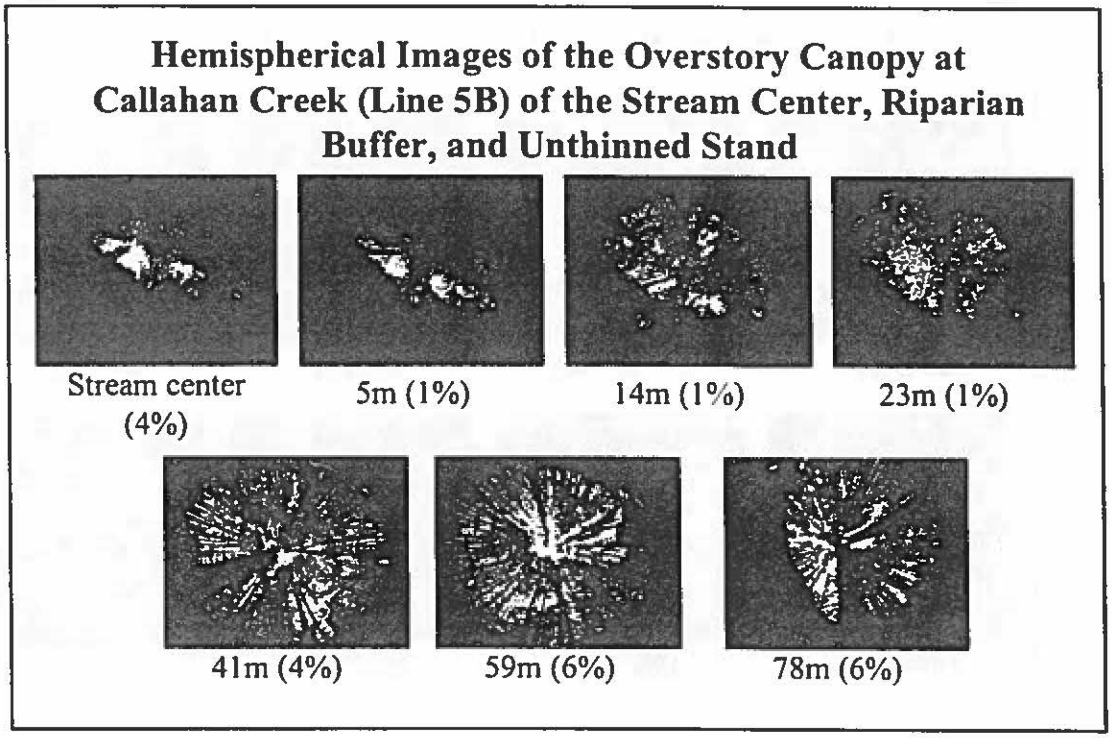


Stream center (4%) | 6m (7%) | 15m (3%) | 24m (3%)



43m (4%) | 61m (4%) | 79m (7%) | 97m (10%)

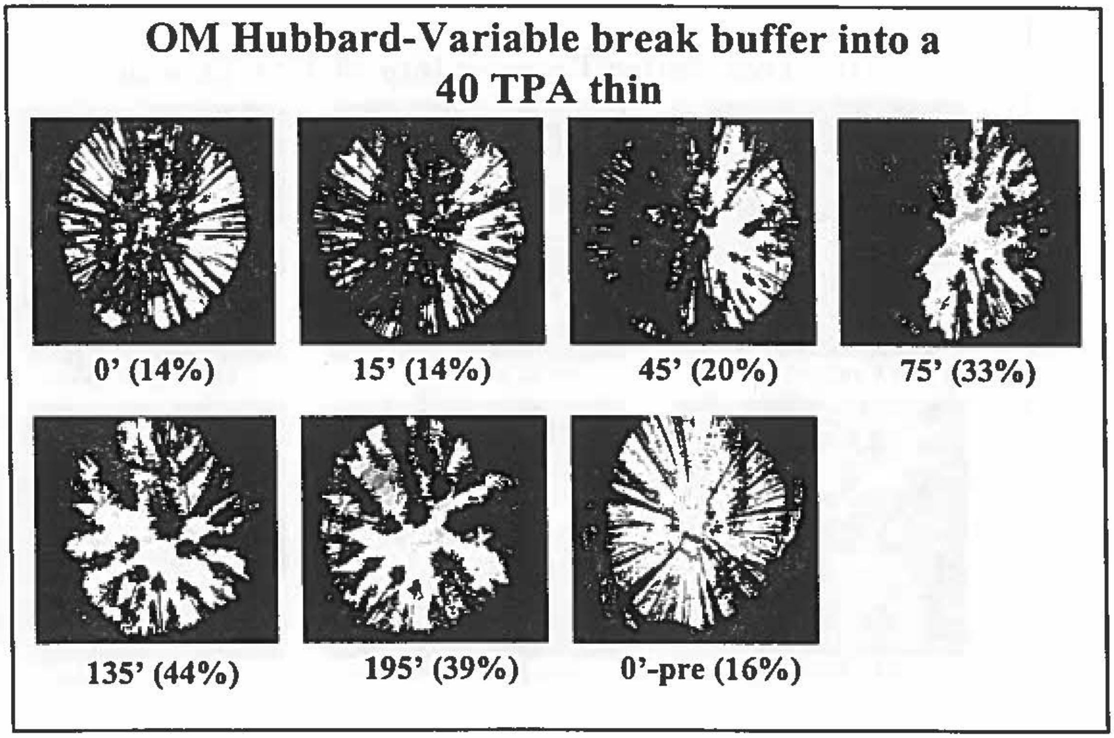
㉗



Hemispherical Images of the Overstory Canopy at Callahan Creek (Line 5B) of the Stream Center, Riparian Buffer, and Unthinned Stand

Stream center (4%)
5m (1%)
14m (1%)
23m (1%)
41m (4%)
59m (6%)
78m (6%)

㉘

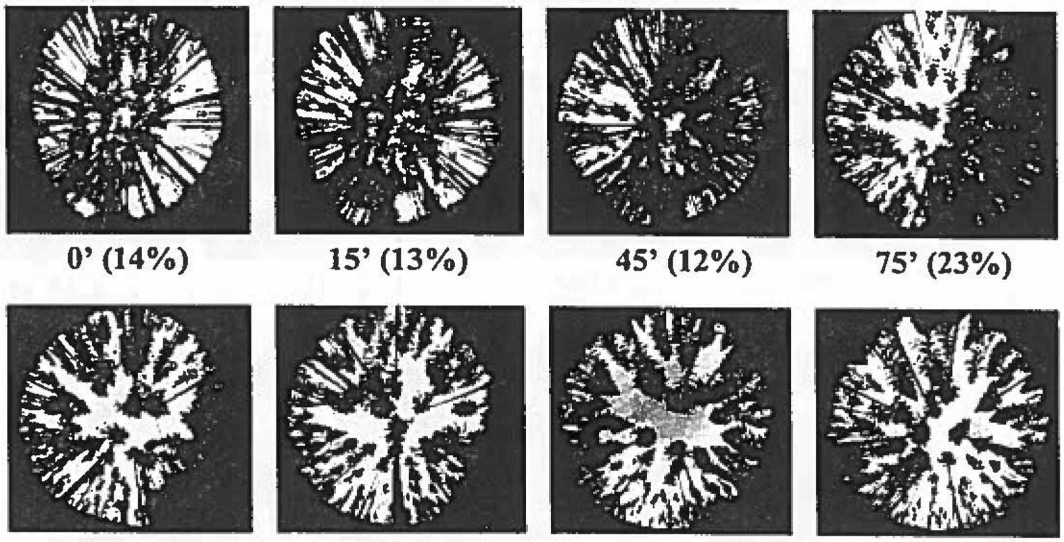


OM Hubbard-Variable break buffer into a 40 TPA thin

0' (14%)
15' (14%)
45' (20%)
75' (33%)
135' (44%)
195' (39%)
0'-pre (16%)

㉙

OM Hubbard- Variable break buffer into an 80 TPA thin

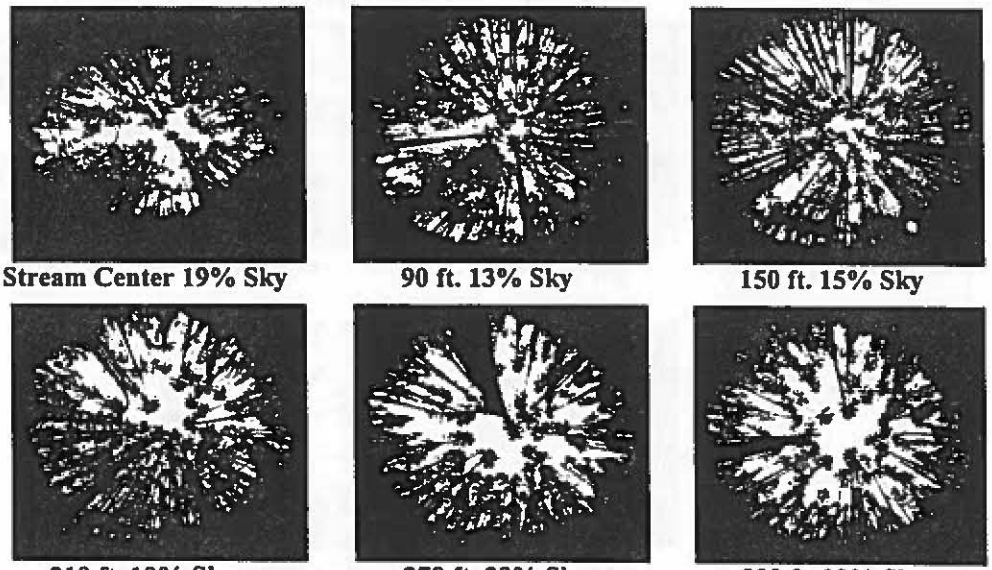


0' (14%) 15' (13%) 45' (12%) 75' (23%)

135' (34%) 195' (36%) 255' (43%) 315' (35%)

㉚

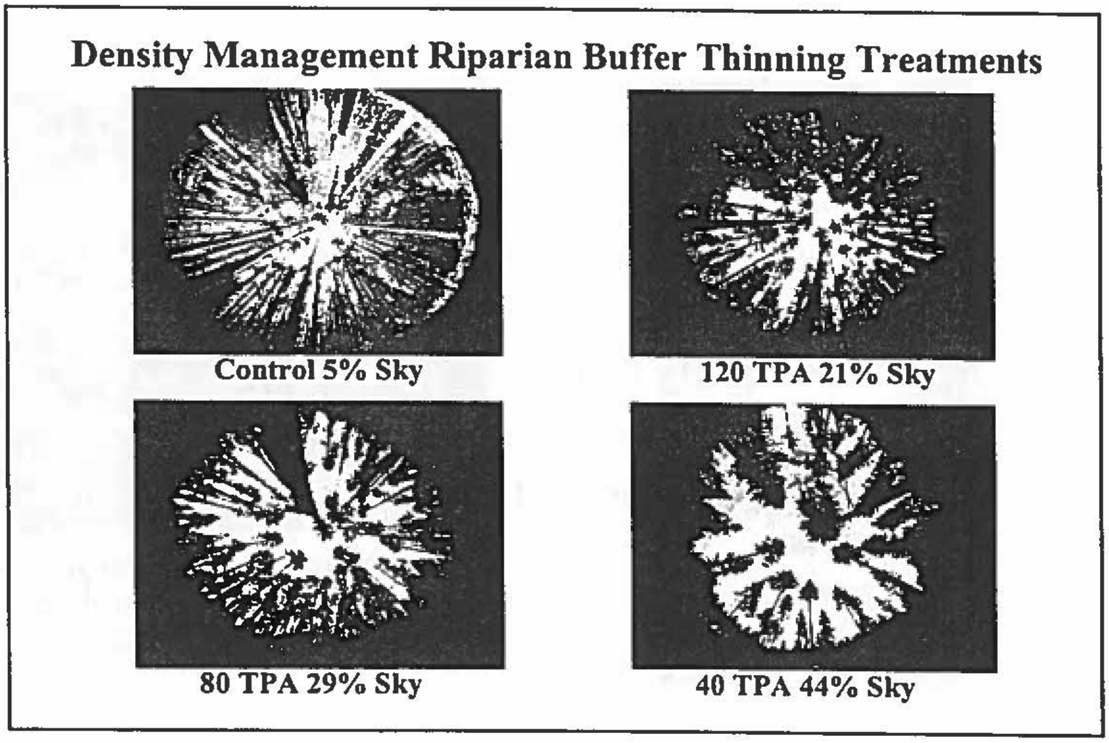
One Tree Buffer Transect into 80 TPA Thinning



Stream Center 19% Sky 90 ft. 13% Sky 150 ft. 15% Sky

210 ft. 19% Sky 270 ft. 29% Sky 330 ft. 29% Sky

㉛



Density Management Riparian Buffer Thinning Treatments

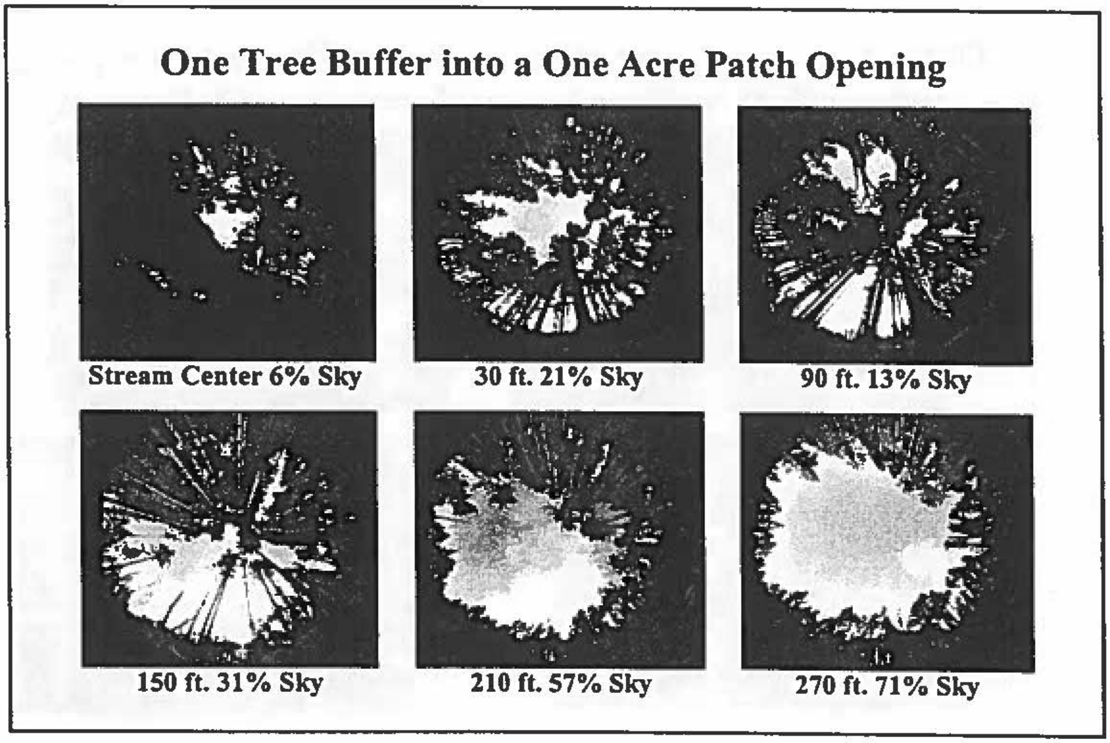
Control 5% Sky

120 TPA 21% Sky

80 TPA 29% Sky

40 TPA 44% Sky

㉜



One Tree Buffer into a One Acre Patch Opening

Stream Center 6% Sky

30 ft. 21% Sky

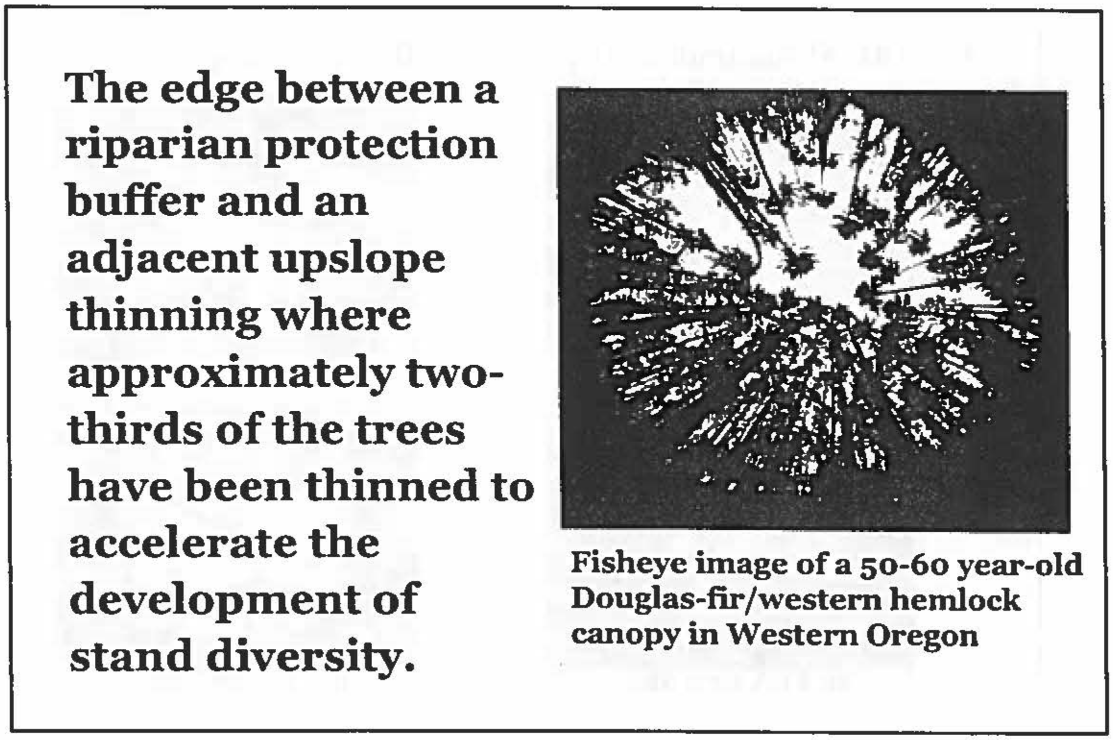
90 ft. 13% Sky

150 ft. 31% Sky

210 ft. 57% Sky

270 ft. 71% Sky

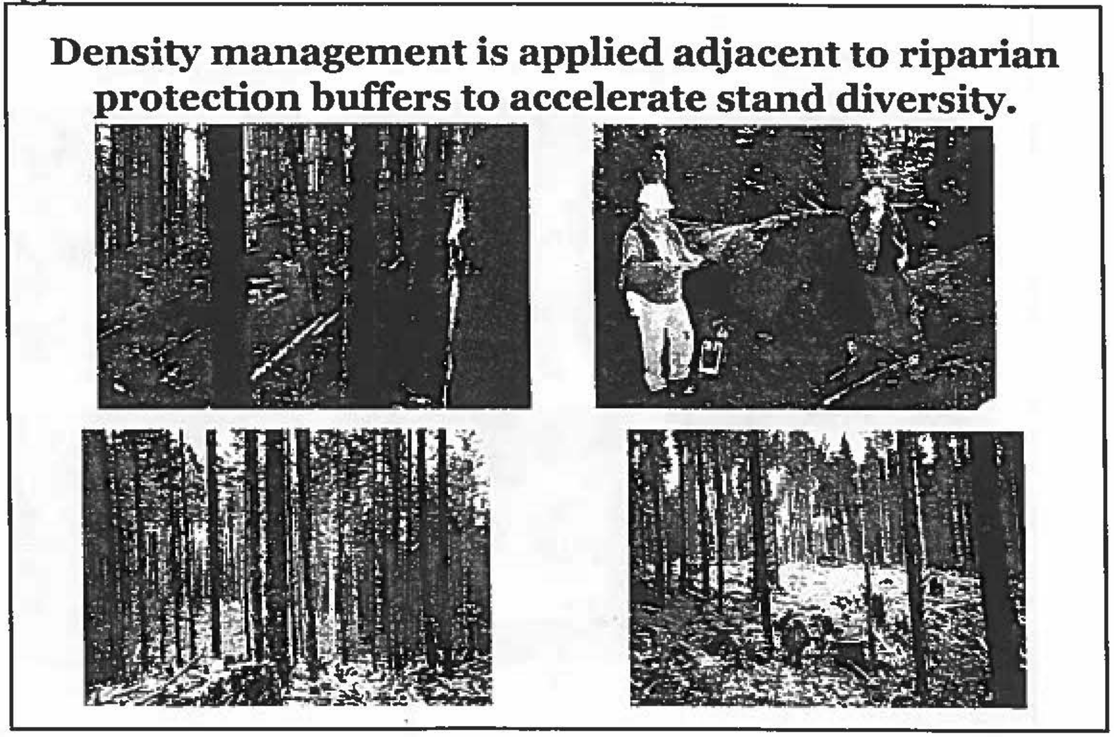
①



The edge between a riparian protection buffer and an adjacent upslope thinning where approximately two-thirds of the trees have been thinned to accelerate the development of stand diversity.

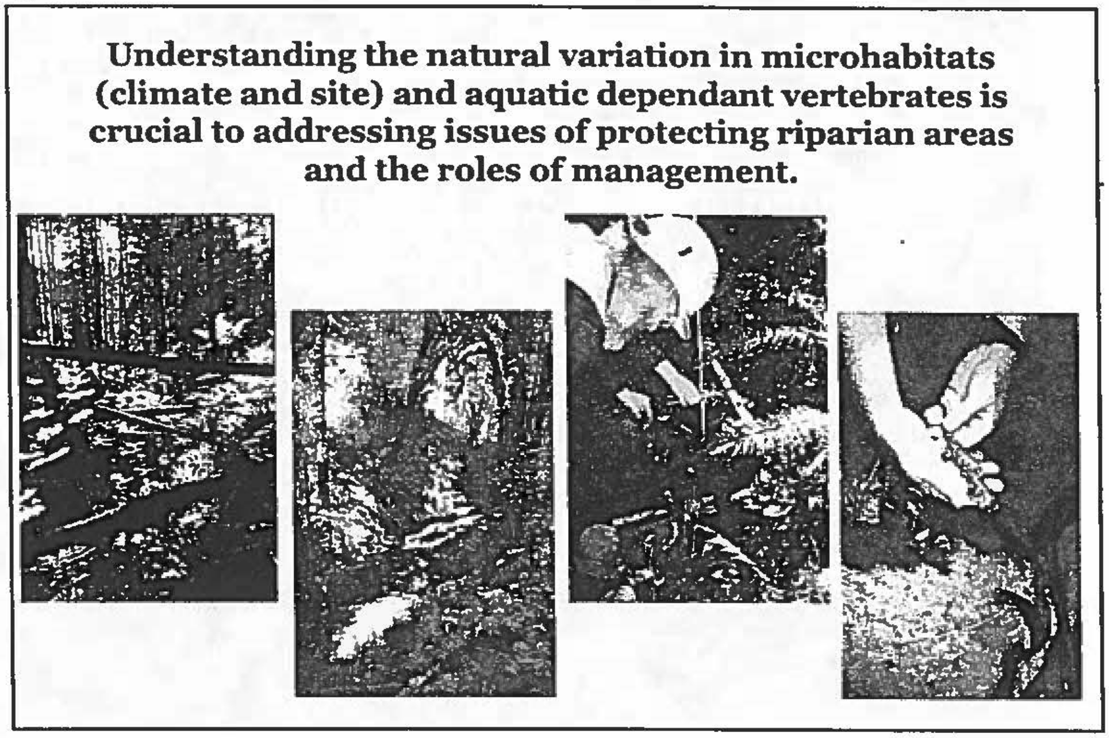
Fisheye image of a 50-60 year-old Douglas-fir/western hemlock canopy in Western Oregon

②



Density management is applied adjacent to riparian protection buffers to accelerate stand diversity.

③



Understanding the natural variation in microhabitats (climate and site) and aquatic dependant vertebrates is crucial to addressing issues of protecting riparian areas and the roles of management.

①

Riparian Microclimate of Managed Forests: Patterns in Mesic Western Oregon and Xeric Eastern Oregon and Washington

Samuel Chan[1] and Robert Danehy[2]

[1]USDA Forest Service, Corvallis OR
[2]Boise-Cascade, Boise ID

②

Riparian - riparian zones interfaces between terrestrial and aquatic ecosystems, with lateral riparian boundaries delineated by the area affected by water

Gregory et al 1991

③

Microclimate--strictly local combinations of atmospheric factors which, owing to uneven topography, plant cover etc., differ from the macroclimate as measured in locations where these modifying factors have negligible influence. Within each area embraced by one macroclimate there exists an intricate matrix of microclimates, at least some of which differ sufficiently to be ecologically important.

Daubenmire, 1947

④

Types of Riparian Moisture Dependent Flora and Fauna

- Lichens
- Bryophytes
- Mollusks
- Amphibians
- Vascular plants
- Birds, mammals, and bats

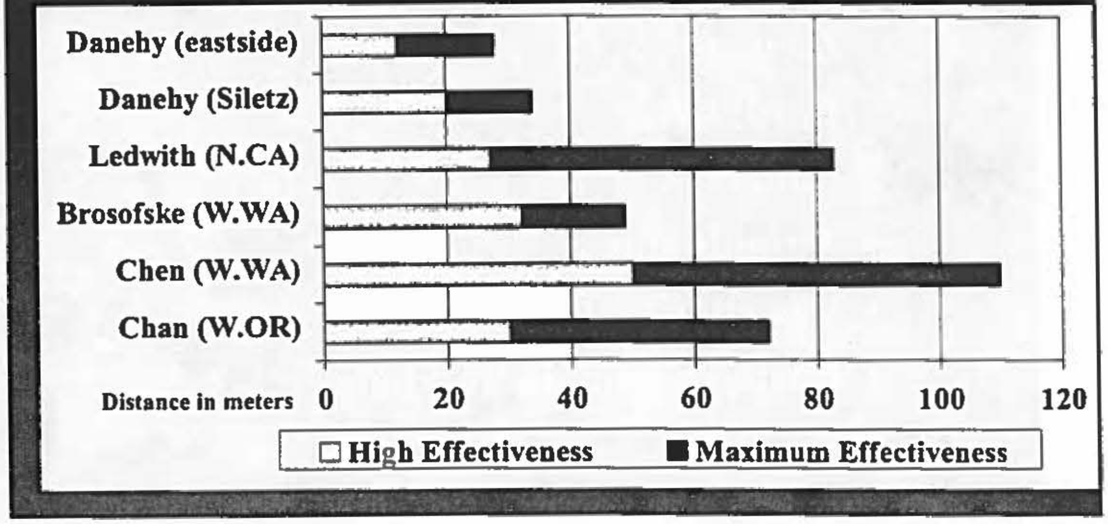
⑤

Factors influencing transpiration of trees in mesic and xeric landscapes

- Duration of Growing
  - Diurnal
  - Seasonal
- Tree Species
  - Determinate - i.e. p. pine, true firs, douglas fir
  - Indeterminate - i.e. hemlock, cedar, alder
- Distance from water
  - Soils - depth and water holding capacity
  - Distance from water

⑥

Comparison of Relative Humidity Gradients of Riparian Buffers in Different Studies Conducted in the Pacific Northwest



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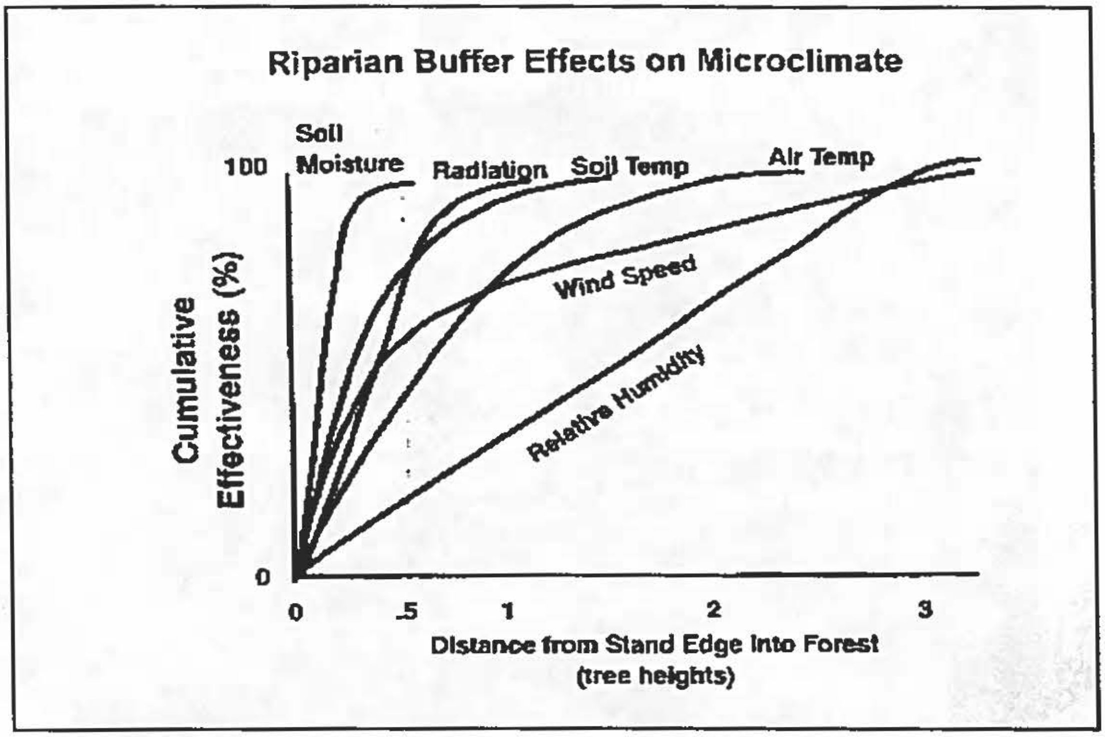
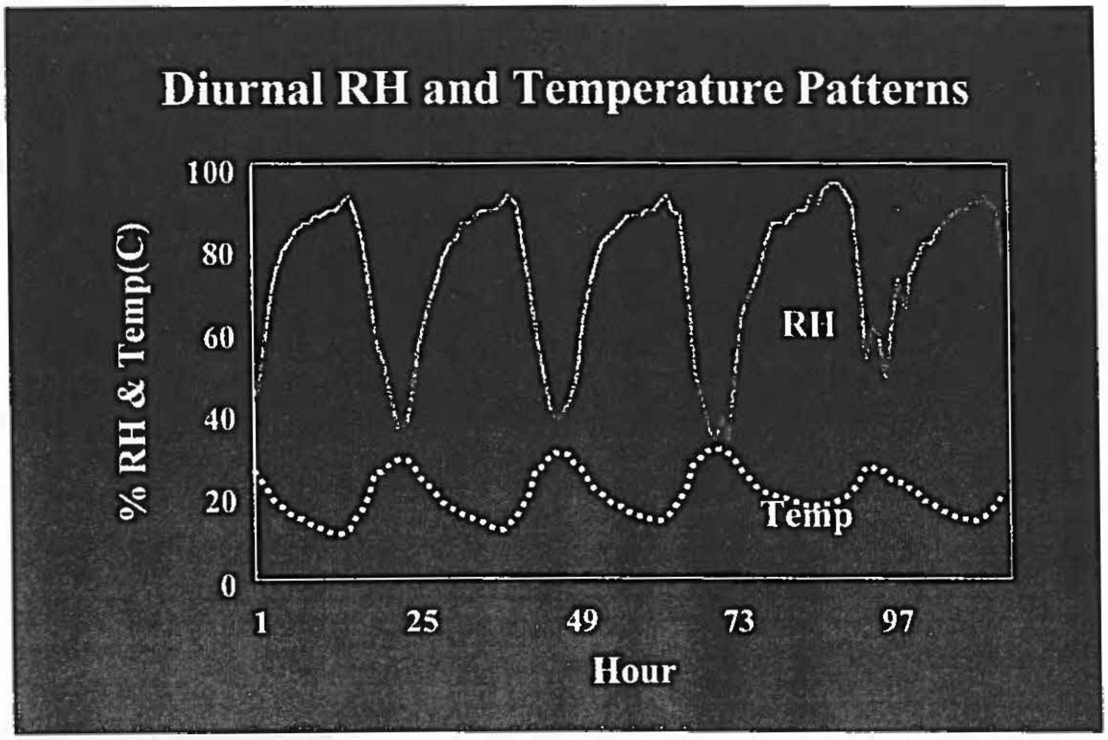


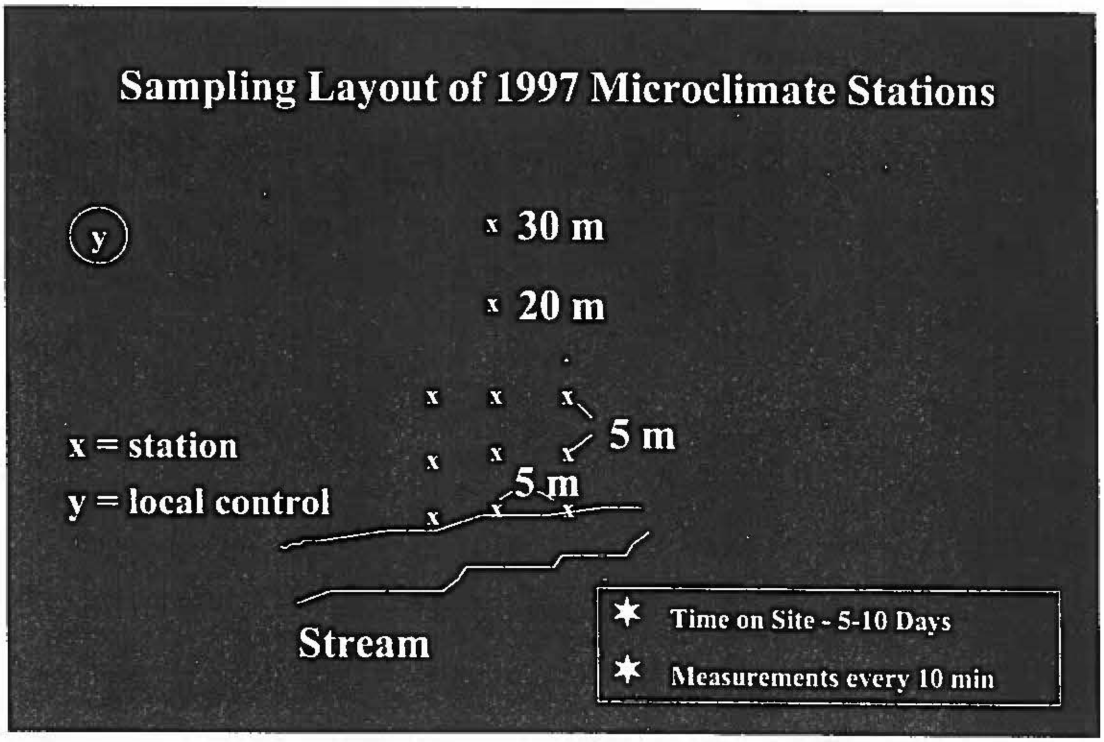
Riparian Buffer Effects on Microclimate

⑧



Diurnal RH and Temperature Patterns

⑨

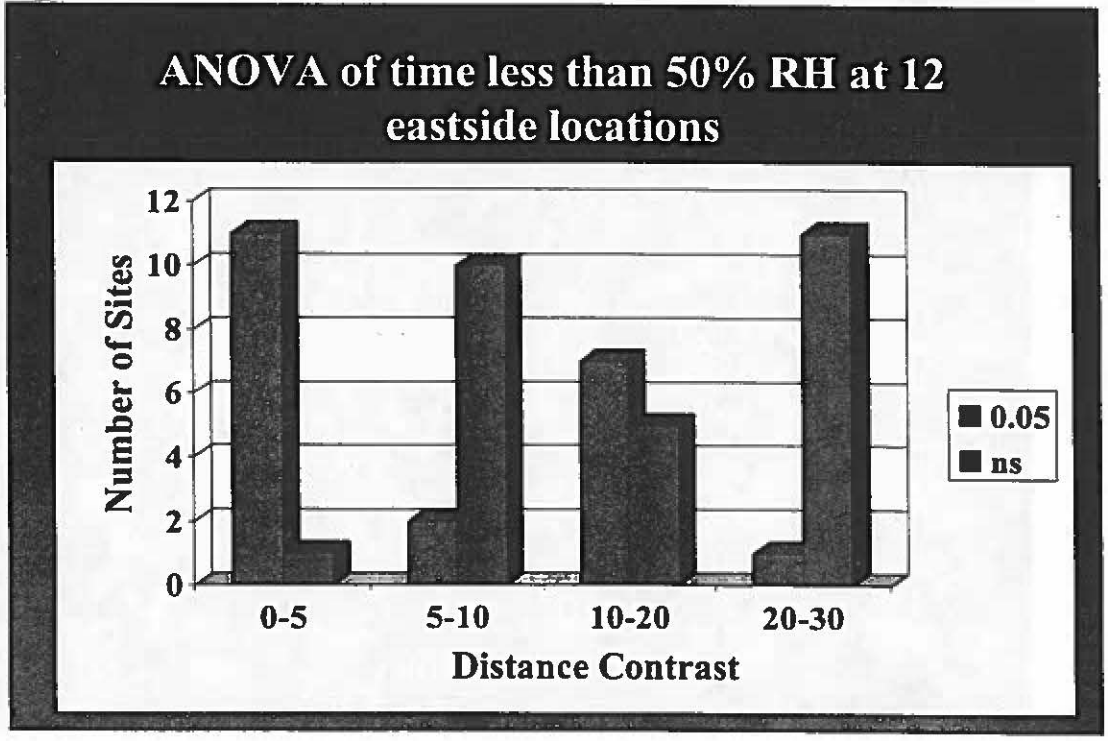


Sampling Layout of 1997 Microclimate Stations

x = station
y = local control

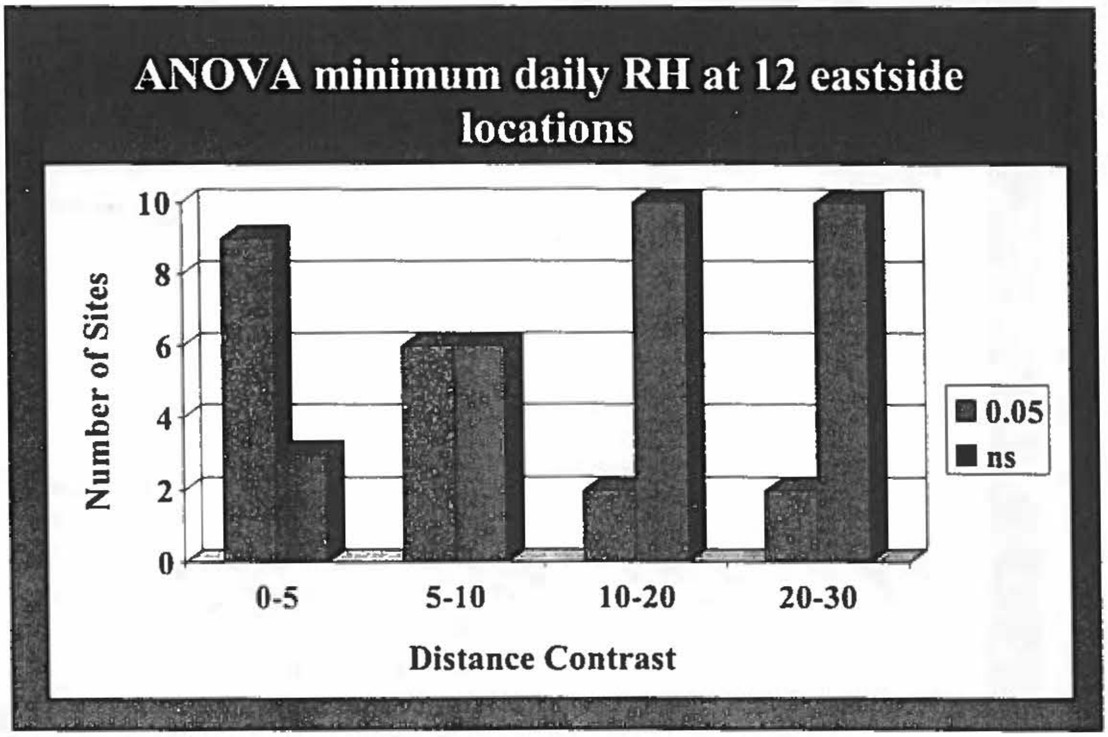
- ✶ Time on Site - 5-10 Days
- ✶ Measurements every 10 min

⑩



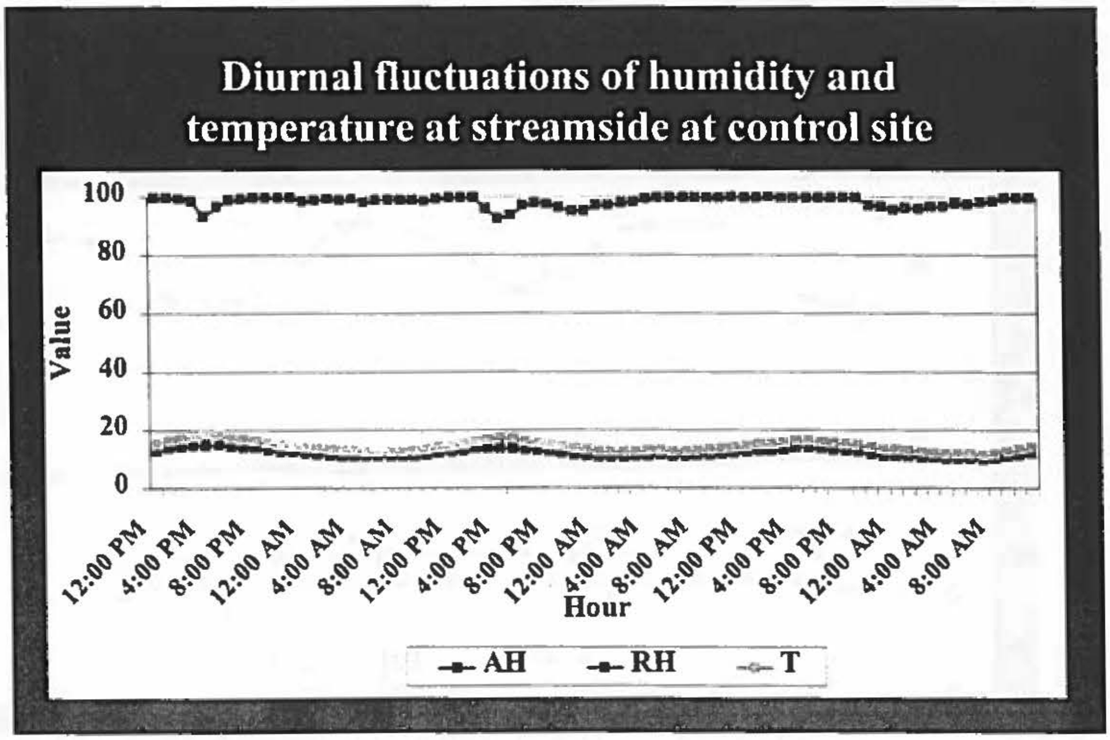
ANOVA of time less than 50% RH at 12 eastside locations

⑪



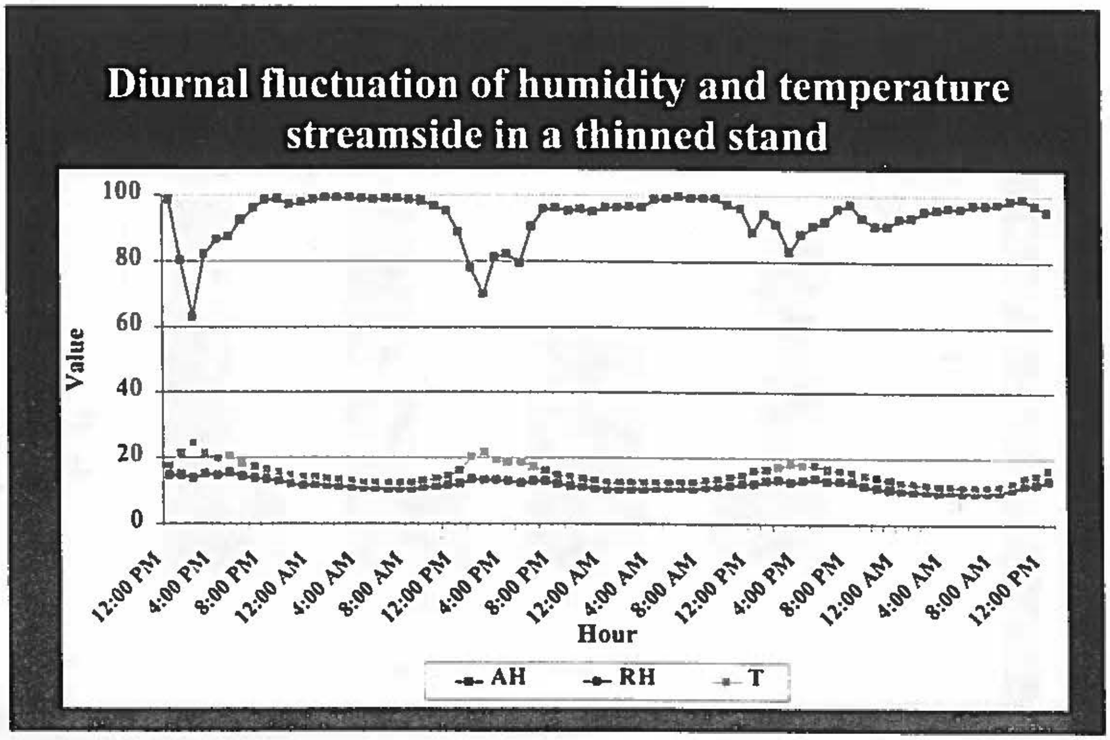
ANOVA minimum daily RH at 12 eastside locations

⑫



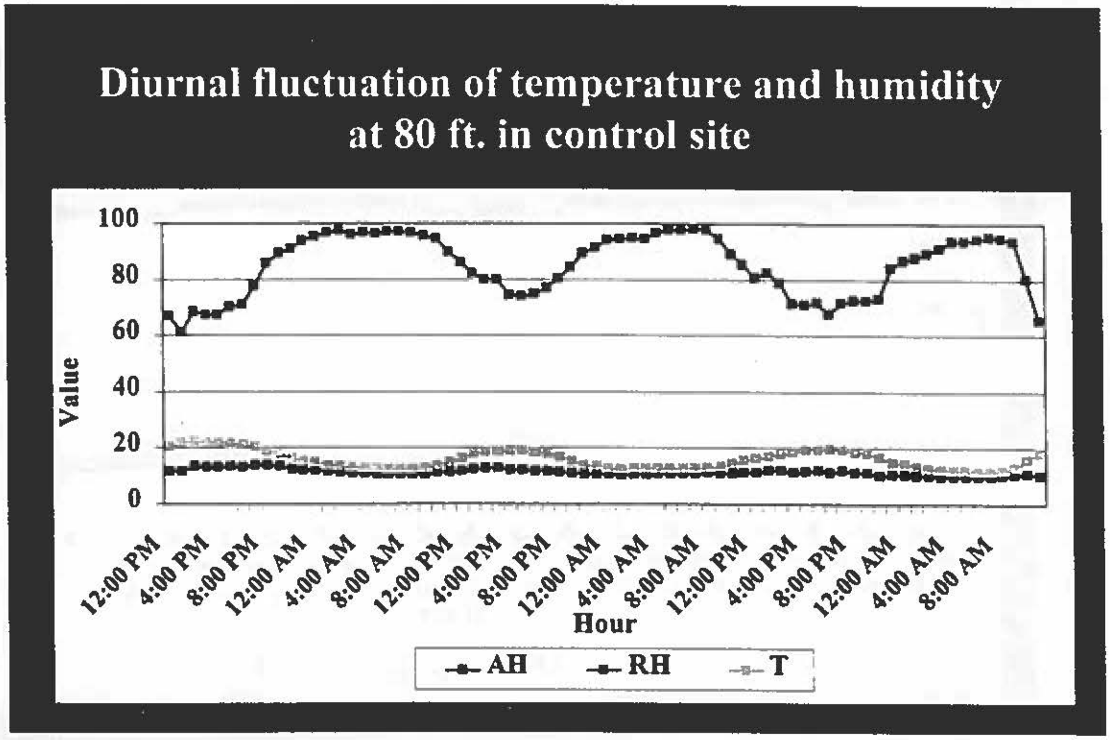
Diurnal fluctuations of humidity and temperature at streamside at control site

⑬



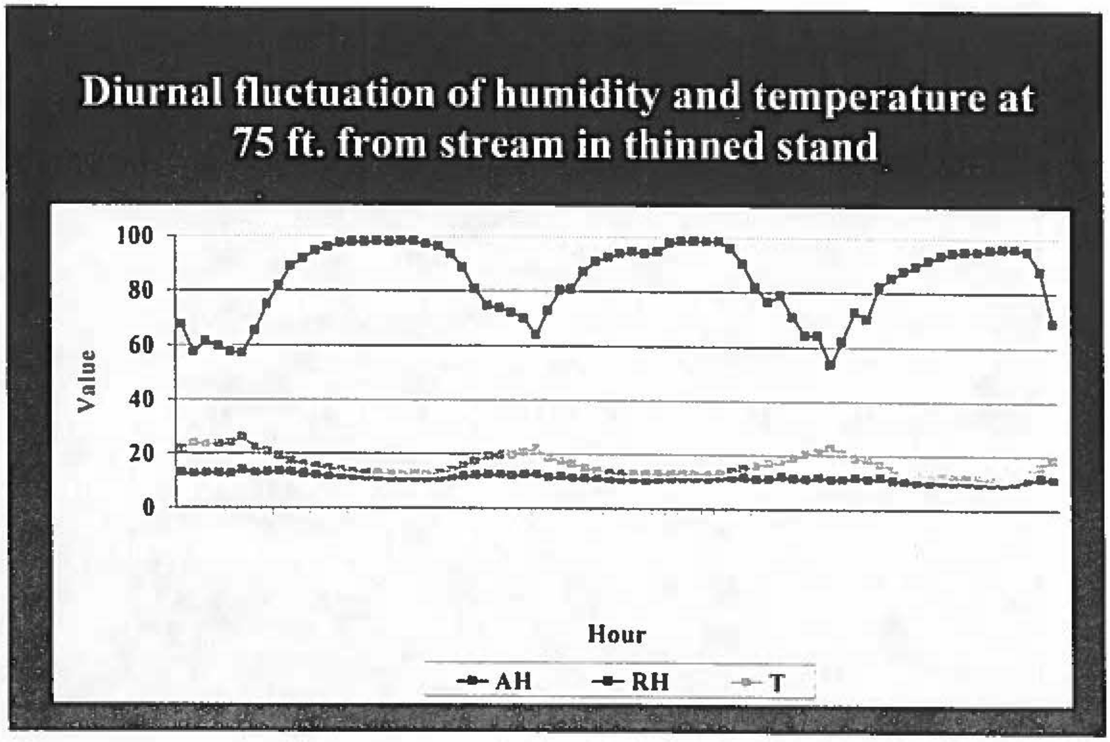
Diurnal fluctuation of humidity and temperature streamside in a thinned stand

⑭



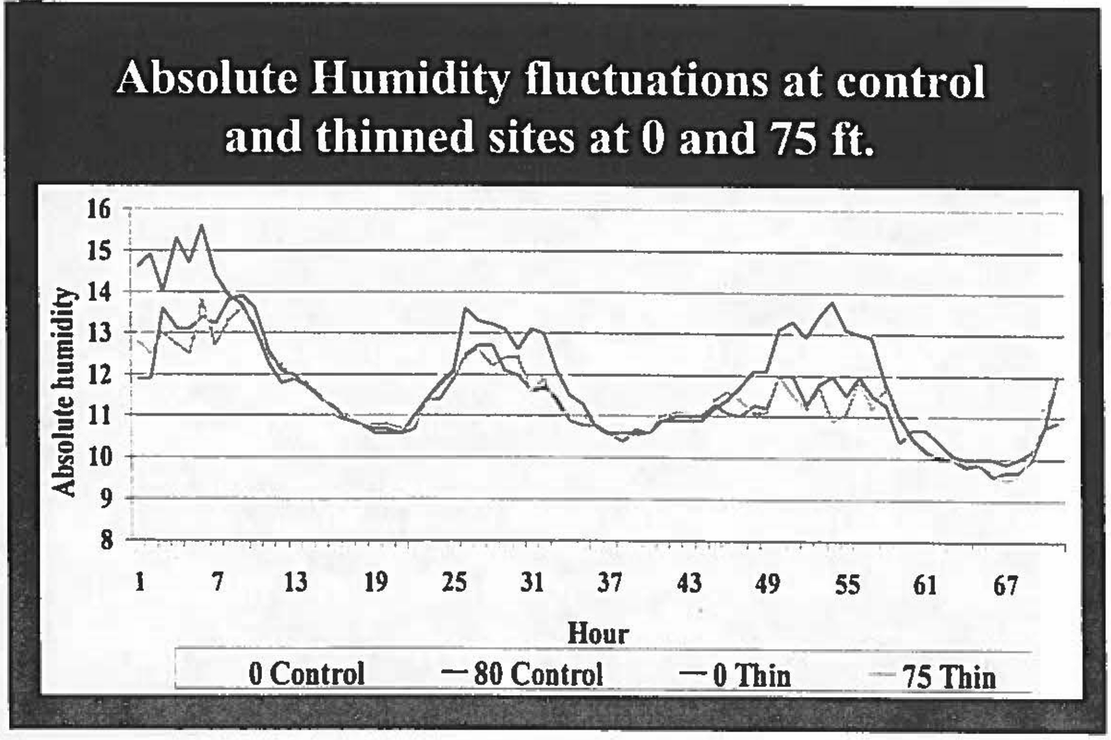
Diurnal fluctuation of temperature and humidity at 80 ft. in control site

(15)



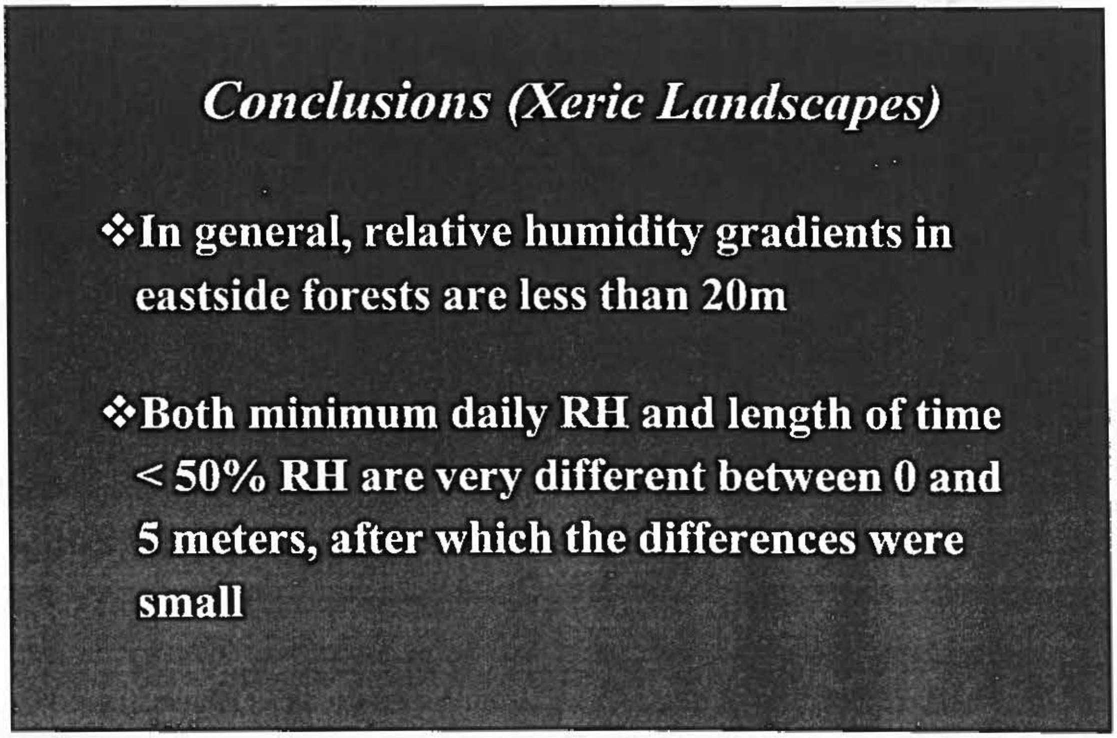
Diurnal fluctuation of humidity and temperature at 75 ft. from stream in thinned stand

(16)



Absolute Humidity fluctuations at control and thinned sites at 0 and 75 ft.

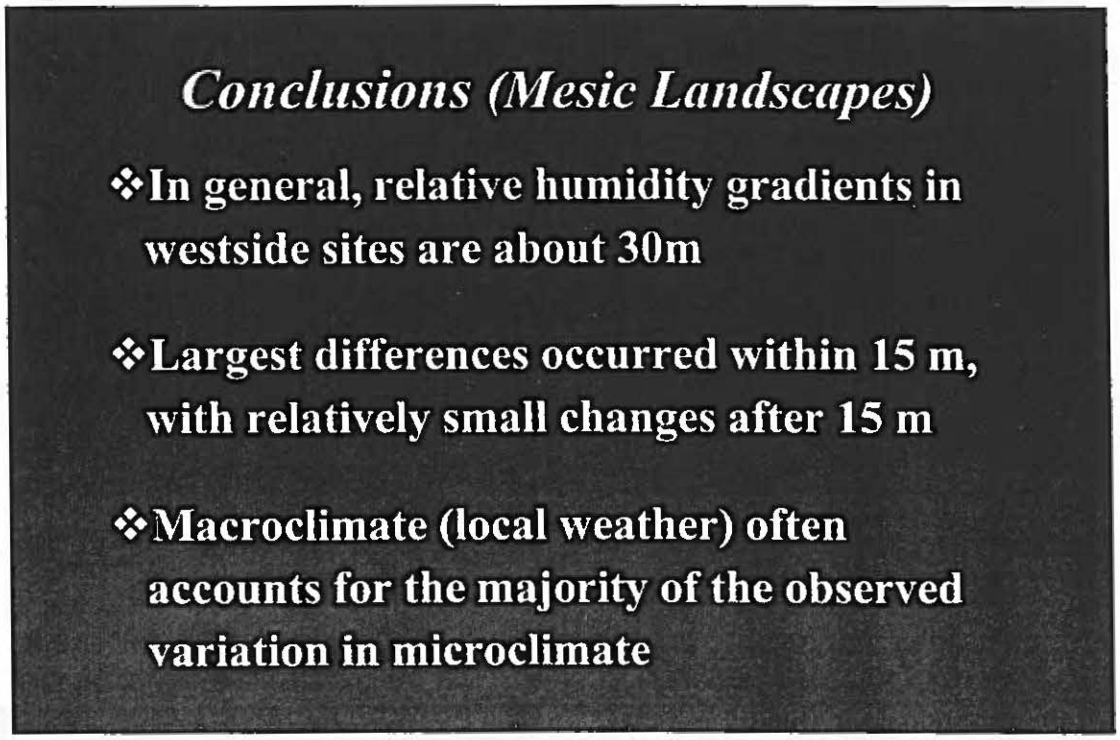
⑰



Conclusions (Xeric Landscapes)

- ❖In general, relative humidity gradients in eastside forests are less than 20m
- ❖Both minimum daily RH and length of time < 50% RH are very different between 0 and 5 meters, after which the differences were small

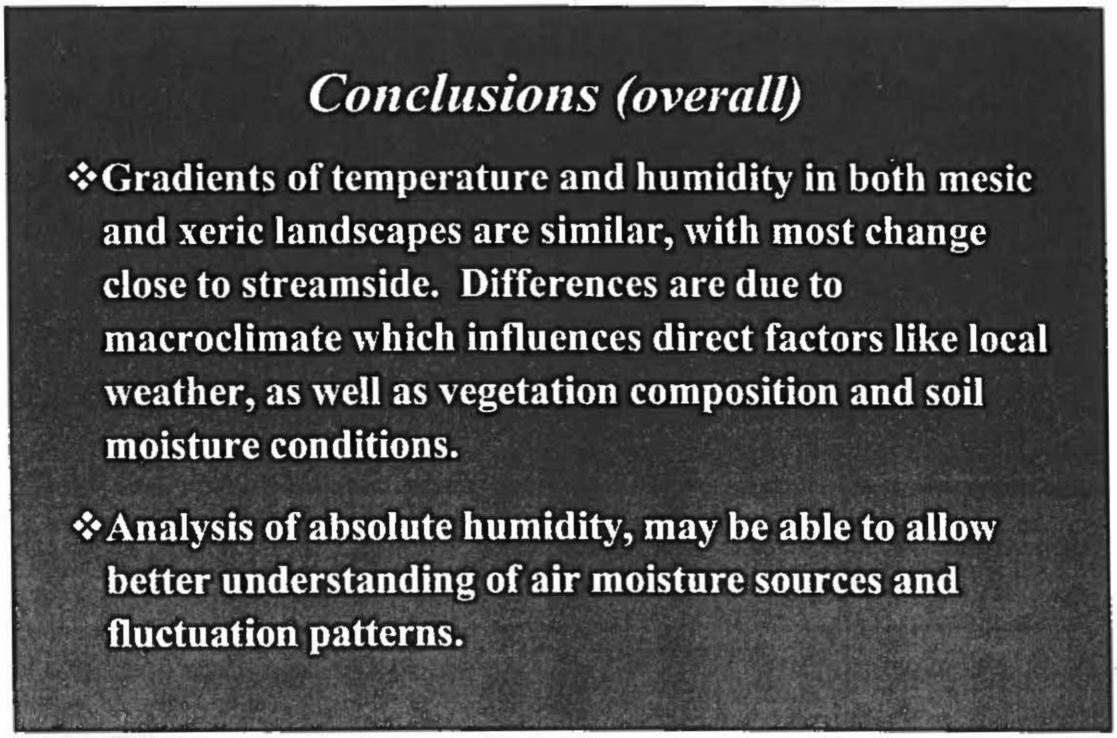
⑱



Conclusions (Mesic Landscapes)

- ❖In general, relative humidity gradients in westside sites are about 30m
- ❖Largest differences occurred within 15 m, with relatively small changes after 15 m
- ❖Macroclimate (local weather) often accounts for the majority of the observed variation in microclimate

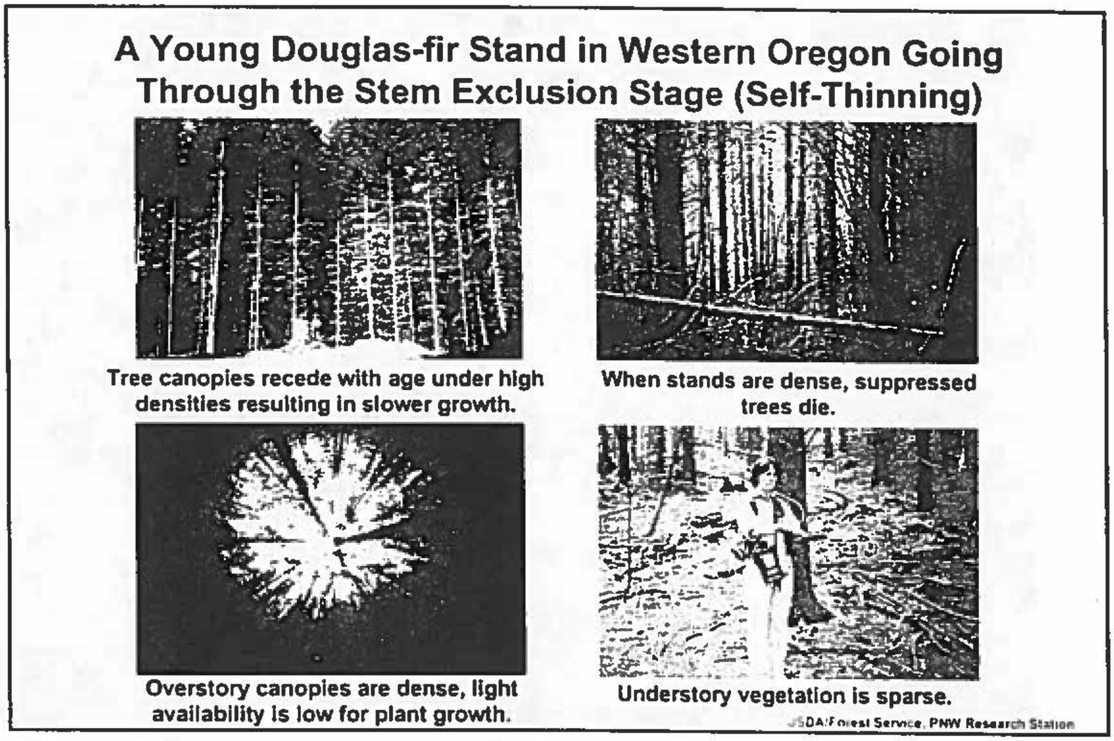
⑲



Conclusions (overall)

- Gradients of temperature and humidity in both mesic and xeric landscapes are similar, with most change close to streamside. Differences are due to macroclimate which influences direct factors like local weather, as well as vegetation composition and soil moisture conditions.
- Analysis of absolute humidity, may be able to allow better understanding of air moisture sources and fluctuation patterns.

①



A Young Douglas-fir Stand in Western Oregon Going Through the Stem Exclusion Stage (Self-Thinning)

Tree canopies recede with age under high densities resulting in slower growth.

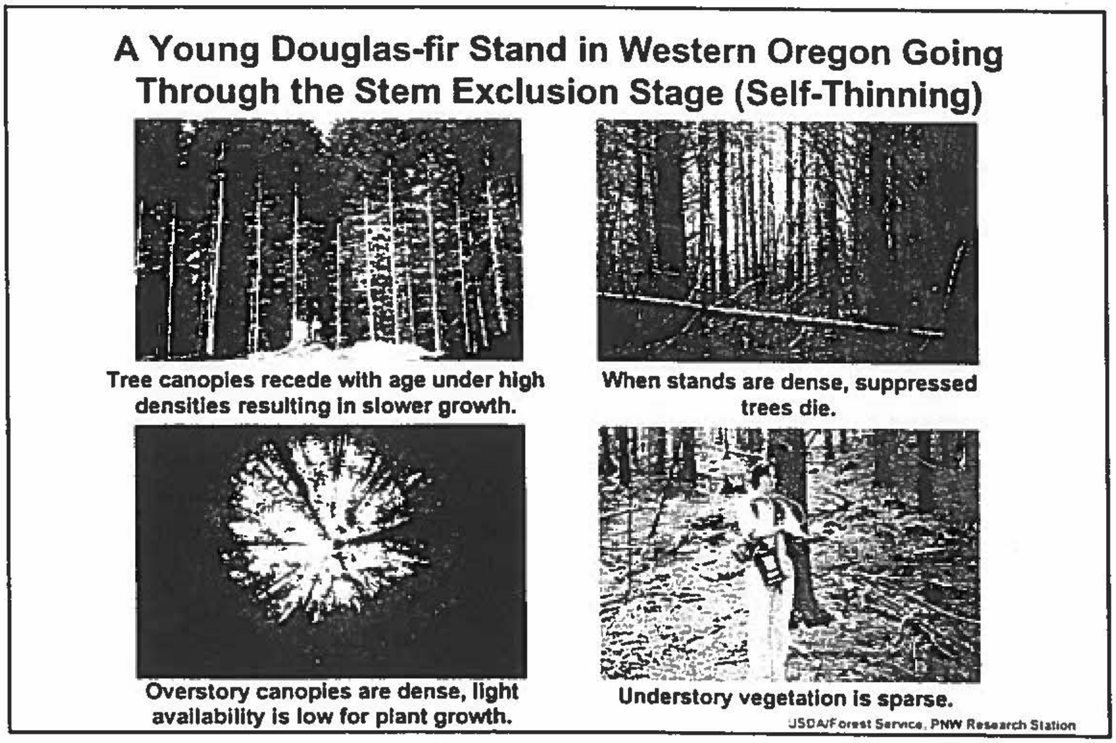
When stands are dense, suppressed trees die.

Overstory canopies are dense, light availability is low for plant growth.

Understory vegetation is sparse.

USDA/Forest Service, PNW Research Station

②



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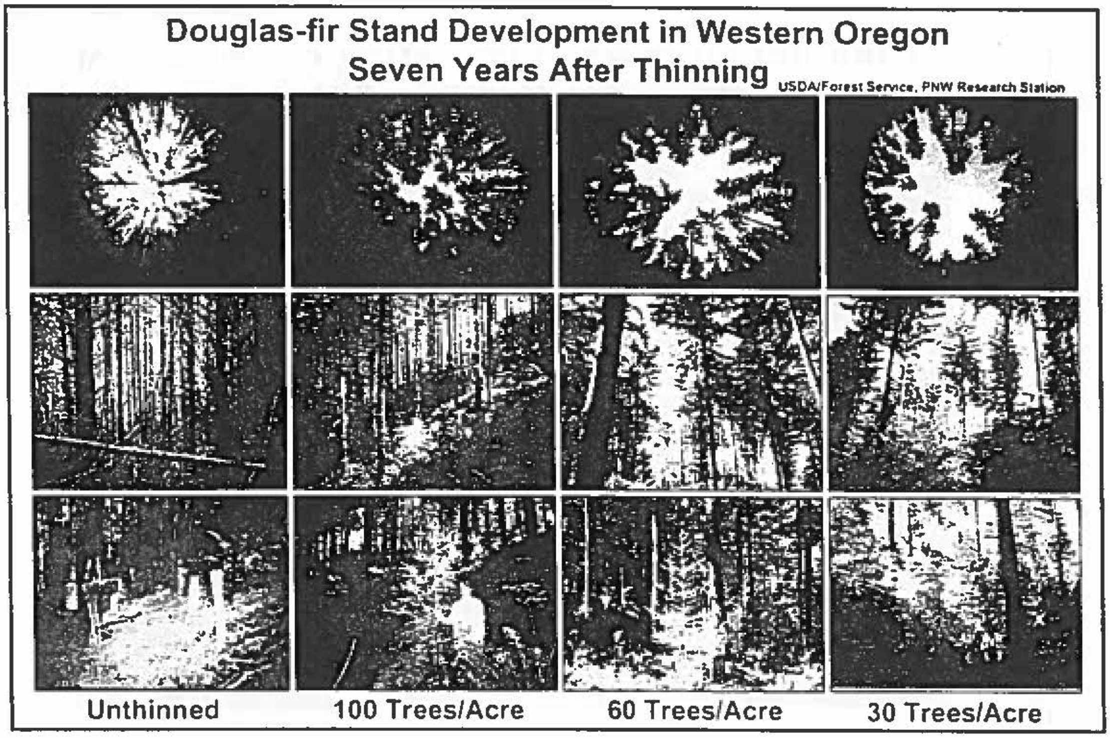
③

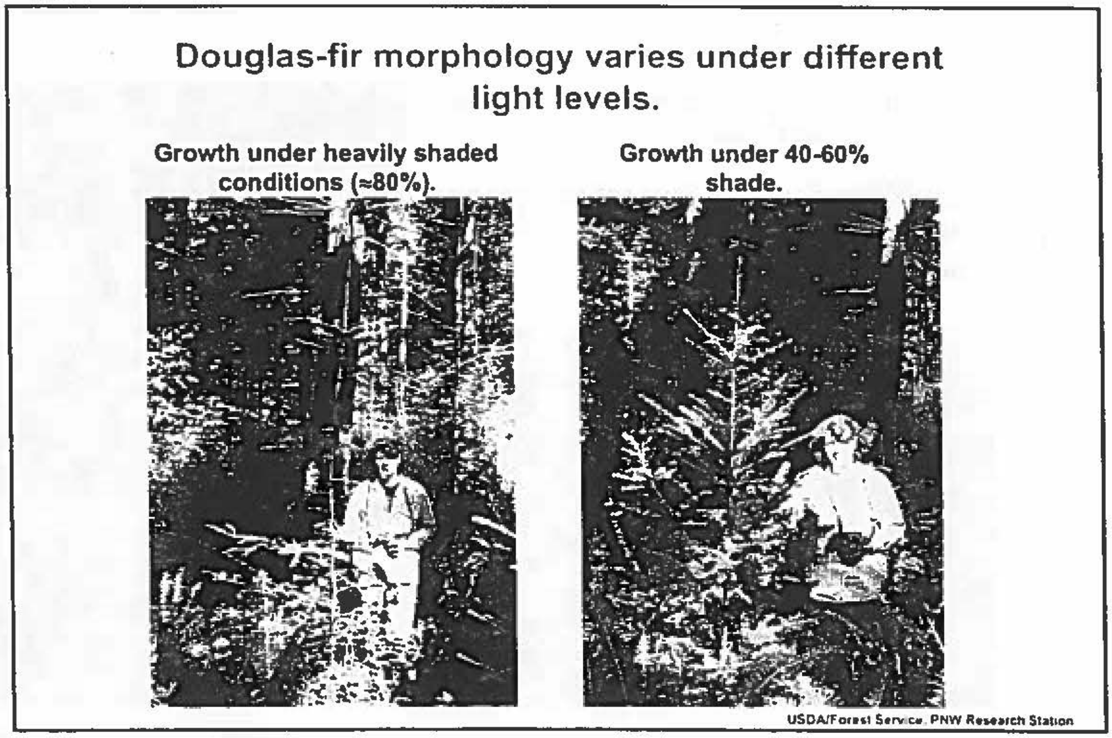


Douglas-fir Stand Development in Western Oregon Seven Years After Thinning

USDA/Forest Service, PNW Research Station

Unthinned | 100 Trees/Acre | 60 Trees/Acre | 30 Trees/Acre

④



Douglas-fir morphology varies under different light levels.

Growth under heavily shaded conditions (≈80%).

Growth under 40-60% shade.

USDA/Forest Service, PNW Research Station

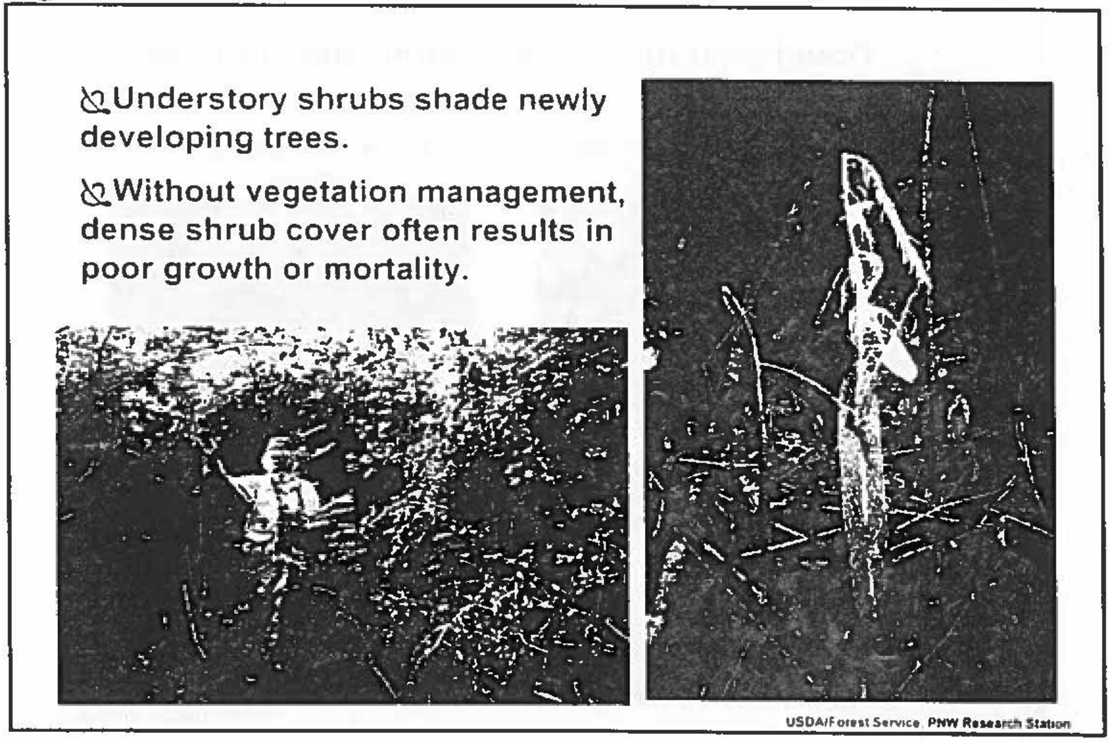
(5)

Thinning promotes understory development.

Understory tree on right received more light than tree on left.
Trees were underplanted seven years ago.

USDA/Forest Service PNW Research Station

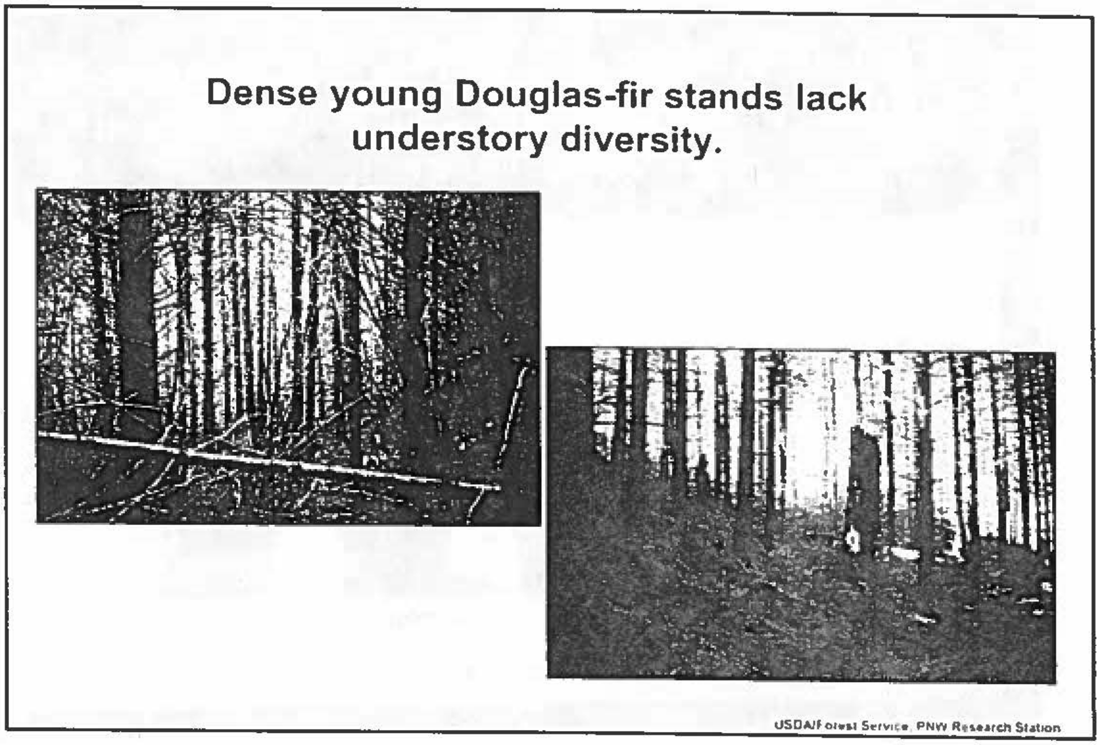
(6)



- Understory shrubs shade newly developing trees.
- Without vegetation management, dense shrub cover often results in poor growth or mortality.

USDA/Forest Service, PNW Research Station

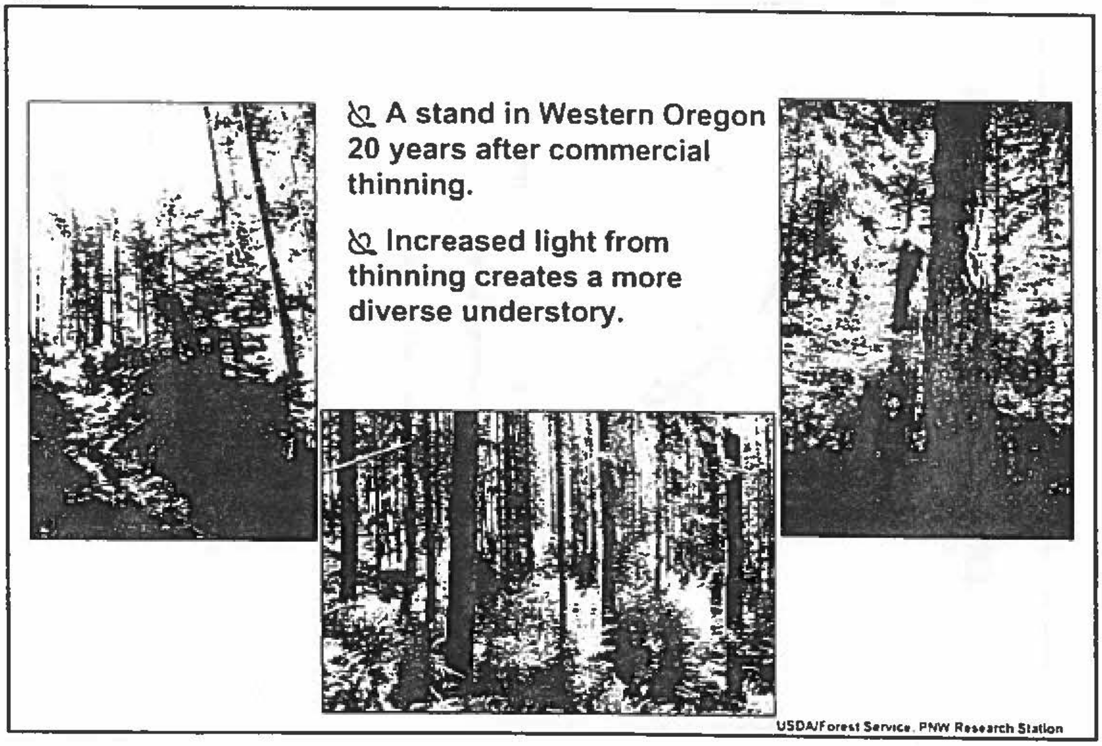
⑦



Dense young Douglas-fir stands lack understory diversity.

USDA/Forest Service, PNW Research Station

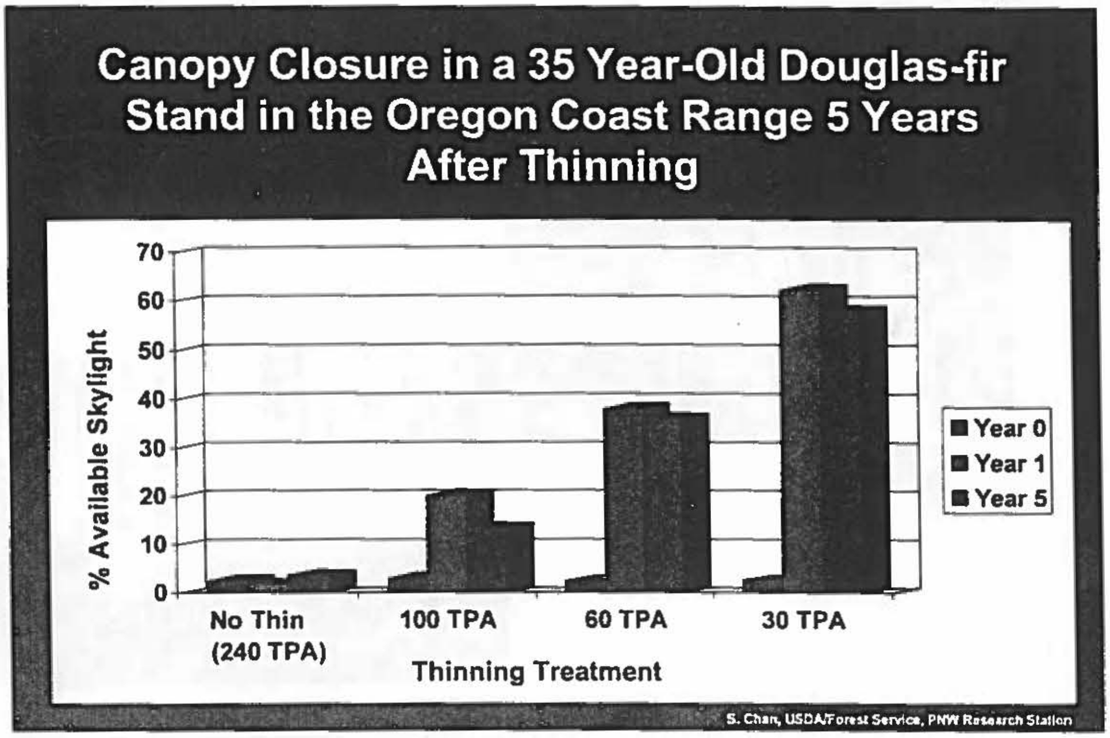
⑧



- A stand in Western Oregon 20 years after commercial thinning.
- Increased light from thinning creates a more diverse understory.

USDA/Forest Service, PNW Research Station

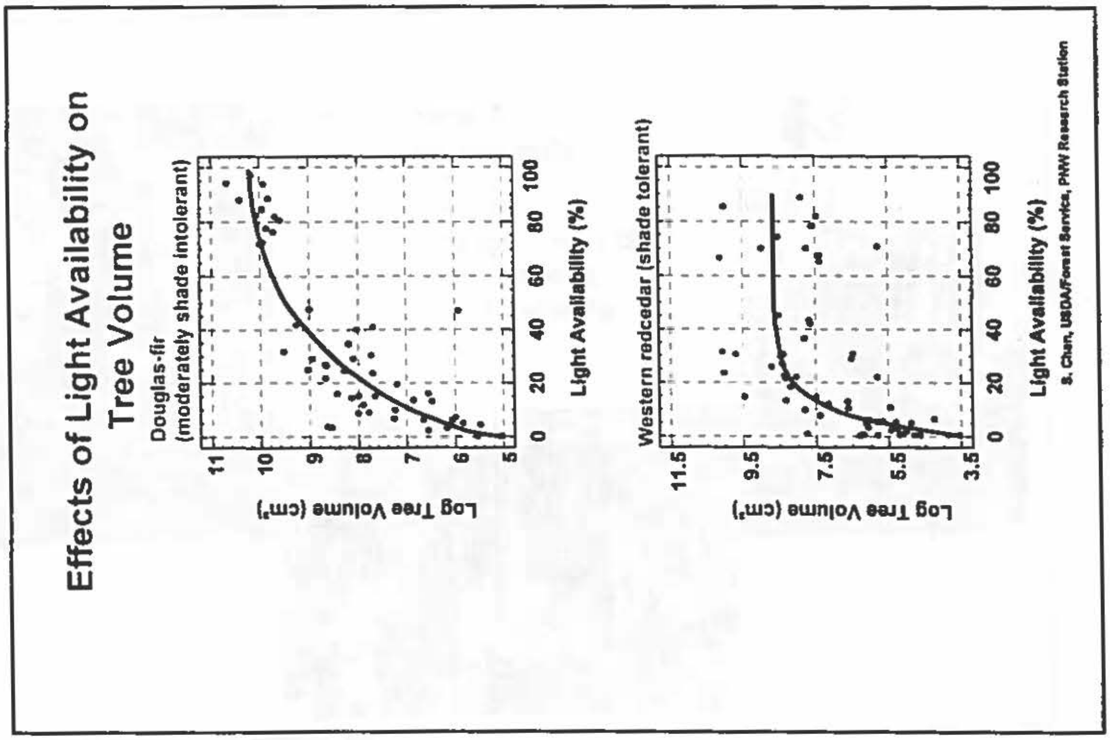
⑨



Canopy Closure in a 35 Year-Old Douglas-fir Stand in the Oregon Coast Range 5 Years After Thinning

S. Chan, USDA/Forest Service, PNW Research Station

⑩

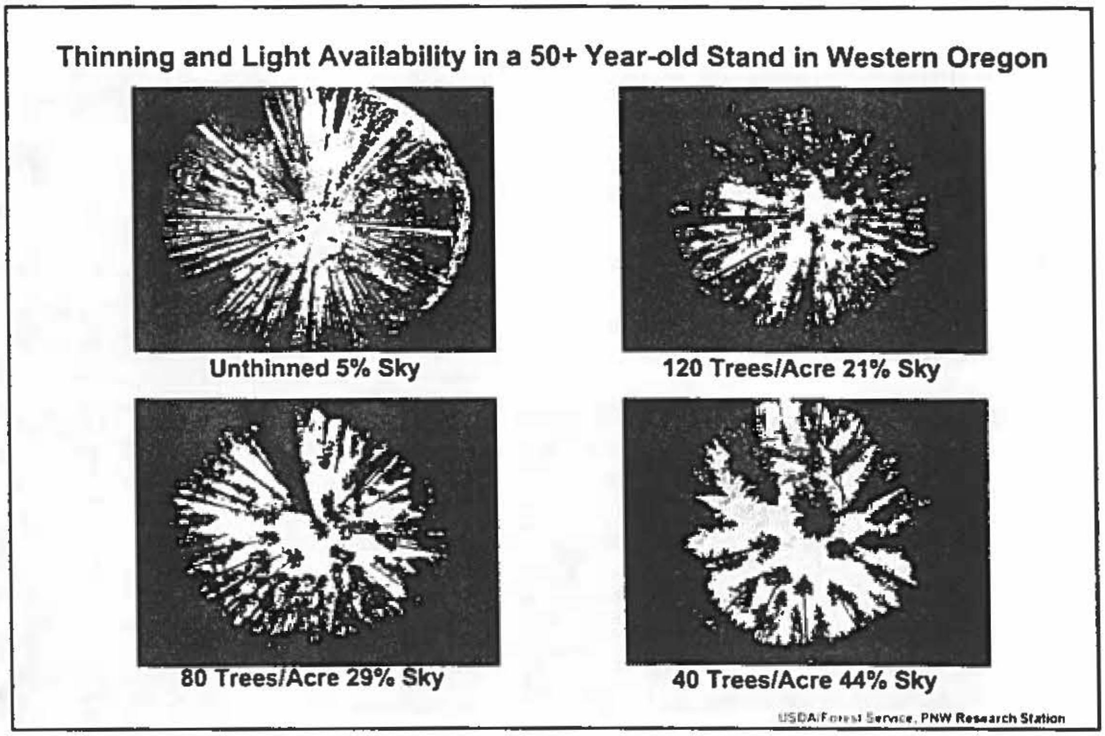


Effects of Light Availability on Tree Volume

S. Chan, USDA/Forest Service, PNW Research Station

33

⑪



Thinning and Light Availability in a 50+ Year-old Stand in Western Oregon

Unthinned 5% Sky

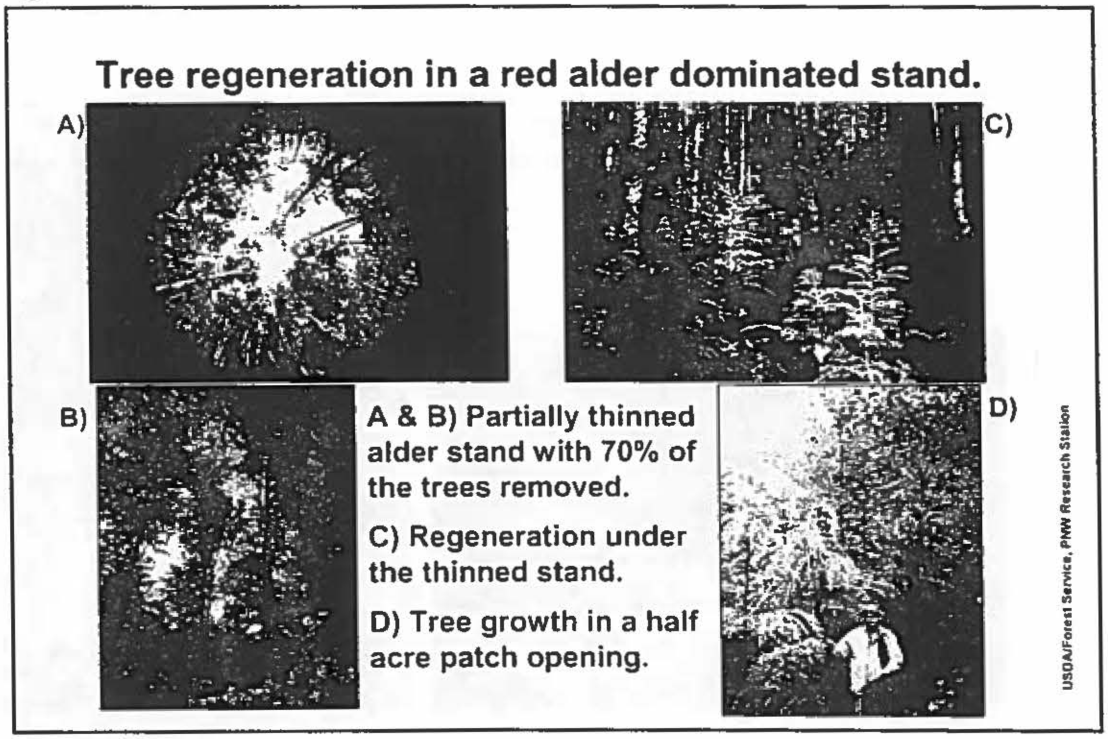
120 Trees/Acre 21% Sky

80 Trees/Acre 29% Sky

40 Trees/Acre 44% Sky

USDA/Forest Service, PNW Research Station

⑫



Tree regeneration in a red alder dominated stand.

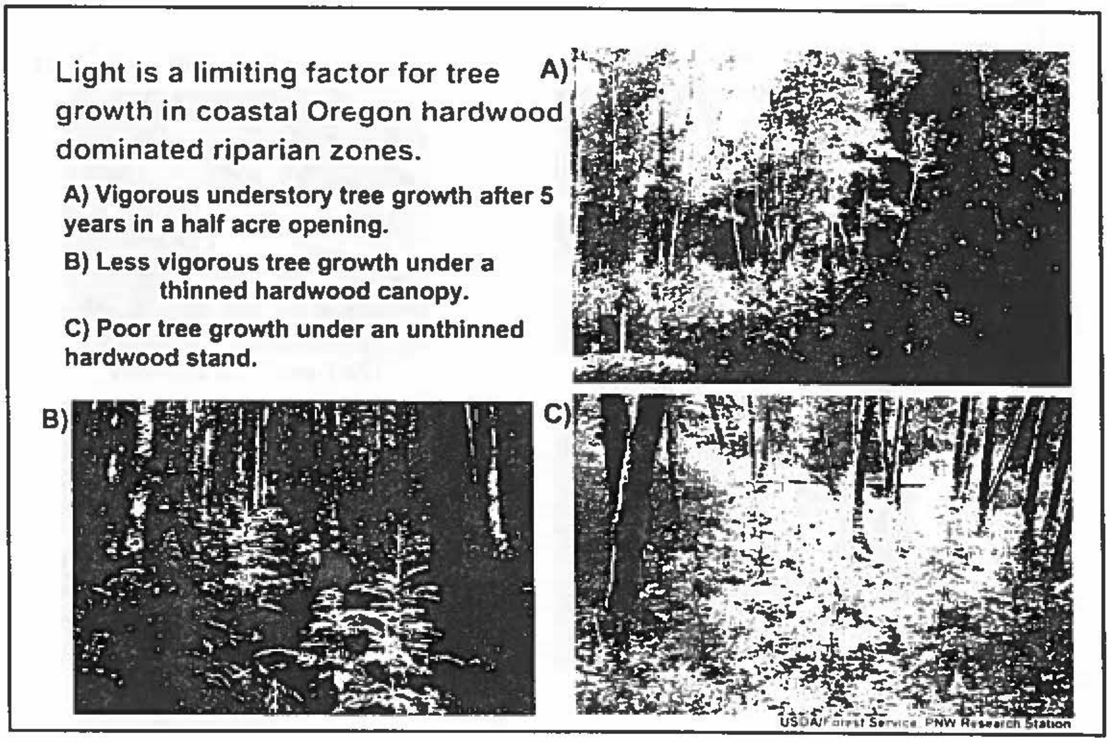
A & B) Partially thinned alder stand with 70% of the trees removed.

C) Regeneration under the thinned stand.

D) Tree growth in a half acre patch opening.

USDA/Forest Service, PNW Research Station

⑬



Light is a limiting factor for tree growth in coastal Oregon hardwood dominated riparian zones.

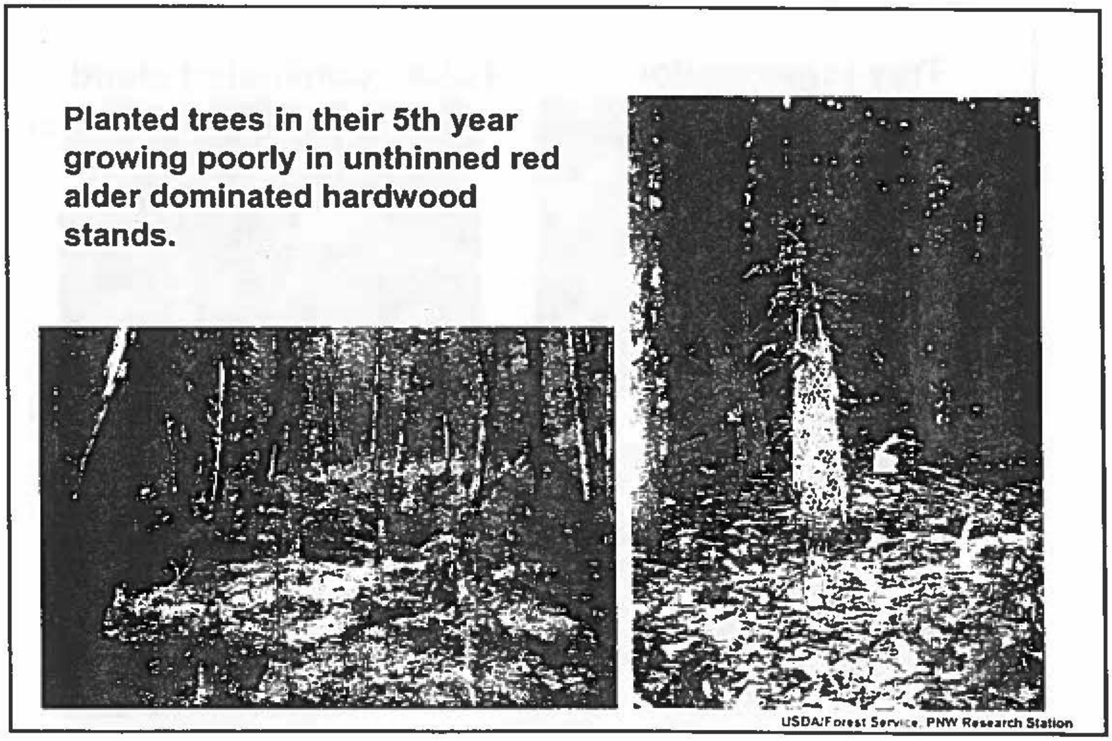
A) Vigorous understory tree growth after 5 years in a half acre opening.

B) Less vigorous tree growth under a thinned hardwood canopy.

C) Poor tree growth under an unthinned hardwood stand.

USDA/Forest Service, PNW Research Station

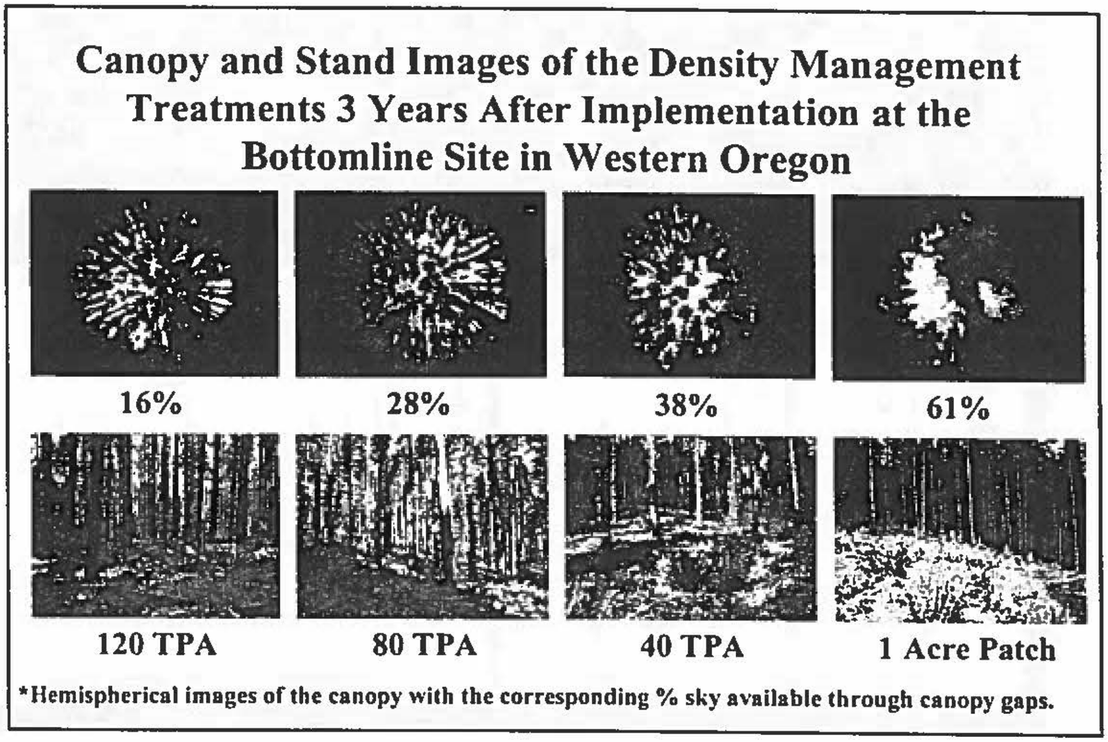
⑭



Planted trees in their 5th year growing poorly in unthinned red alder dominated hardwood stands.

USDA/Forest Service, PNW Research Station

①



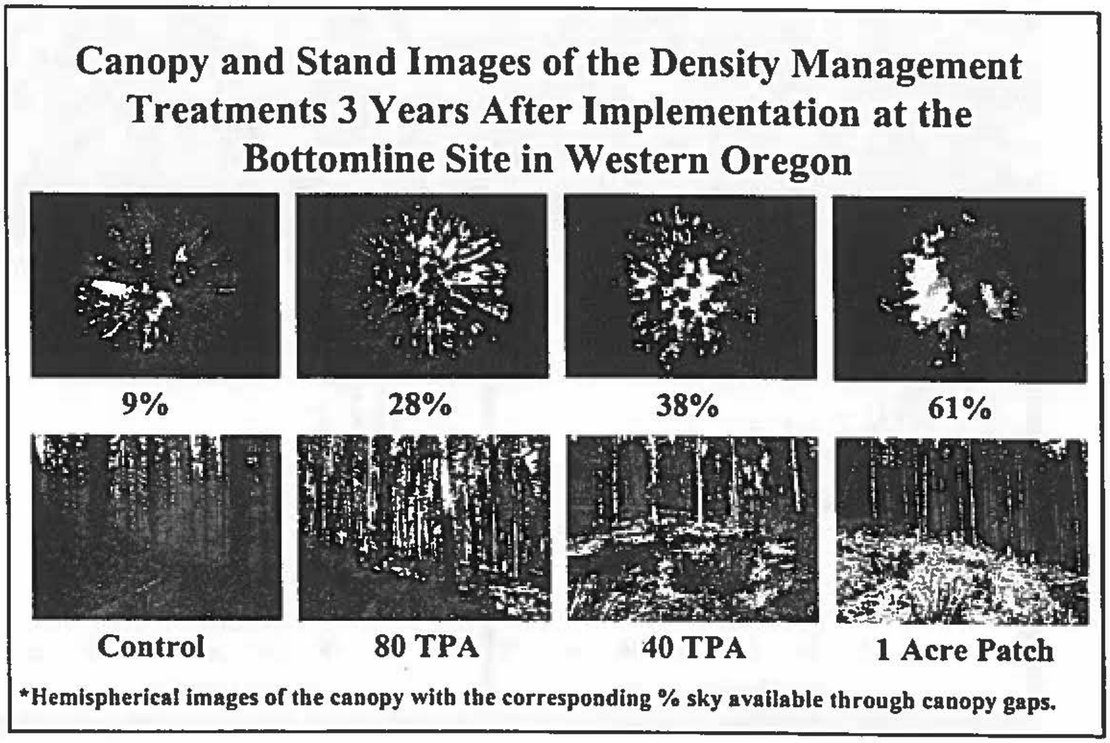
Canopy and Stand Images of the Density Management Treatments 3 Years After Implementation at the Bottomline Site in Western Oregon

16% 28% 38% 61%

120 TPA 80 TPA 40 TPA 1 Acre Patch

*Hemispherical images of the canopy with the corresponding % sky available through canopy gaps.

②



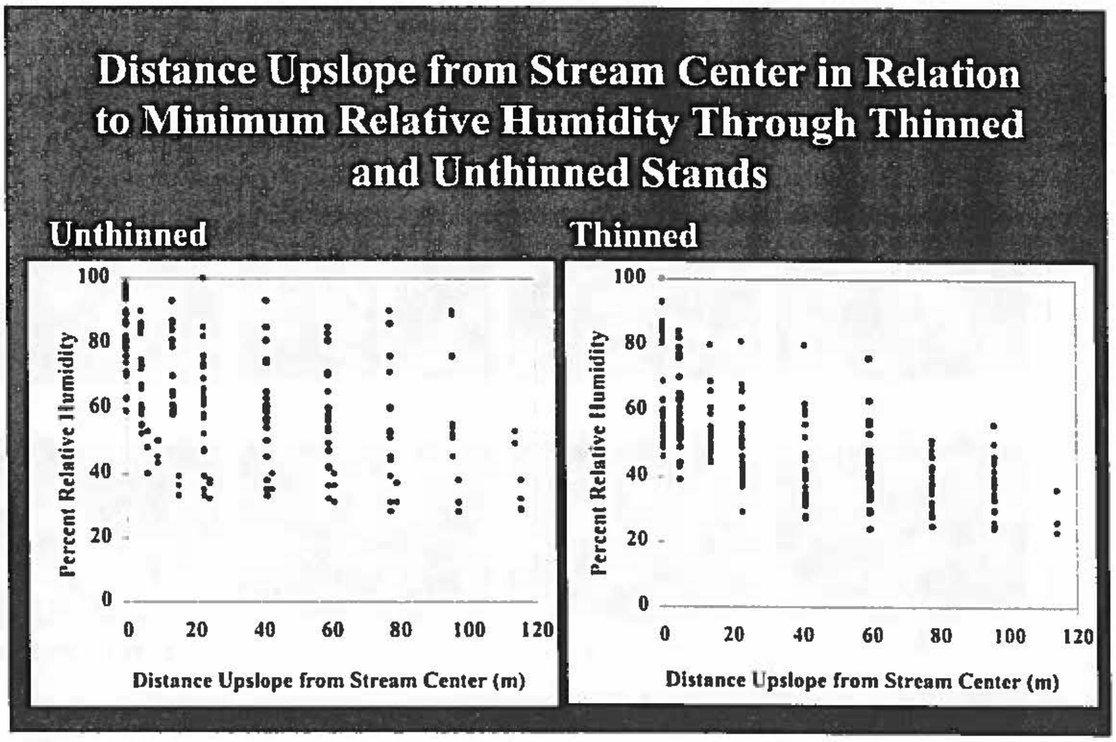
Canopy and Stand Images of the Density Management Treatments 3 Years After Implementation at the Bottomline Site in Western Oregon

9% 28% 38% 61%

Control 80 TPA 40 TPA 1 Acre Patch

*Hemispherical images of the canopy with the corresponding % sky available through canopy gaps.

③

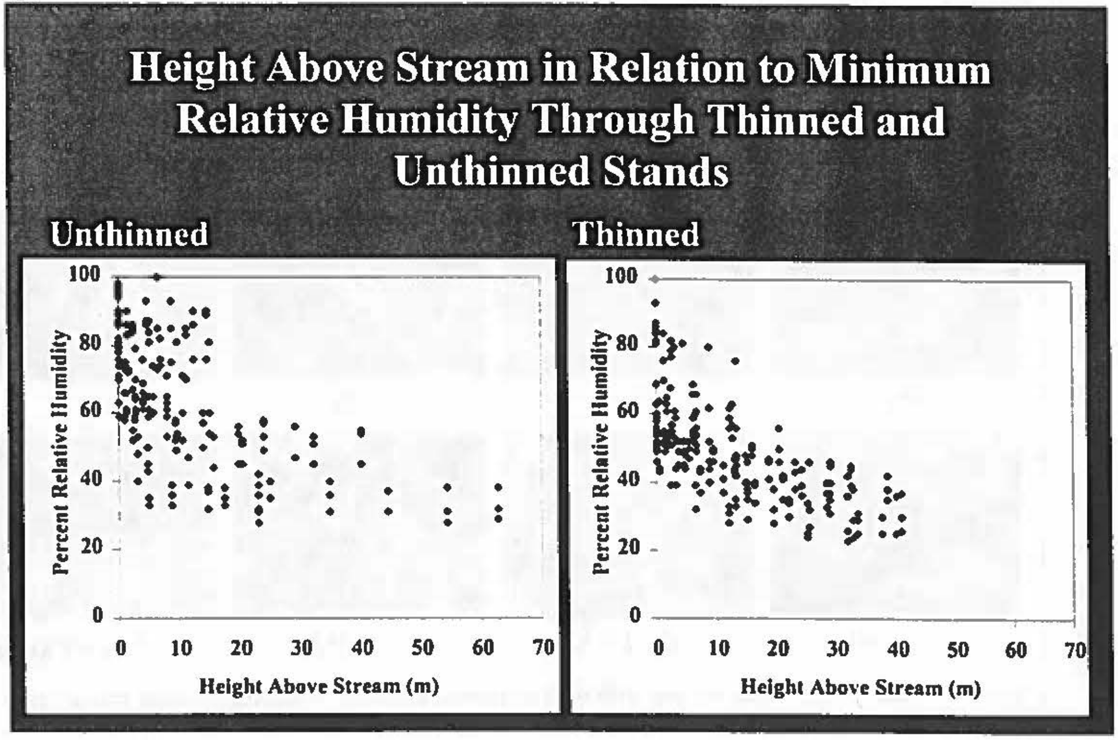


Distance Upslope from Stream Center in Relation to Minimum Relative Humidity Through Thinned and Unthinned Stands

Unthinned

Thinned

④

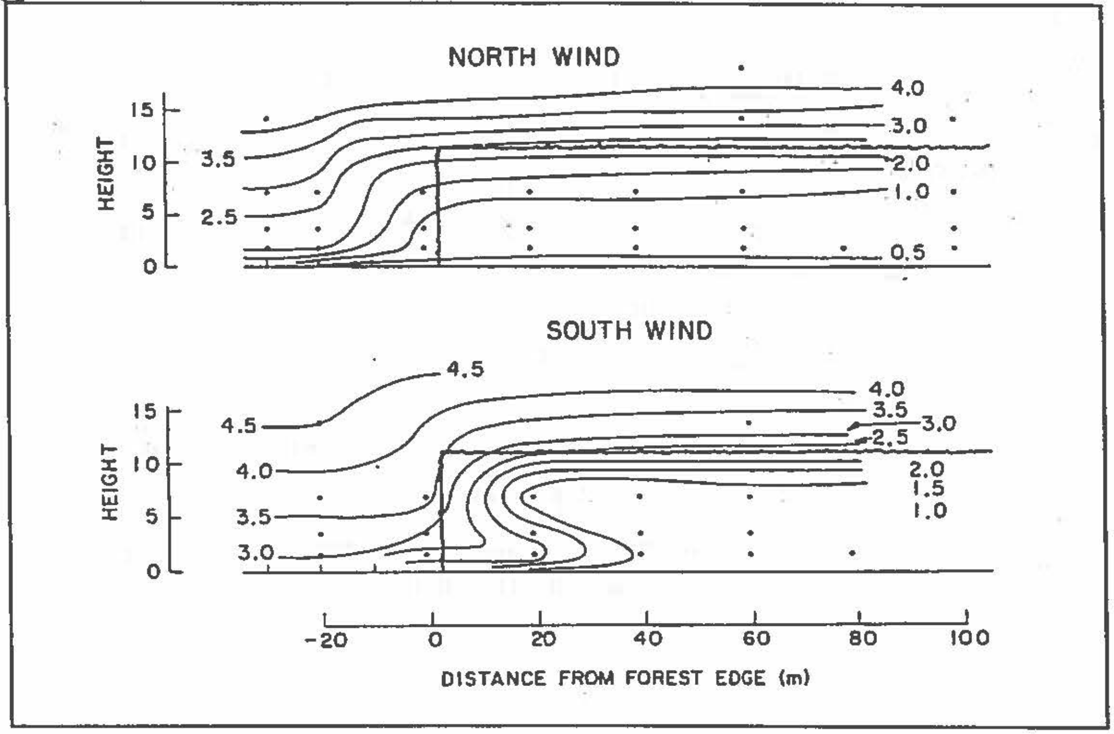


Height Above Stream in Relation to Minimum Relative Humidity Through Thinned and Unthinned Stands

Unthinned

Thinned

⑤

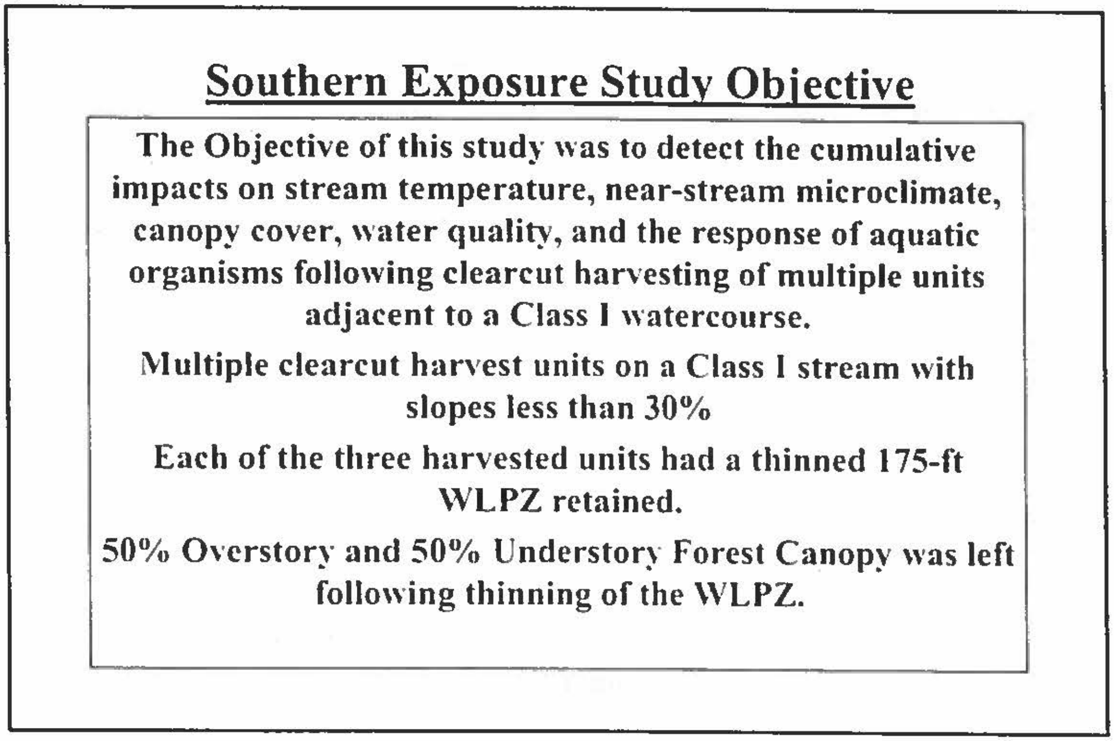


⑥

Southern Exposure Research Project

Cajun James
Principle Research Scientist
Sierra Pacific Industries

⑦



Southern Exposure Study Objective

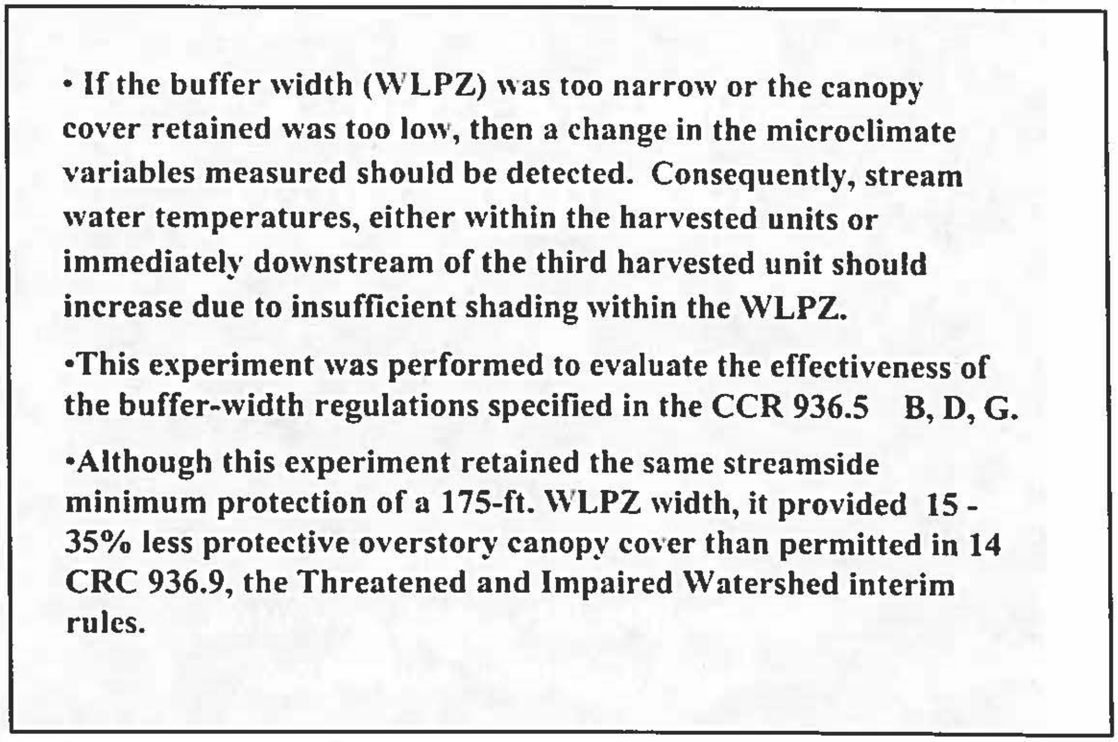
The Objective of this study was to detect the cumulative impacts on stream temperature, near-stream microclimate, canopy cover, water quality, and the response of aquatic organisms following clearcut harvesting of multiple units adjacent to a Class I watercourse.

Multiple clearcut harvest units on a Class I stream with slopes less than 30%

Each of the three harvested units had a thinned 175-ft WLPZ retained.

50% Overstory and 50% Understory Forest Canopy was left following thinning of the WLPZ.

⑧

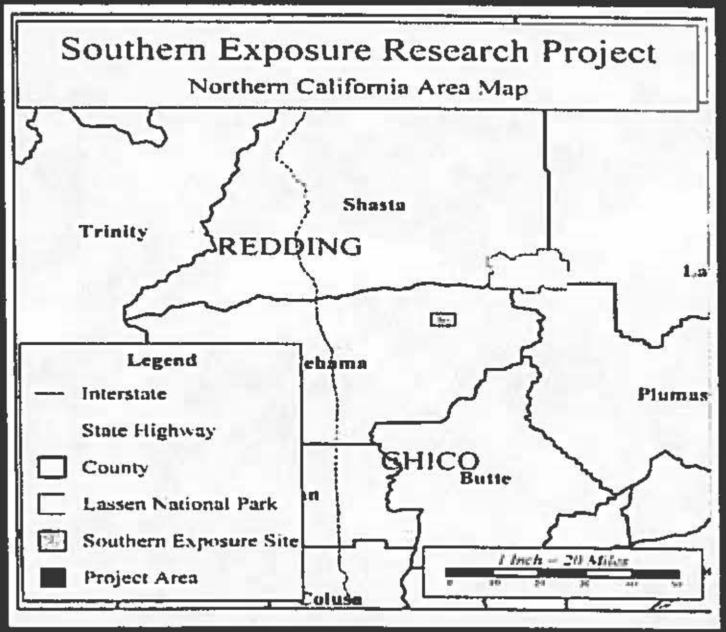


- If the buffer width (WLPZ) was too narrow or the canopy cover retained was too low, then a change in the microclimate variables measured should be detected. Consequently, stream water temperatures, either within the harvested units or immediately downstream of the third harvested unit should increase due to insufficient shading within the WLPZ.
- This experiment was performed to evaluate the effectiveness of the buffer-width regulations specified in the CCR 936.5 B, D, G.
- Although this experiment retained the same streamside minimum protection of a 175-ft. WLPZ width, it provided 15 - 35% less protective overstory canopy cover than permitted in 14 CRC 936.9, the Threatened and Impaired Watershed interim rules.

⑨

- For a Class I stream with slopes less than 30% the interim rules are as follows: the first 75 ft. of the WLPZ must retain 85% overstory canopy, the second 75 ft. must retain 65% and the remaining 25 ft. is a special harvesting zone that would retain all understory and mid-canopy conifer and hardwood trees.
- Given the pre-harvest canopy measurements, no harvesting would have been allowed under the interim rules.
- This experiment provided less protection than currently exists. Approval before new rules took place.

⑩



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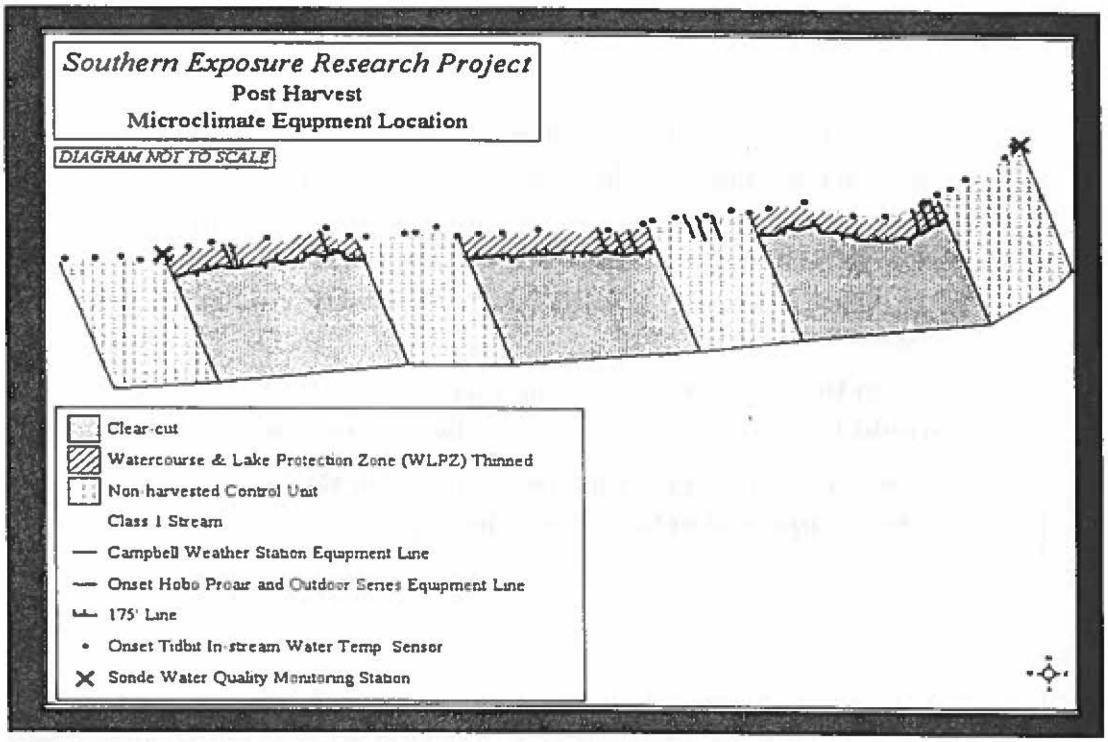


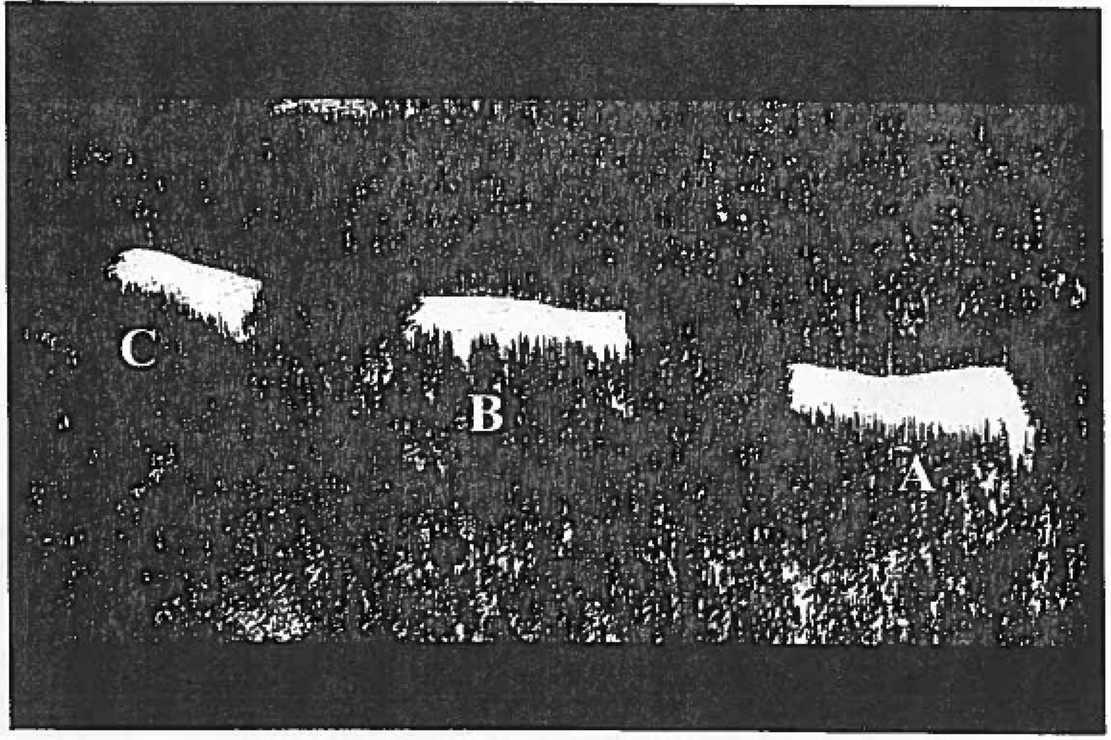
Southern Exposure Research Project

Post Harvest
Microclimate Equipment Location

DIAGRAM NOT TO SCALE

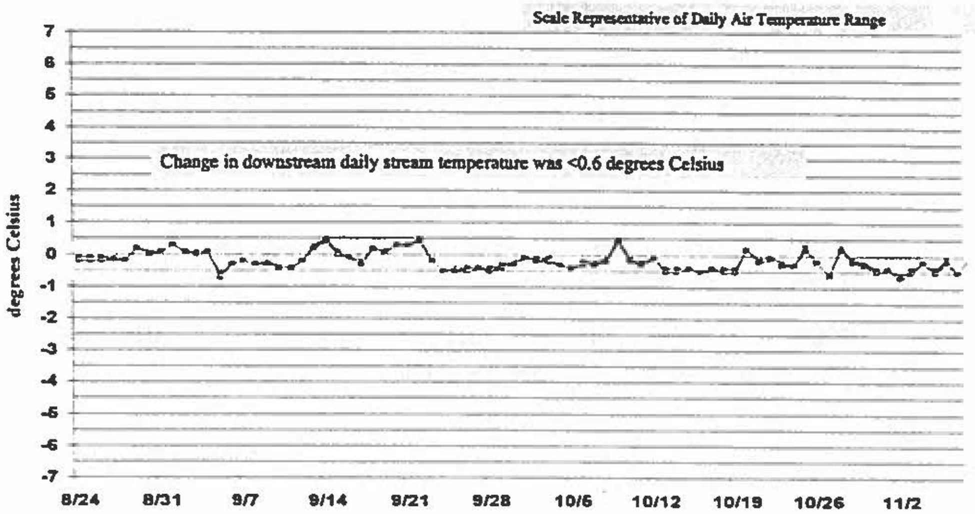
- ▒ Clear-cut
- ▨ Watercourse & Lake Protection Zone (WLPZ) Thinned
- ⁞ Non-harvested Control Unit
- Class I Stream
- — Campbell Weather Station Equipment Line
- — Onset Hobo Proair and Outdoor Series Equipment Line
- ⊥⊥ 175' Line
- • Onset Tidbit In-stream Water Temp. Sensor
- ✕ Sonde Water Quality Monitoring Station

⑫



⑬

Southern Exposure 2000 Daily Stream Temperature
Control 4 deviation from Control 1



Scale Representative of Daily Air Temperature Range

Change in downstream daily stream temperature was <0.6 degrees Celsius

Gray portion represents 0.5 degrees Celsius accuracy of stream temperature sensor

⑭

Southern Exposure Results

- Stream Temperature deviated from upstream reference values <.6 degrees Celsius.
- Essentially a finding of no measurable effect, since the instream temperature device accuracy is +/- .5 degrees Celsius.
- No increase in stream water temperature was found in any of the harvested blocks (A, B, or C) and no cumulative increase was detected.
- Microclimate data showed similar patterns prior to and following harvest.

⑮

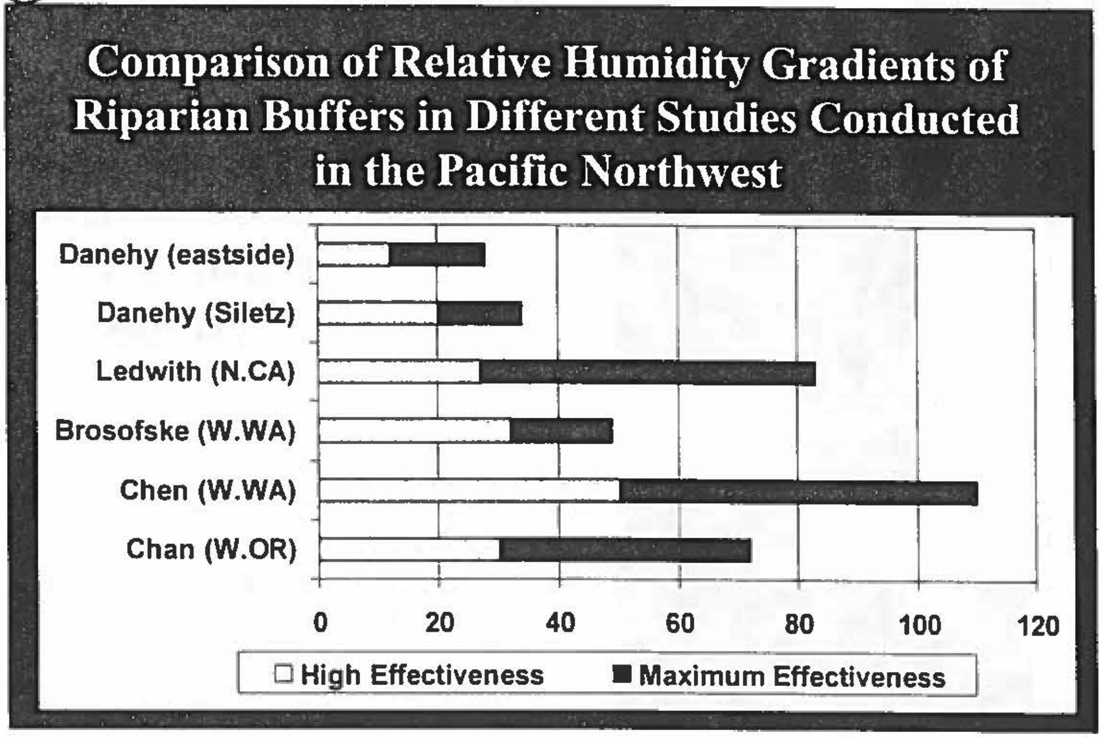
- Post-harvest vertical projected canopy was measured to be at the state-mandated minimum of 50%.
- Vertical projected canopy was reduced nearly 10% due to harvesting.
- Forest angular canopy density was reduced <5% at mid-stream and less than 3% at mid-WLPZ for all three harvested blocks.
- Post-harvest, angular canopy density was 88% mid-stream and 85% mid WLPZ.

⑯

Conclusions

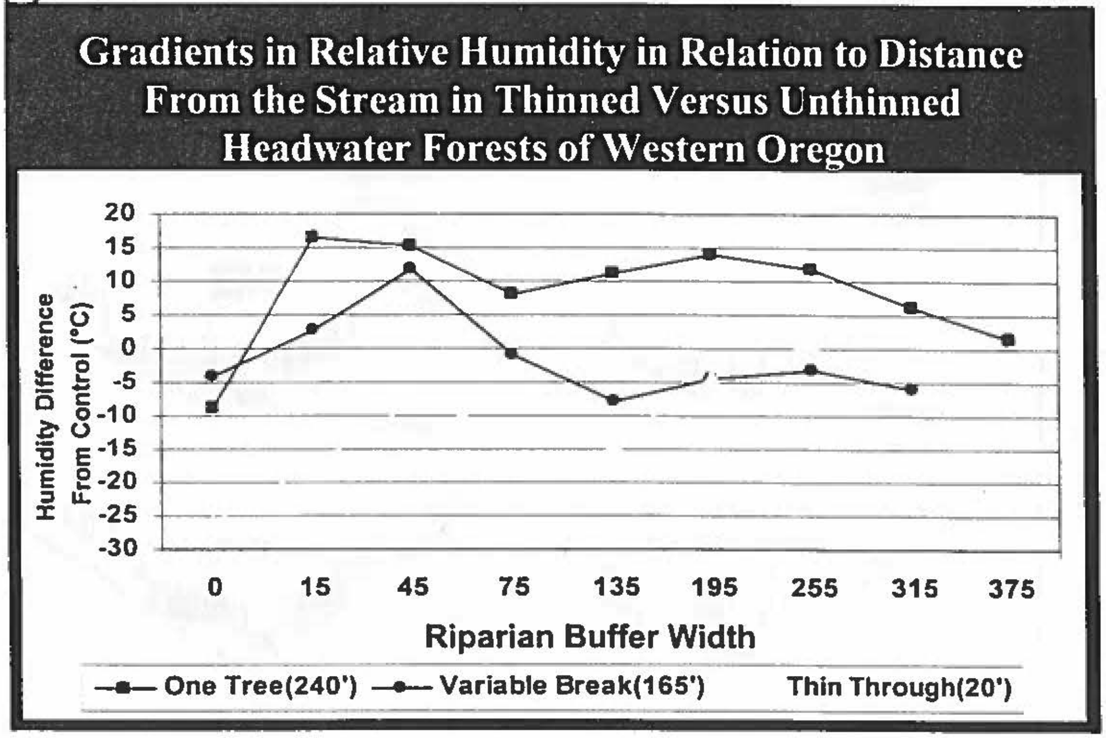
- Both research projects over the last two years, Millseat and Southern Exposure, have found no increase in stream temperature caused by the prescribed forest harvest.
- By using multiple canopy estimators, I have established that 50% vertical projected canopy equates to greater than 85% angular canopy when measured at a WLPZ buffer width of 75 ft. or greater.
- Water quality data collected has shown no negative increase in turbidity, specific conductivity or dissolved oxygen.
- There has been no increase in sediment production in these two research sites.
- No negative increases as a result of forest harvest operations. Regulations as of 1999 were effective.

⑰



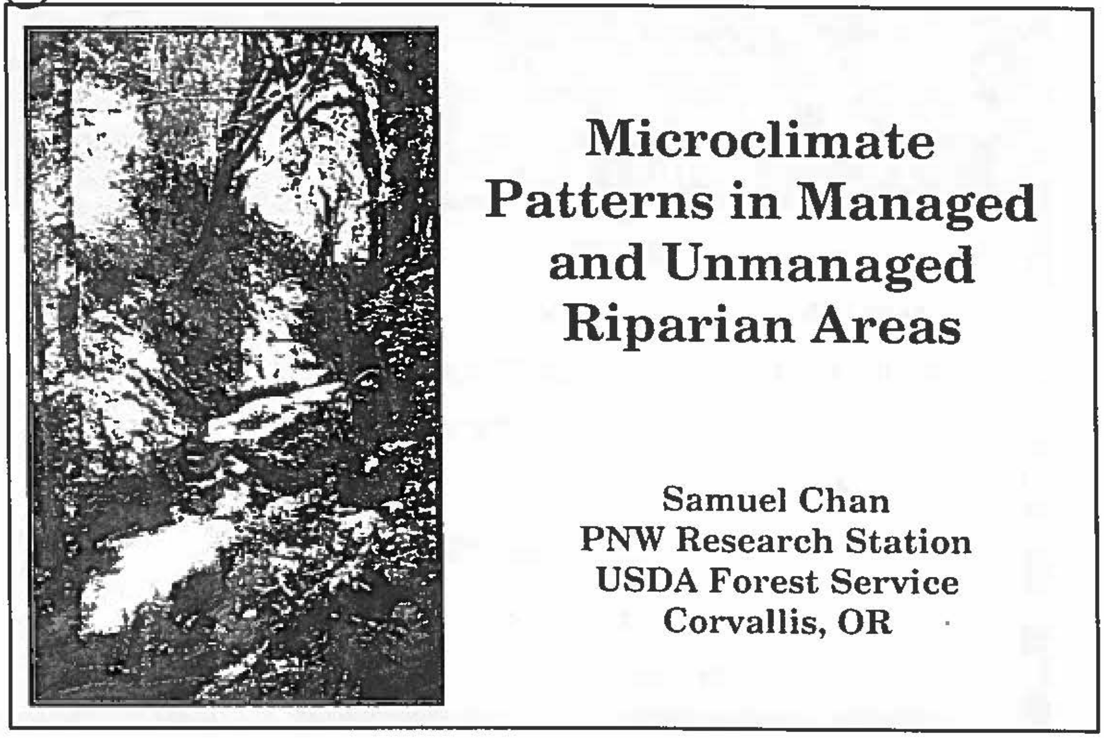
Comparison of Relative Humidity Gradients of Riparian Buffers in Different Studies Conducted in the Pacific Northwest

⑱



Gradients in Relative Humidity in Relation to Distance From the Stream in Thinned Versus Unthinned Headwater Forests of Western Oregon

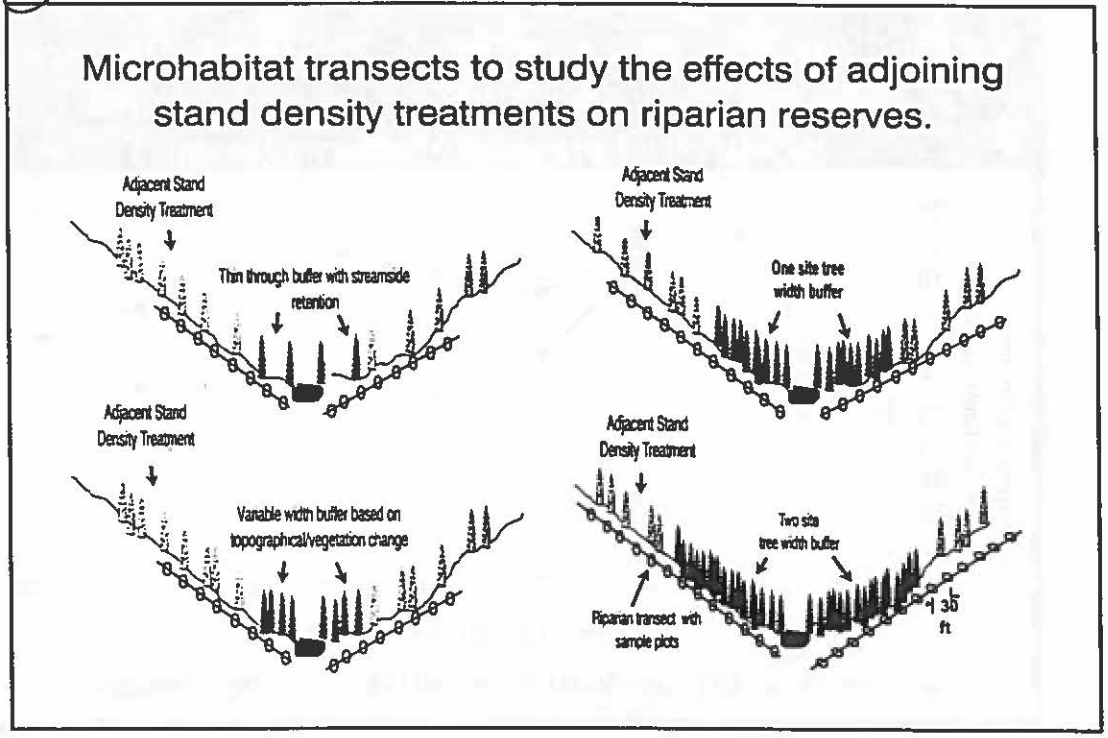
19



Microclimate Patterns in Managed and Unmanaged Riparian Areas

Samuel Chan
PNW Research Station
USDA Forest Service
Corvallis, OR

20

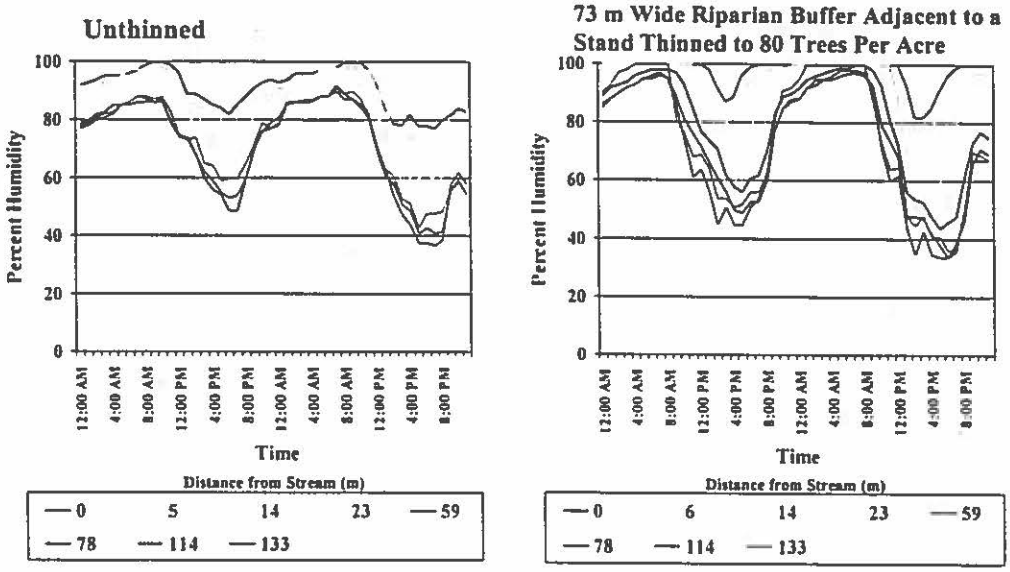


Microhabitat transects to study the effects of adjoining stand density treatments on riparian reserves.

45

(21)

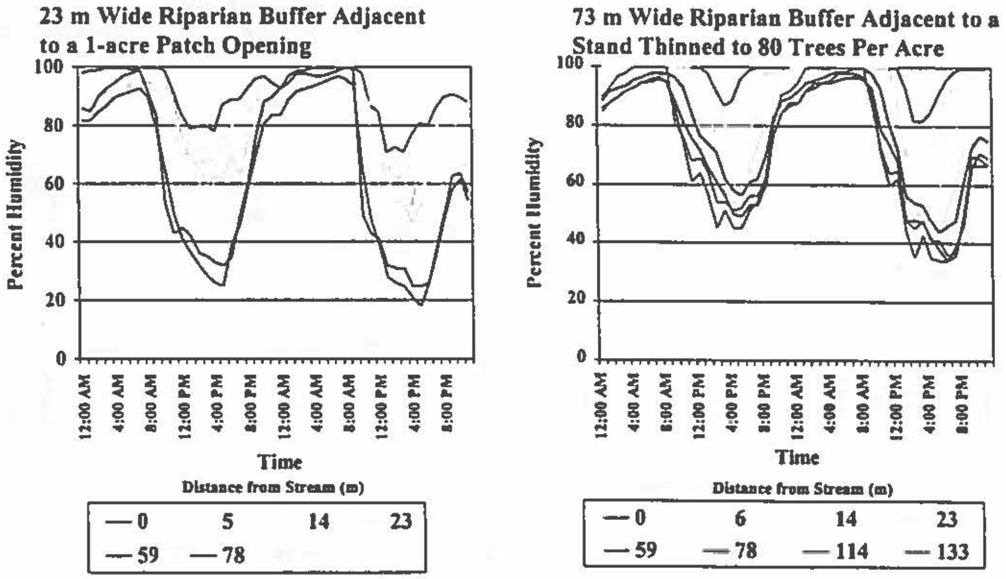
Keel Mountain Humidity


Unthinned

73 m Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre

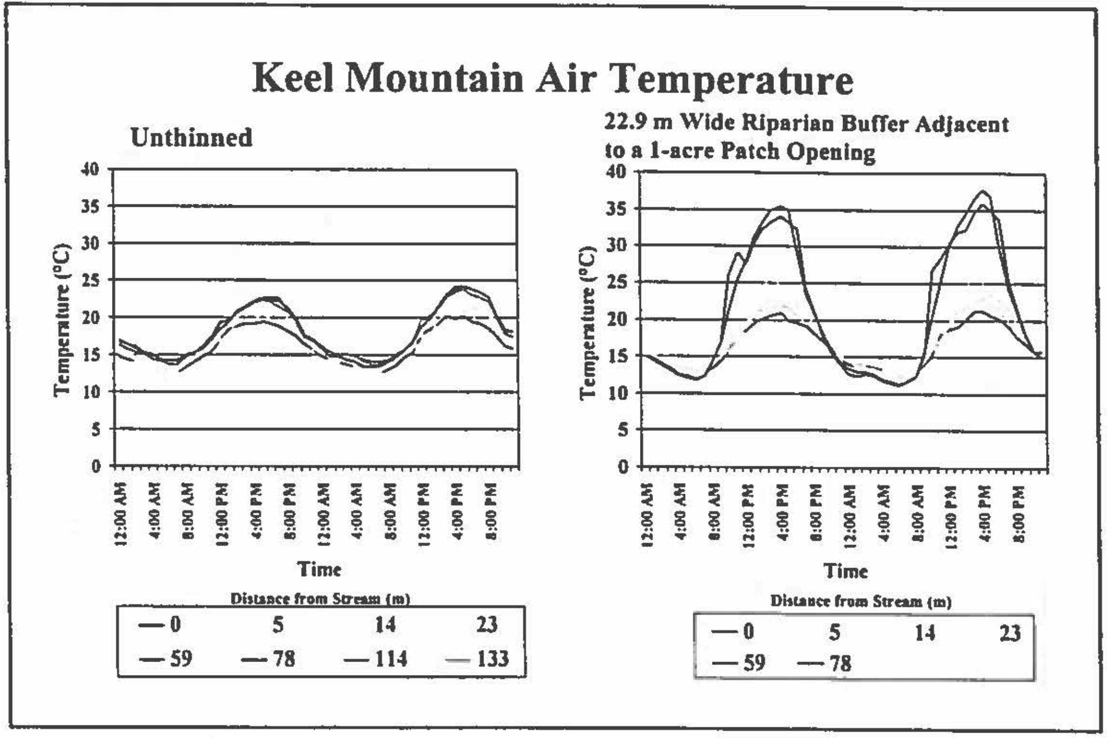
(22)

Keel Mountain Humidity


23 m Wide Riparian Buffer Adjacent to a 1-acre Patch Opening

73 m Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre

23

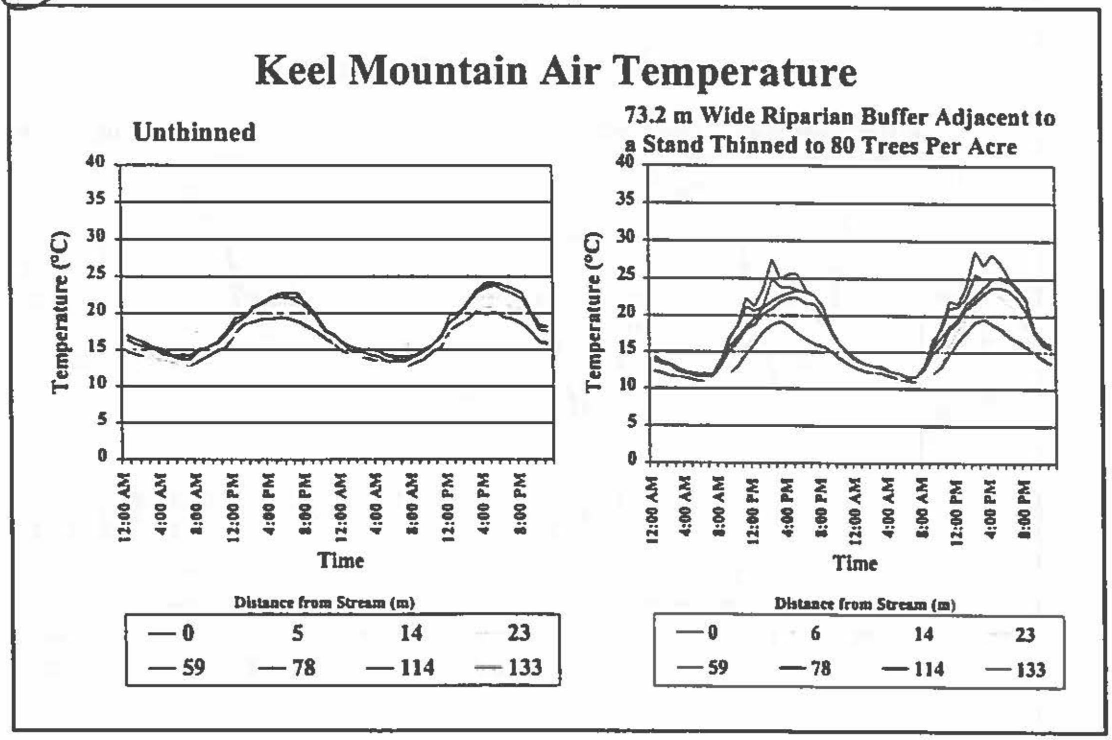


Keel Mountain Air Temperature

Unthinned

22.9 m Wide Riparian Buffer Adjacent to a 1-acre Patch Opening

24

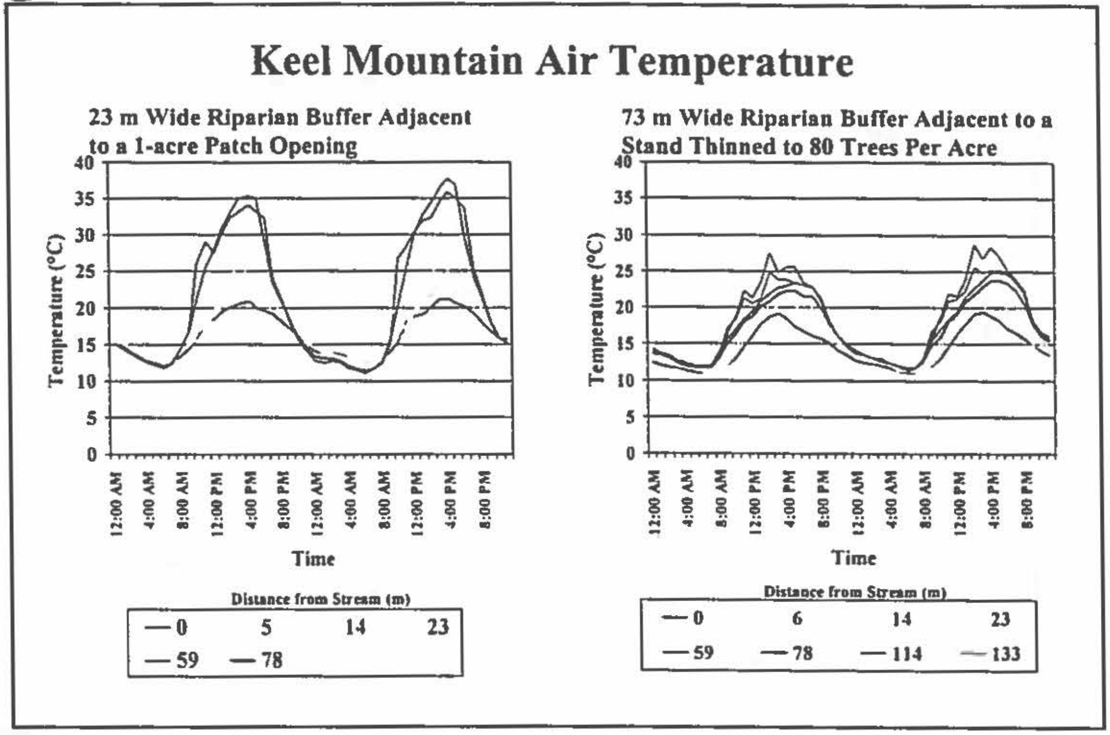


Keel Mountain Air Temperature

Unthinned

73.2 m Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre

25

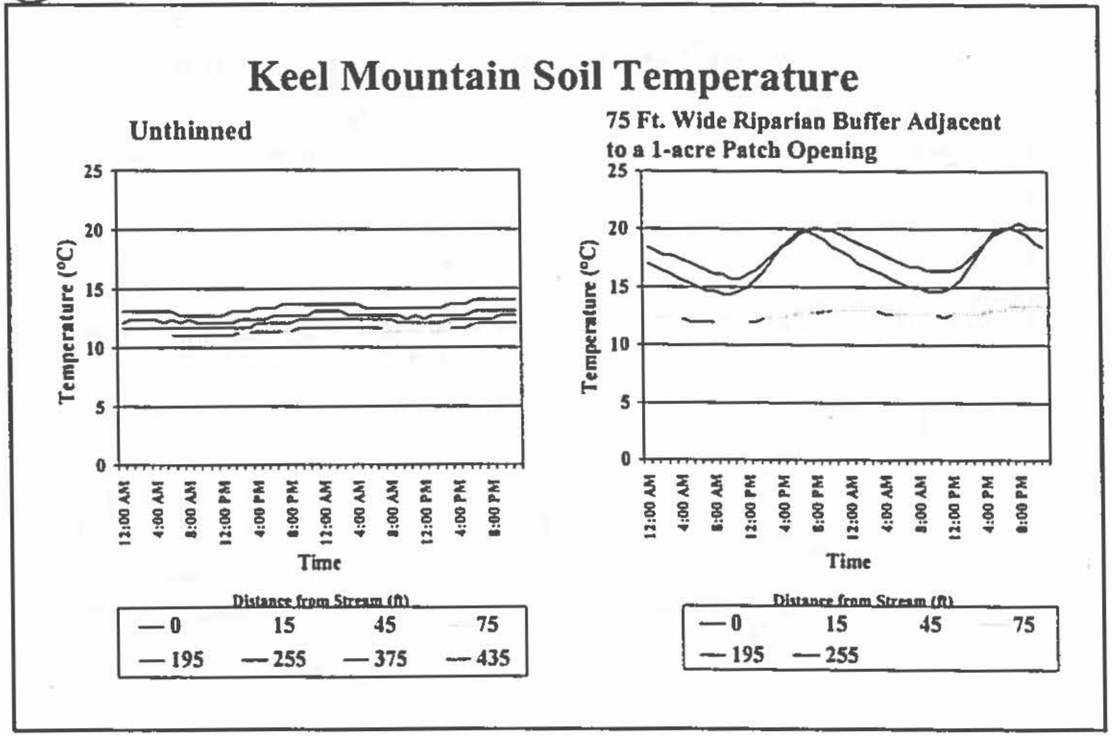


Keel Mountain Air Temperature

23 m Wide Riparian Buffer Adjacent to a 1-acre Patch Opening

73 m Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre

26



Keel Mountain Soil Temperature

Unthinned

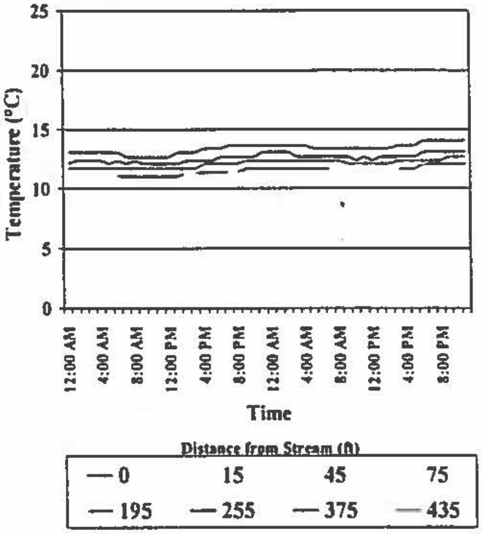
75 Ft. Wide Riparian Buffer Adjacent to a 1-acre Patch Opening

48

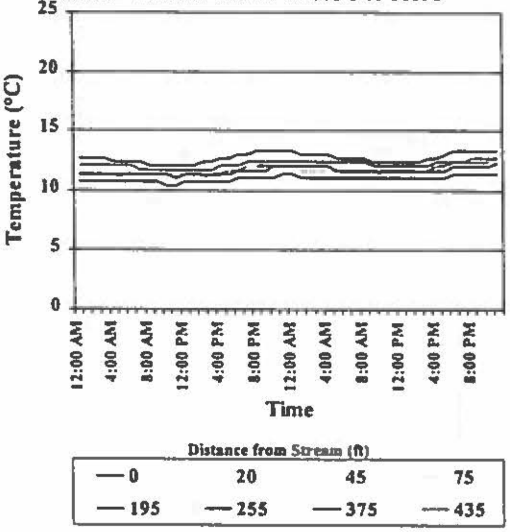
27

Keel Mountain Soil Temperature

Unthinned



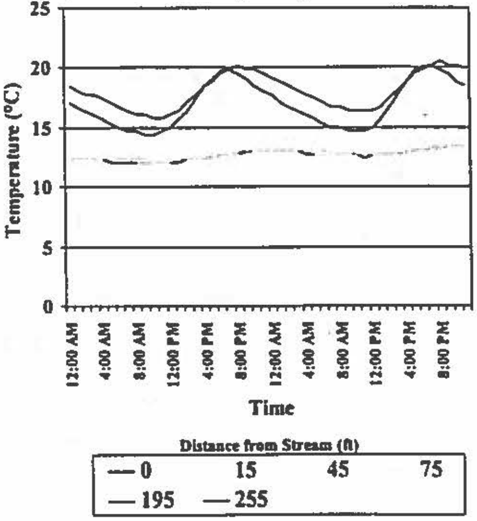
240 Ft. Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre



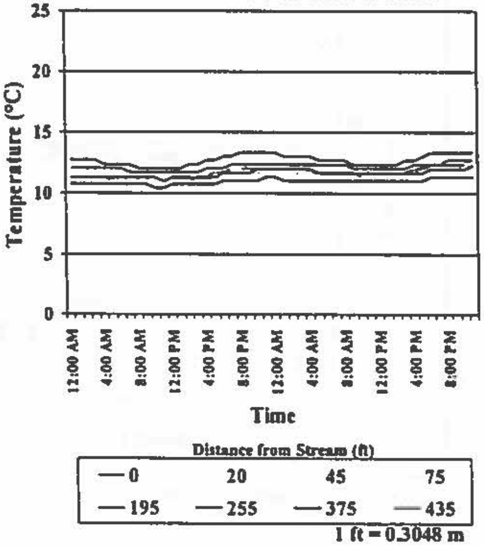
28

Keel Mountain Soil Temperature

75 Ft. Wide Riparian Buffer Adjacent to a 1-acre Patch Opening



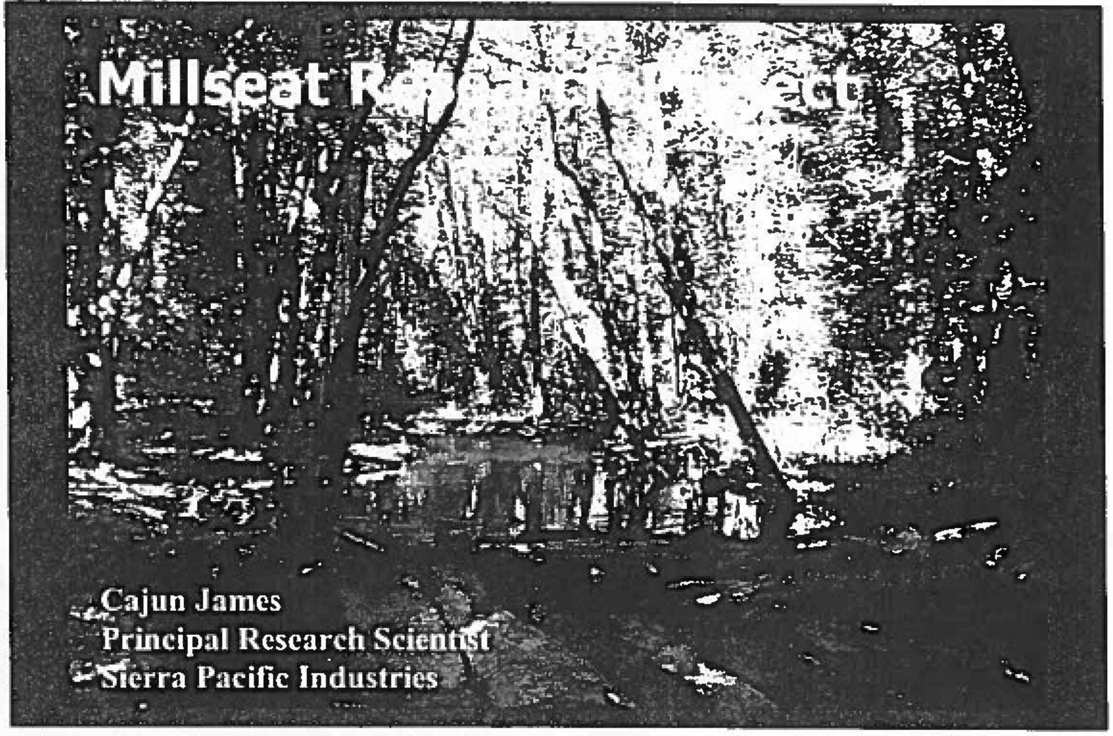
240 Ft. Wide Riparian Buffer Adjacent to a Stand Thinned to 80 Trees Per Acre



1 ft = 0.3048 m

49

(29)



Millseat R[illegible]ct

Cajun James
Principal Research Scientist
Sierra Pacific Industries

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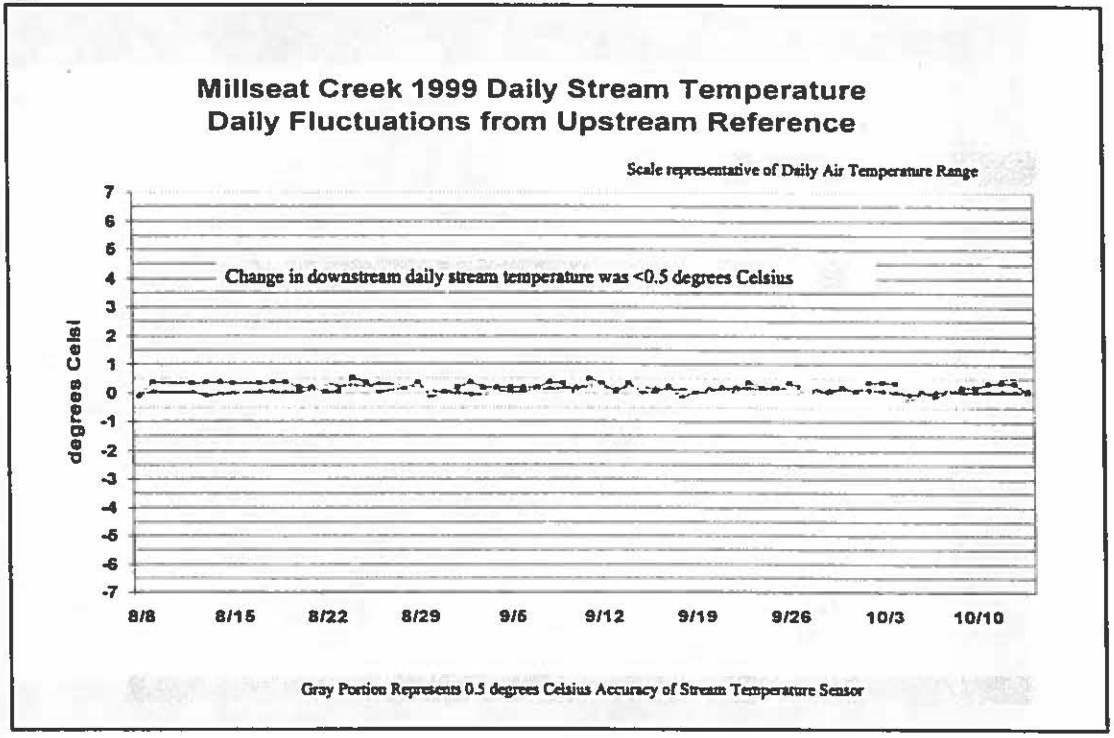


Millseat Creek 1999 Daily Stream Temperature
Daily Fluctuations from Upstream Reference

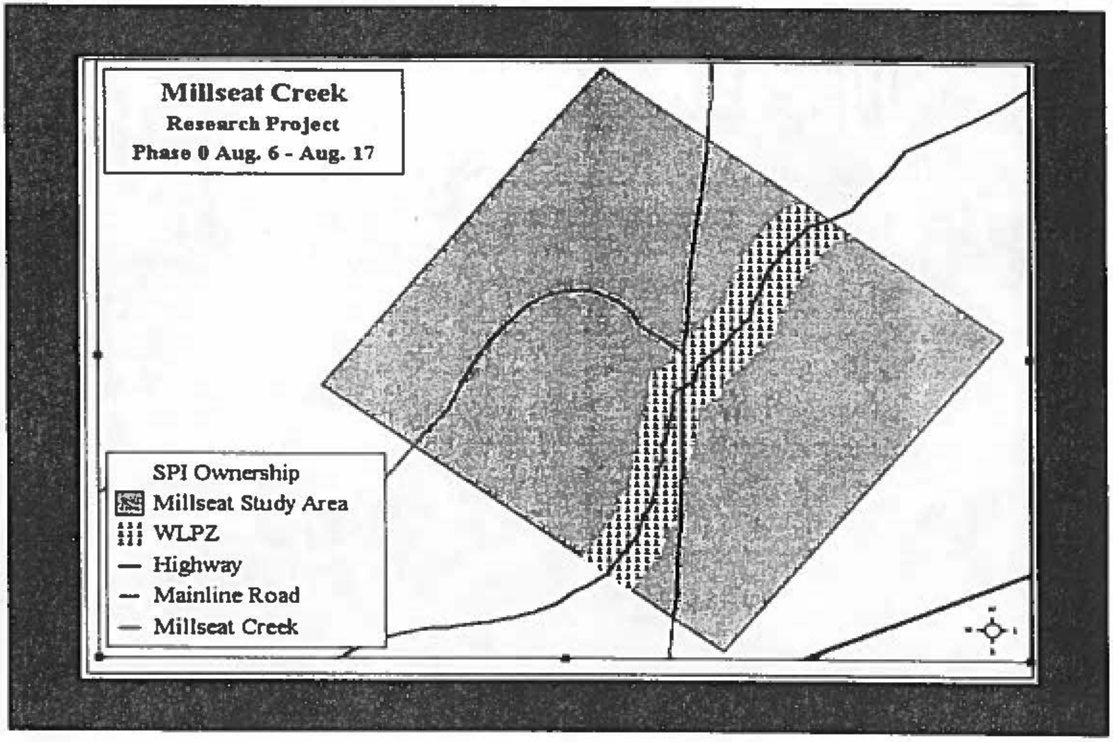
Scale representative of Daily Air Temperature Range

Change in downstream daily stream temperature was <0.5 degrees Celsius

Gray Portion Represents 0.5 degrees Celsius Accuracy of Stream Temperature Sensor

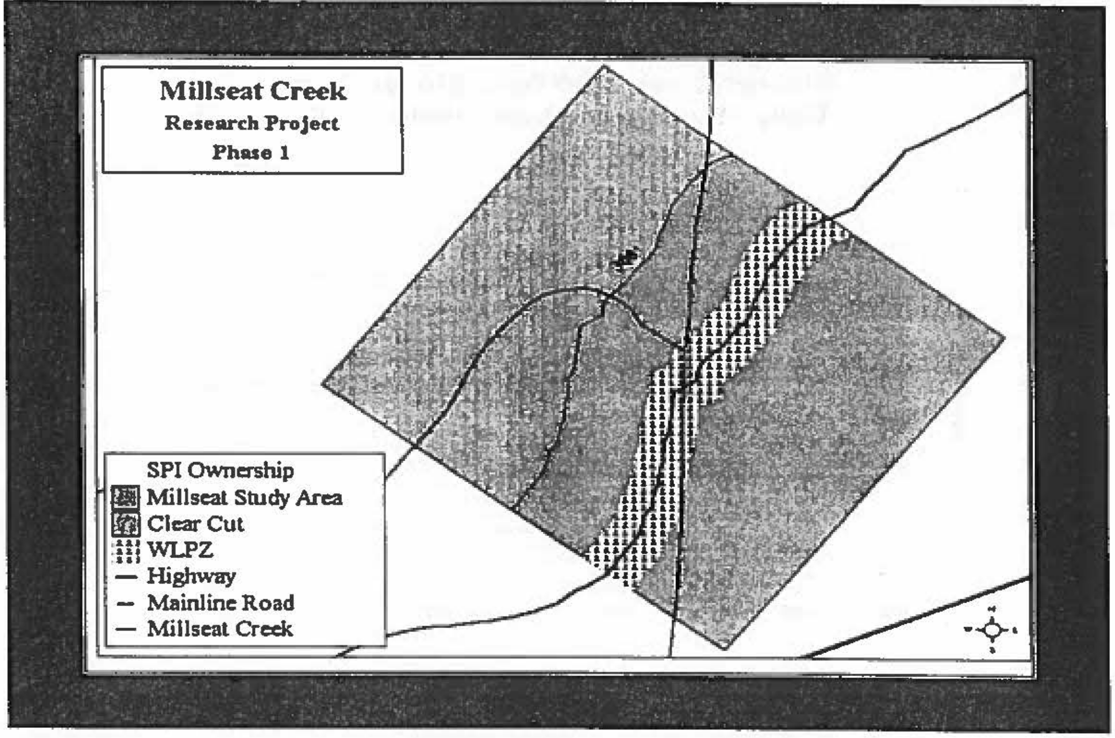
56

(31)



Millseat Creek
Research Project
Phase 0 Aug. 6 - Aug. 17

(32)



Millseat Creek
Research Project
Phase 1

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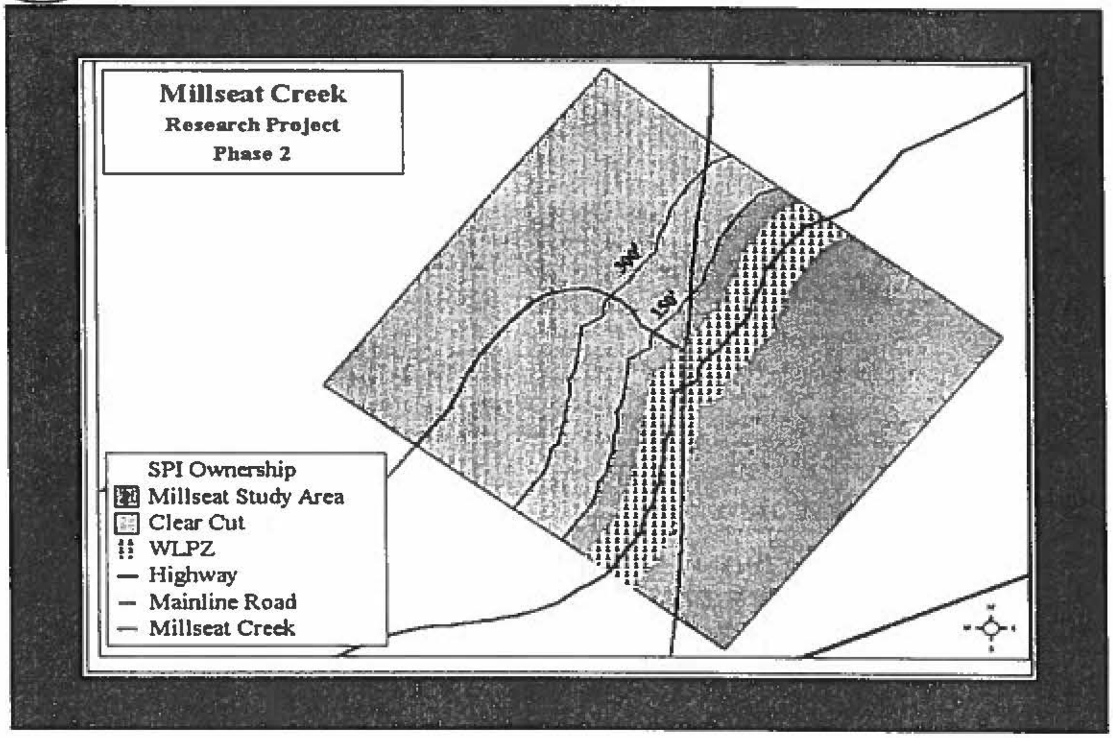

Millseat Creek
Research Project
Phase 2

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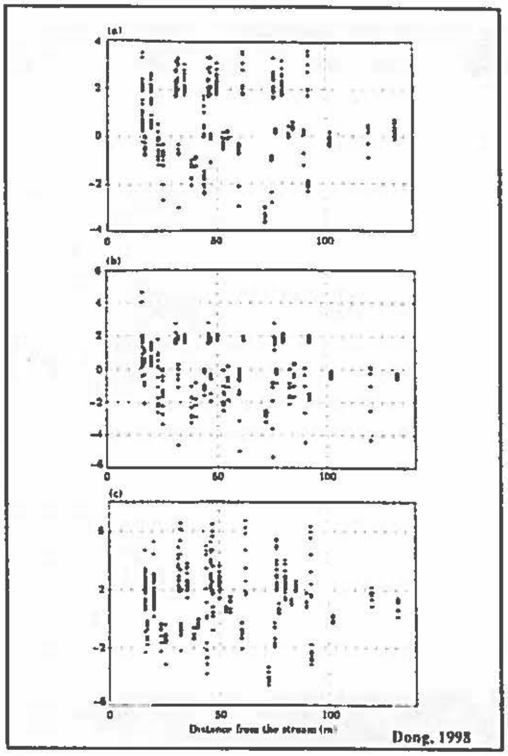
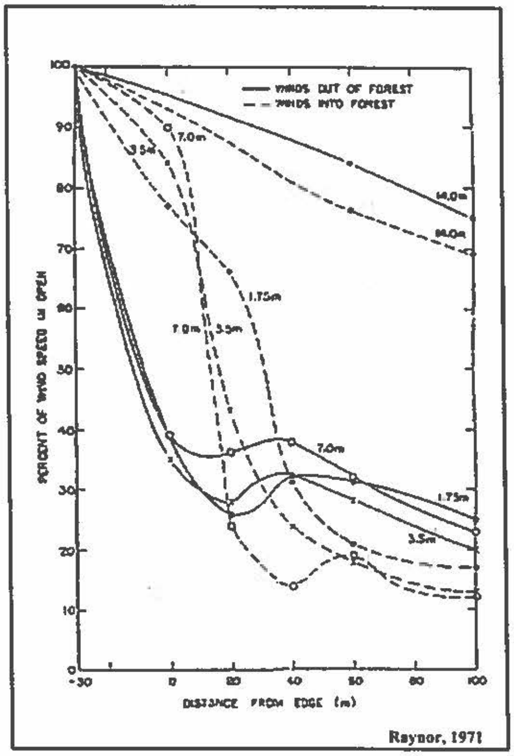


Dong, 1998

②



Raynor, 1971

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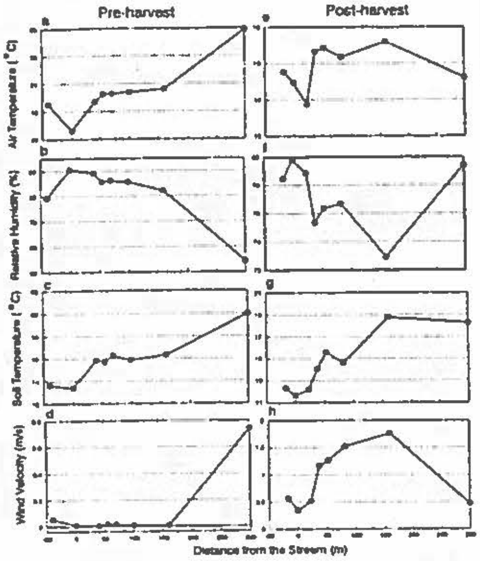

Chen et al, 1999

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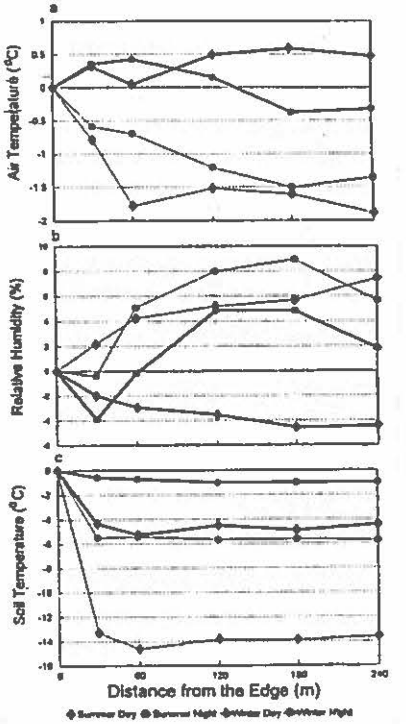

Chen et al, 1999

54

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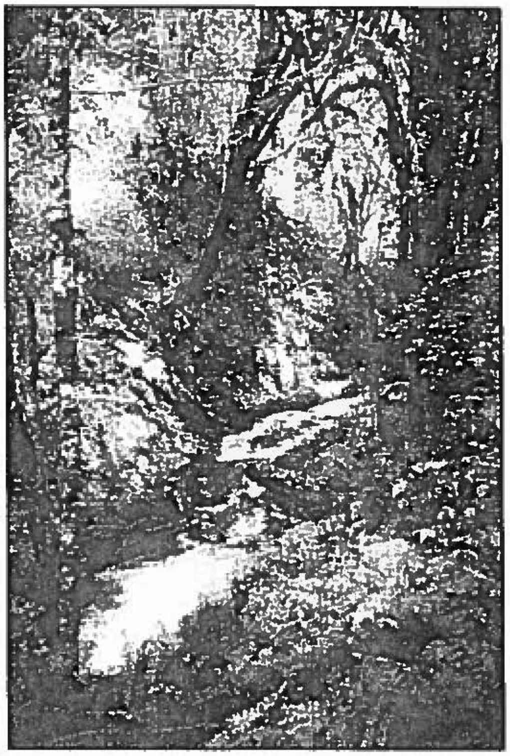

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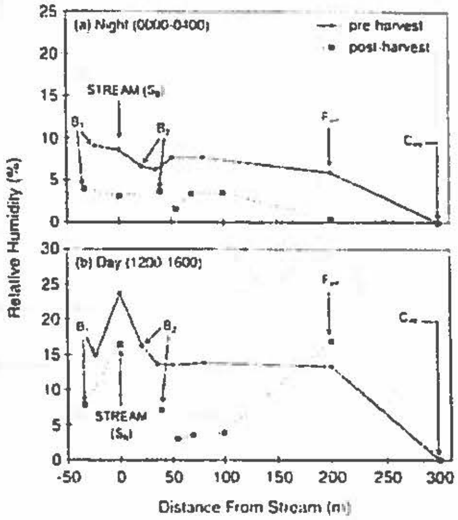

Brosofske et al, 1997

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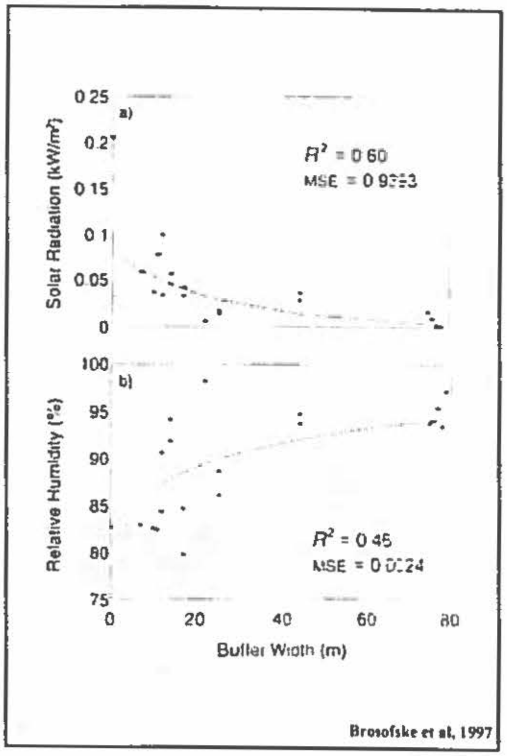

Brosofske et al, 1997

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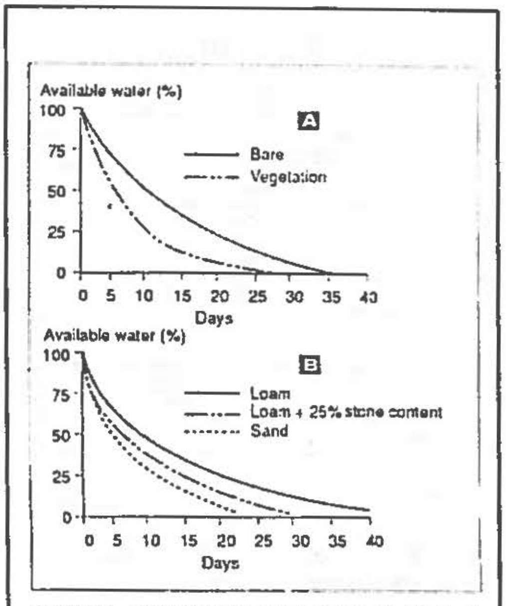

FIGURE 6. Available water in the surface 20 cm of soil decreases with time through evapotranspiration and lack of rain. (A) Competing vegetation dries the soil, reducing the amount of water available to seedlings. (B) Soil texture and stone content affect the amount of water that can be stored in the soil.

Stathers et al, 1992

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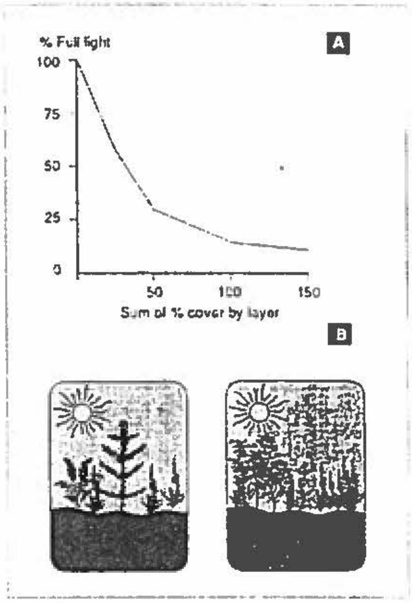

FIGURE 2 (A) Increasing vegetation cover reduces the intensity of light beneath the vegetation. Seedling photosynthesis will be significantly reduced by greater than 50% cover. Vegetation press will also be a problem. (B) Seeding growth form is poor under heavy shade

Stathers et al, 1992

(10)

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57

①

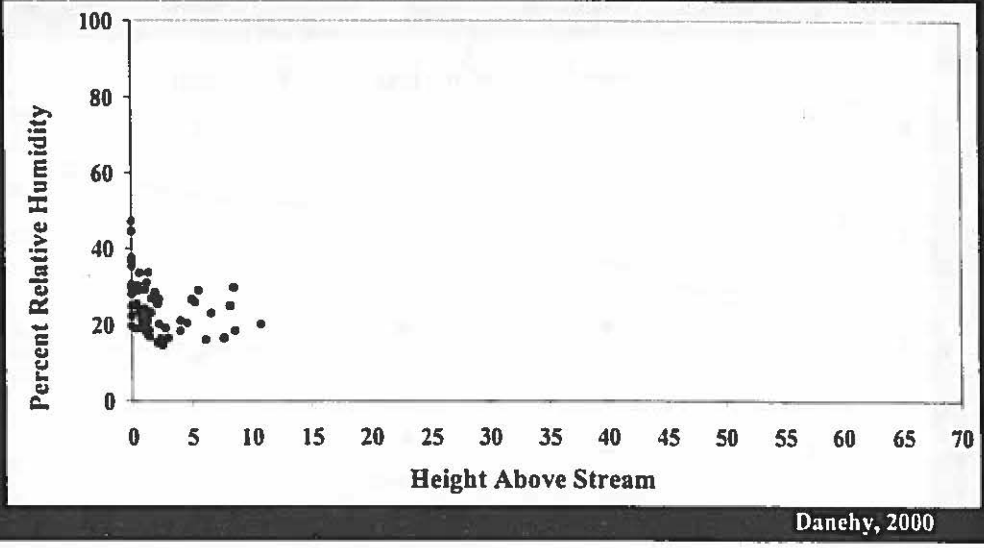
Microclimate Characteristics of Transect 3B 1.0 meter height at Callahan Creek (PM)

	Total Radiation ($w/m^2/sec$)	PAR ($\mu mole/m^2/sec$)	Soil Temp. (°C)	Air Temp. (°C)	Relative Humidity (%)
FORESTED	34	9	18	25	66
CLEARCUT	893	1809	17	30	42
STREAM	59	8	16*	23	72

* streambed temperature

②

Relationships Between Height Above Stream and Minimum Relative Humidity in Thinned Forest Stands of Eastern Oregon and Washington



Danehy, 2000

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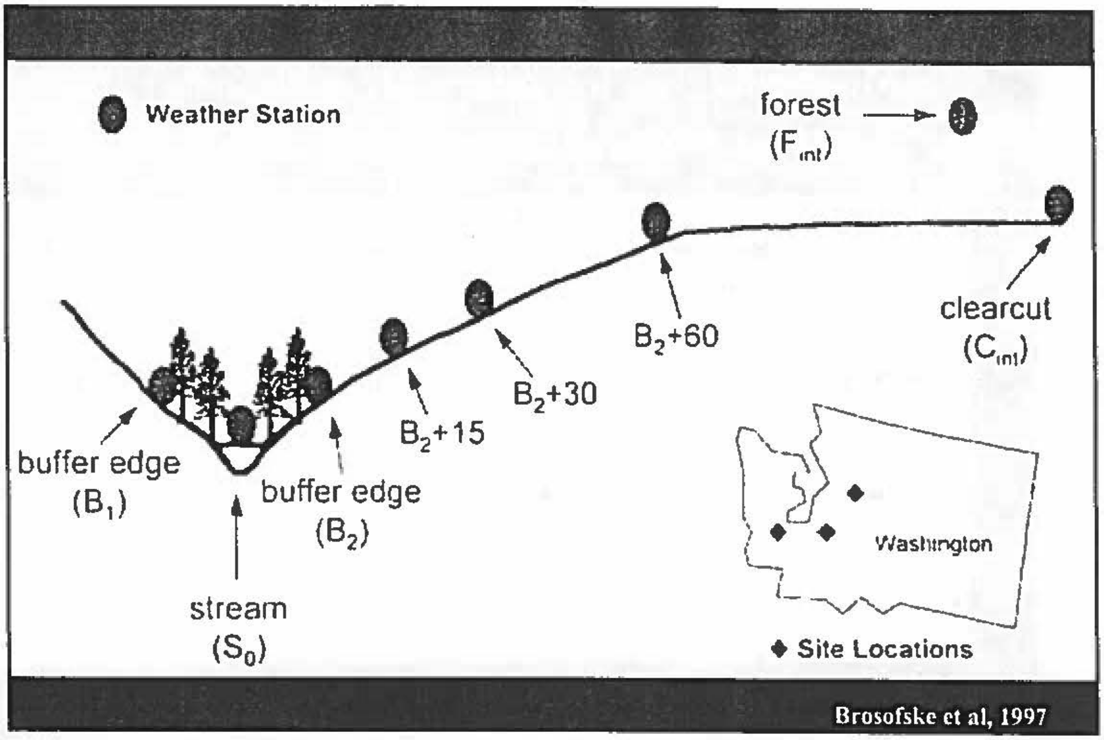
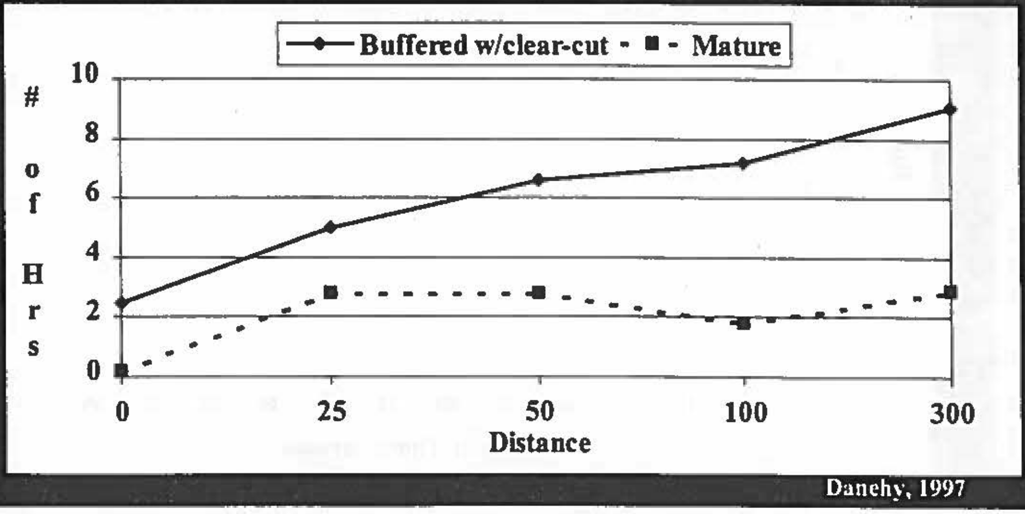


Brosofske et al, 1997

④

Mean minimum daily number of hours relative humidity was less than 50% at a treatment with a 50 ft. buffer between a clear-cut and at a treatment with mature tree cover on the Siletz River.



Danehy, 1997

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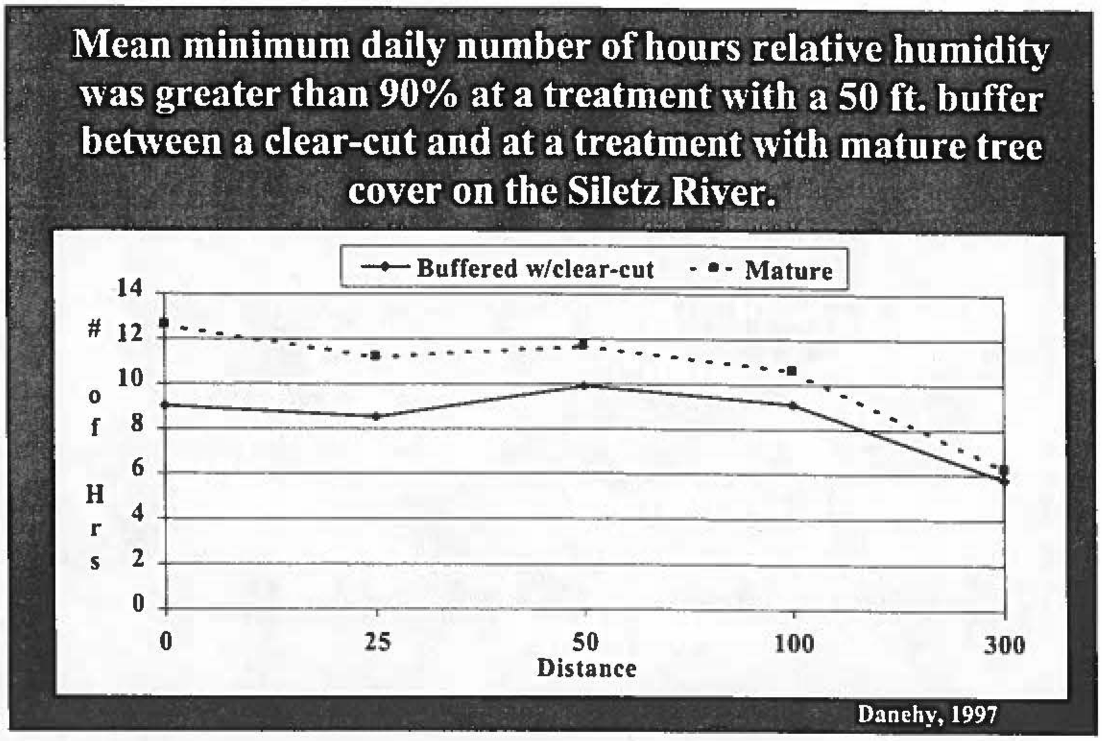

Mean minimum daily number of hours relative humidity was greater than 90% at a treatment with a 50 ft. buffer between a clear-cut and at a treatment with mature tree cover on the Siletz River.

Danehy, 1997

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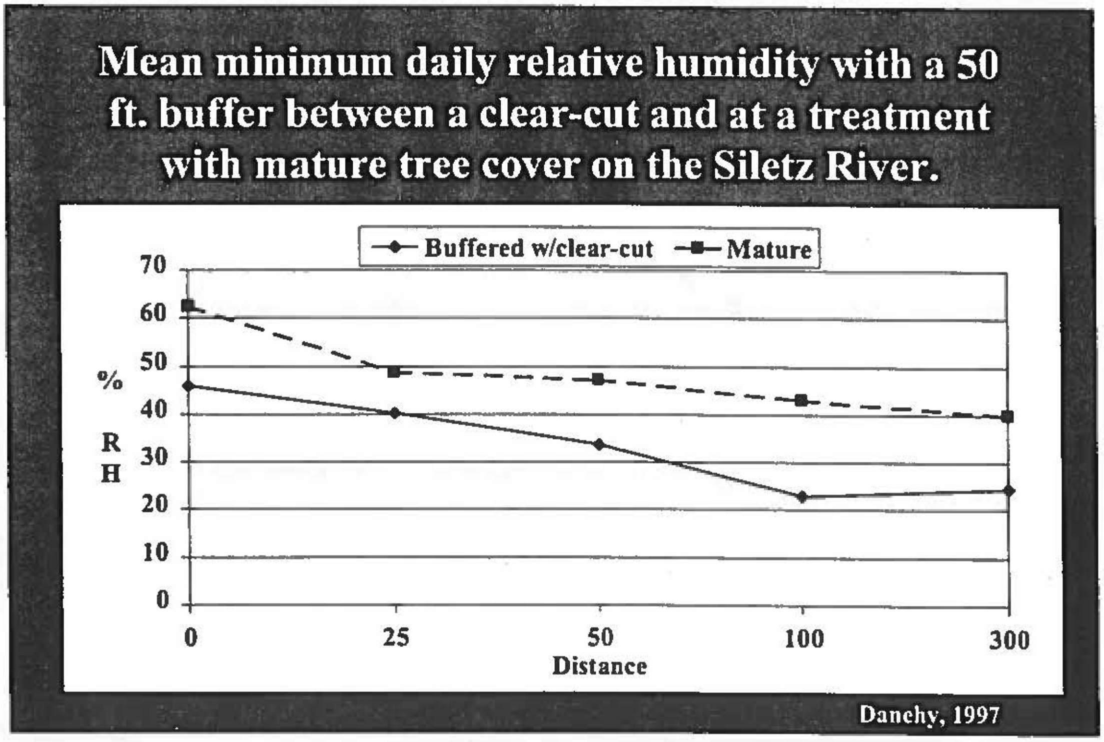

Mean minimum daily relative humidity with a 50 ft. buffer between a clear-cut and at a treatment with mature tree cover on the Siletz River.

Danehy, 1997

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Forest Microclimate

- Solar radiation
- Precipitation
- Air Humidity
- Wind
- Air Temperature
- Soil Moisture
- Soil Temperature

⑧

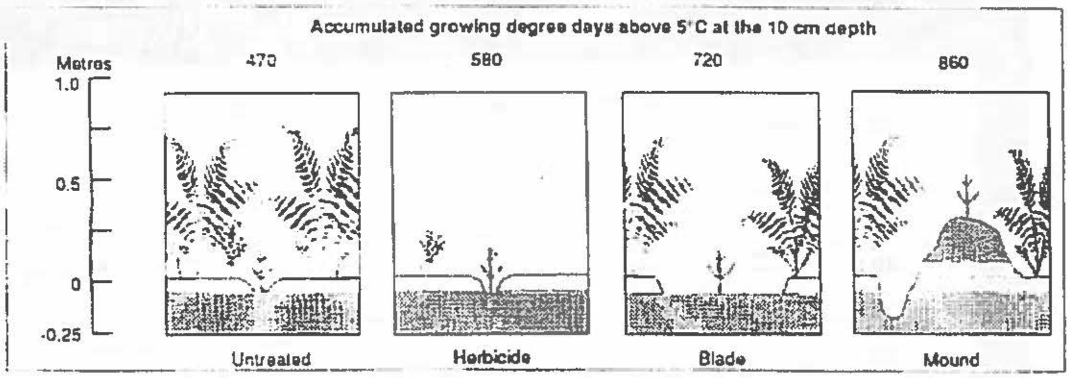
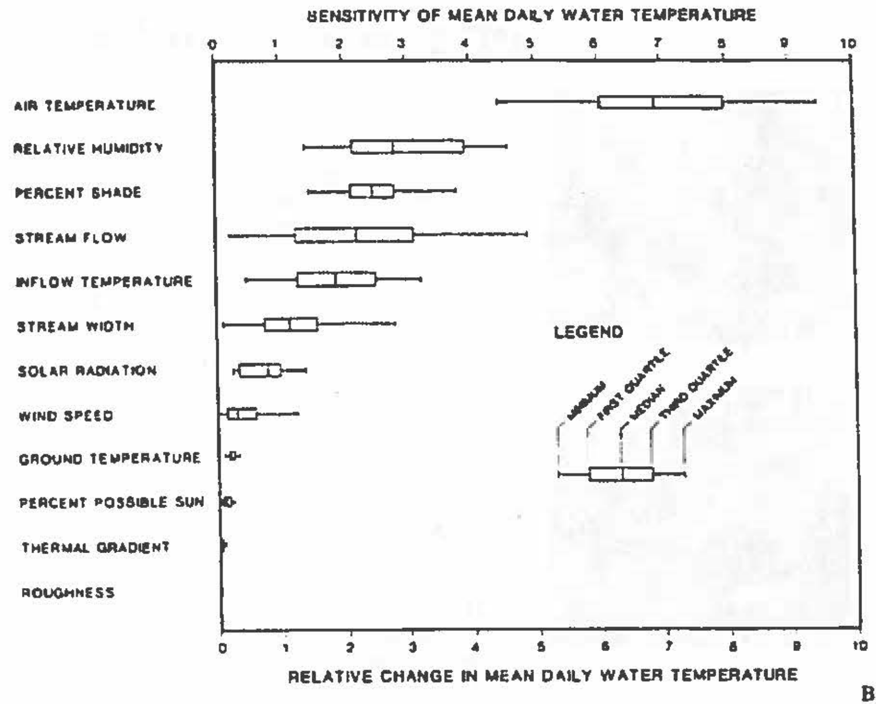


FIGURE 8 Site preparation improves soil warming at a wet Sub-Boreal Spruce site. Mounding provides the greatest accumulation of heat by exposing mineral soil (removing shade and insulation) and improving soil drying (drainage) and heating. The blade treatment exposes mineral soil, but does not provide as good drying as mounding. The herbicide treatment only removes the shading vegetation. Hatching indicates organic material; shading indicates mineral soil.

Stathers et al, 1992

(9)



Bartholow, 1989

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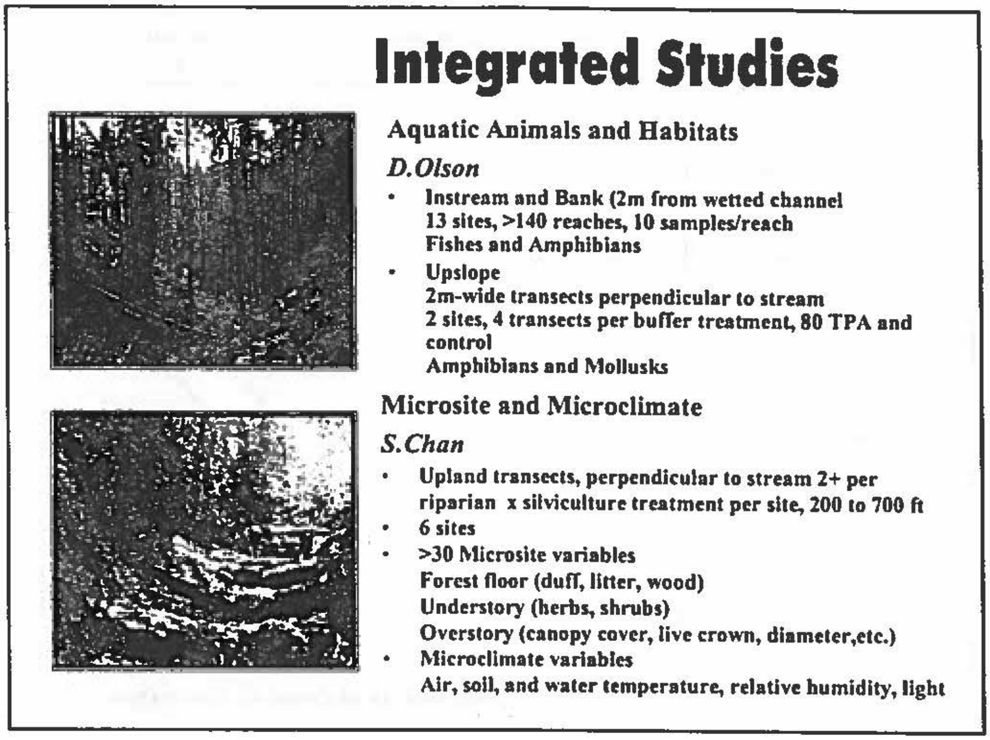


Integrated Studies

Aquatic Animals and Habitats

D.Olson

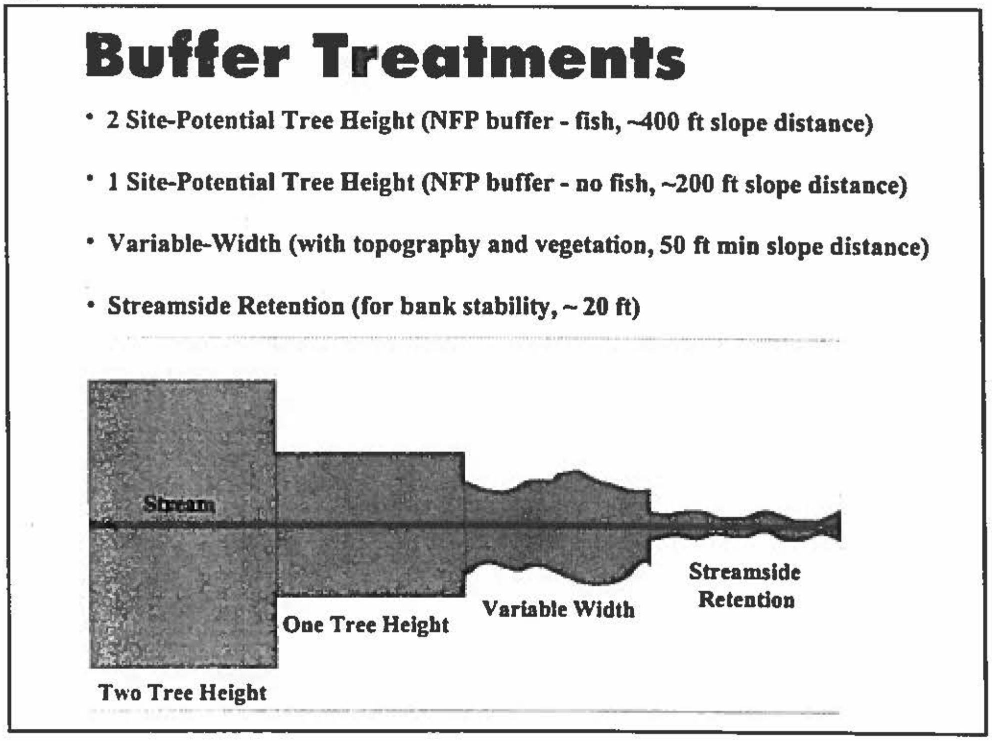
- **Instream and Bank (2m from wetted channel**
  13 sites, >140 reaches, 10 samples/reach
  Fishes and Amphibians
- **Upslope**
  2m-wide transects perpendicular to stream
  2 sites, 4 transects per buffer treatment, 80 TPA and control
  Amphibians and Mollusks

Microsite and Microclimate

S.Chan

- **Upland transects, perpendicular to stream 2+ per riparian x silviculture treatment per site, 200 to 700 ft**
- **6 sites**
- **>30 Microsite variables**
  Forest floor (duff, litter, wood)
  Understory (herbs, shrubs)
  Overstory (canopy cover, live crown, diameter,etc.)
- **Microclimate variables**
  Air, soil, and water temperature, relative humidity, light

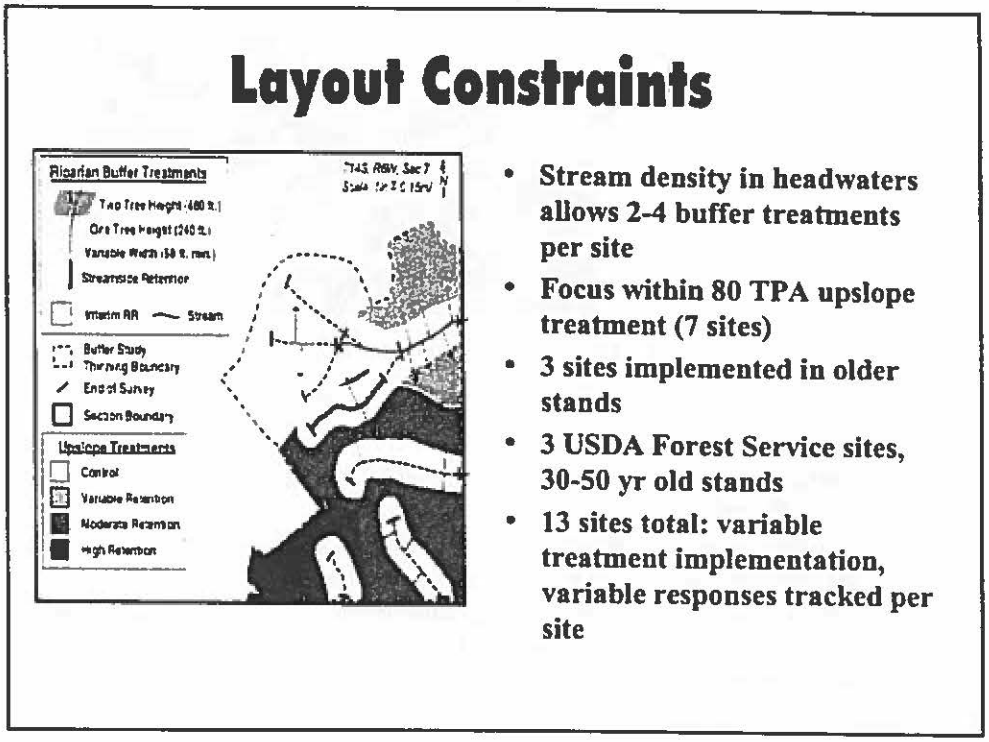
②



Buffer Treatments

- **2 Site-Potential Tree Height (NFP buffer - fish, ~400 ft slope distance)**
- **1 Site-Potential Tree Height (NFP buffer - no fish, ~200 ft slope distance)**
- **Variable-Width (with topography and vegetation, 50 ft min slope distance)**
- **Streamside Retention (for bank stability, ~ 20 ft)**

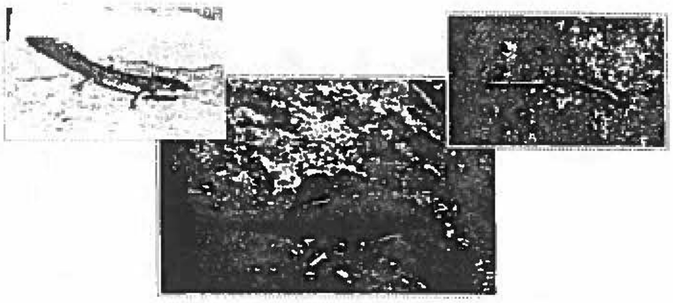
③



Layout Constraints

- Stream density in headwaters allows 2-4 buffer treatments per site
- Focus within 80 TPA upslope treatment (7 sites)
- 3 sites implemented in older stands
- 3 USDA Forest Service sites, 30-50 yr old stands
- 13 sites total: variable treatment implementation, variable responses tracked per site

①



Perennial Streams and Banks: a Diverse Community

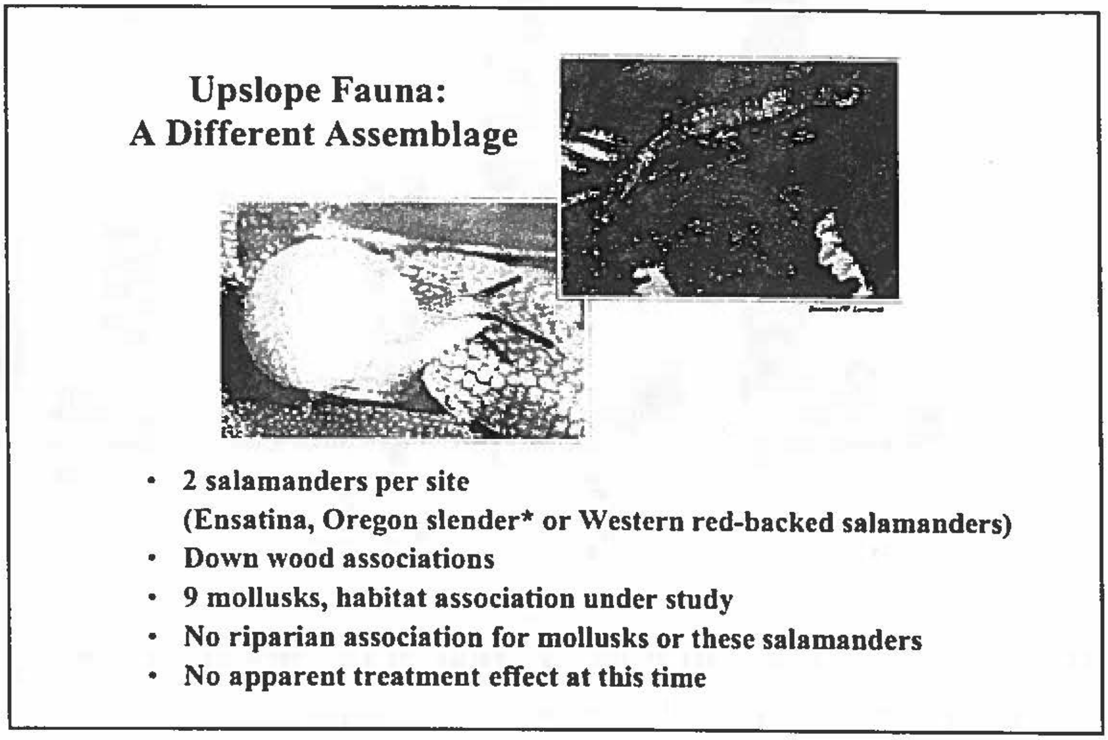
- **16 fish and amphibian spp observed**
- **Cutthroat trout*, Sculpin, Pacific Giant salamander dominate instream assemblages**
- **Dunn's salamander, Western red-backed salamander dominate streambank assemblages (also along discontinuous streams)**
- **Tailed frog*, 4 spp pond breeding amphibian*, 3 spp terrestrial salamander* and lamprey incidentally captured**
- **Variable treatment responses at this time**

②

Leave Island Study: 2001 Study Proposal

- **Examines roles of leave islands in managed forests**
- **Potential "Lifeboats" for low mobility species: Vascular plants, lichens, bryophytes, salamanders, mollusks**
- **Potential key ecological functions for other taxa: small mammals, birds, macroinvertebrates**

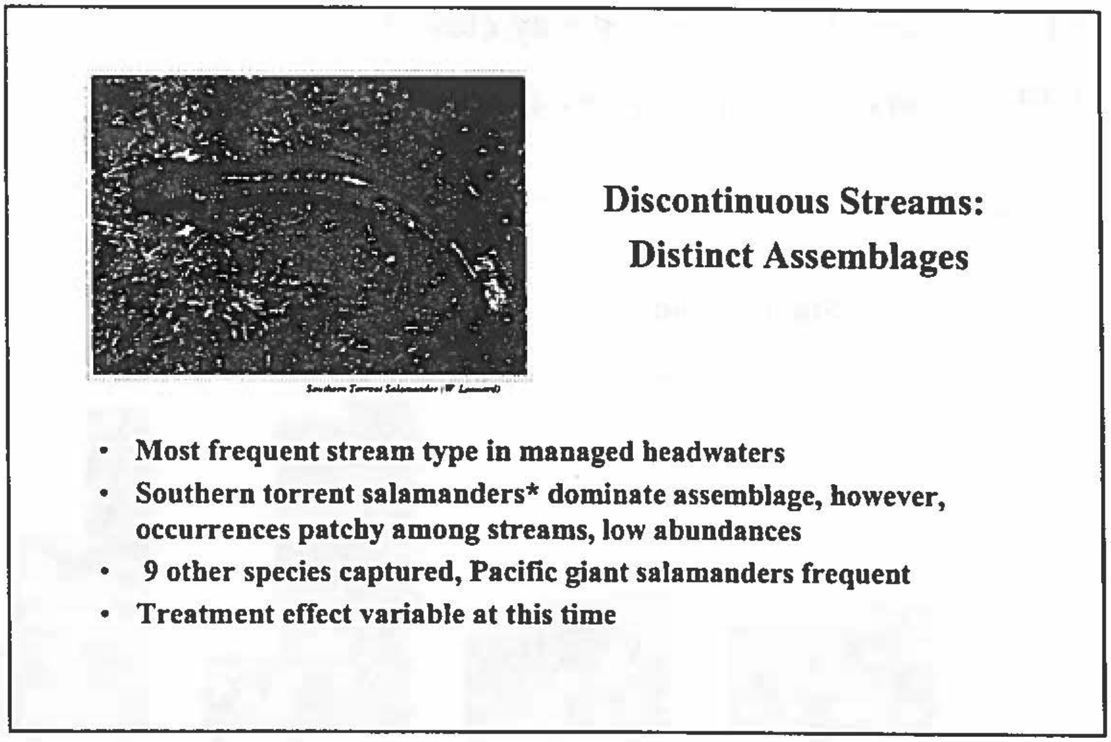
①



Upslope Fauna: A Different Assemblage

- 2 salamanders per site
  (Ensatina, Oregon slender* or Western red-backed salamanders)
- Down wood associations
- 9 mollusks, habitat association under study
- No riparian association for mollusks or these salamanders
- No apparent treatment effect at this time

②



Southern Torrent Salamander (W Leonard)

Discontinuous Streams: Distinct Assemblages

- Most frequent stream type in managed headwaters
- Southern torrent salamanders* dominate assemblage, however, occurrences patchy among streams, low abundances
- 9 other species captured, Pacific giant salamanders frequent
- Treatment effect variable at this time

①

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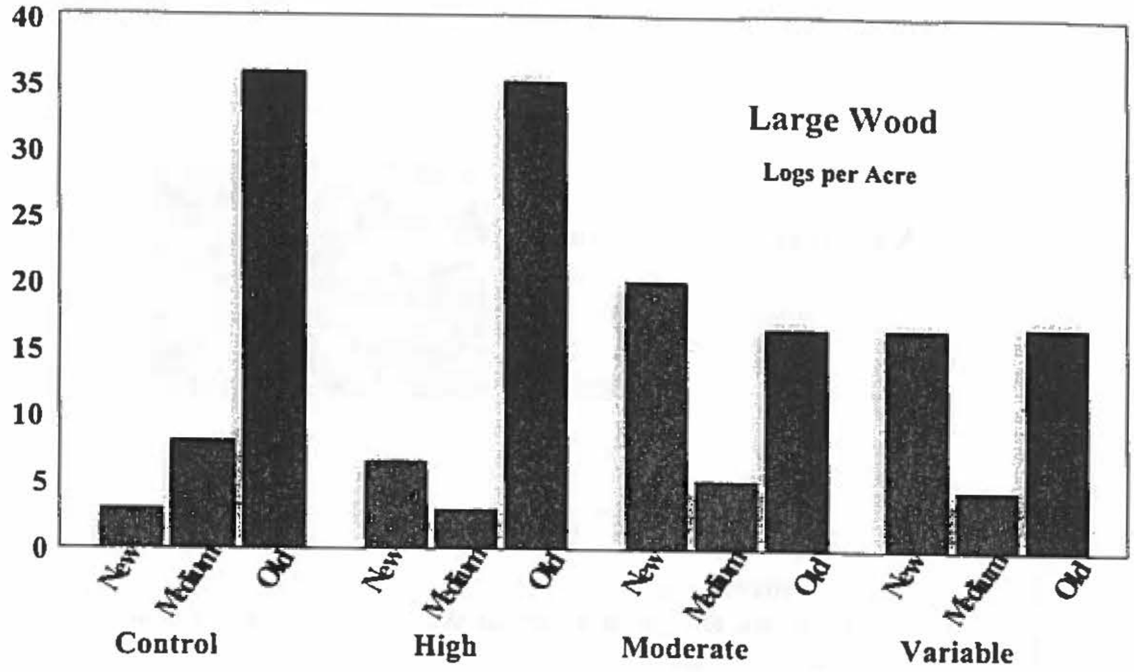


Down wood present in upland areas of the Bottom Line replicate.

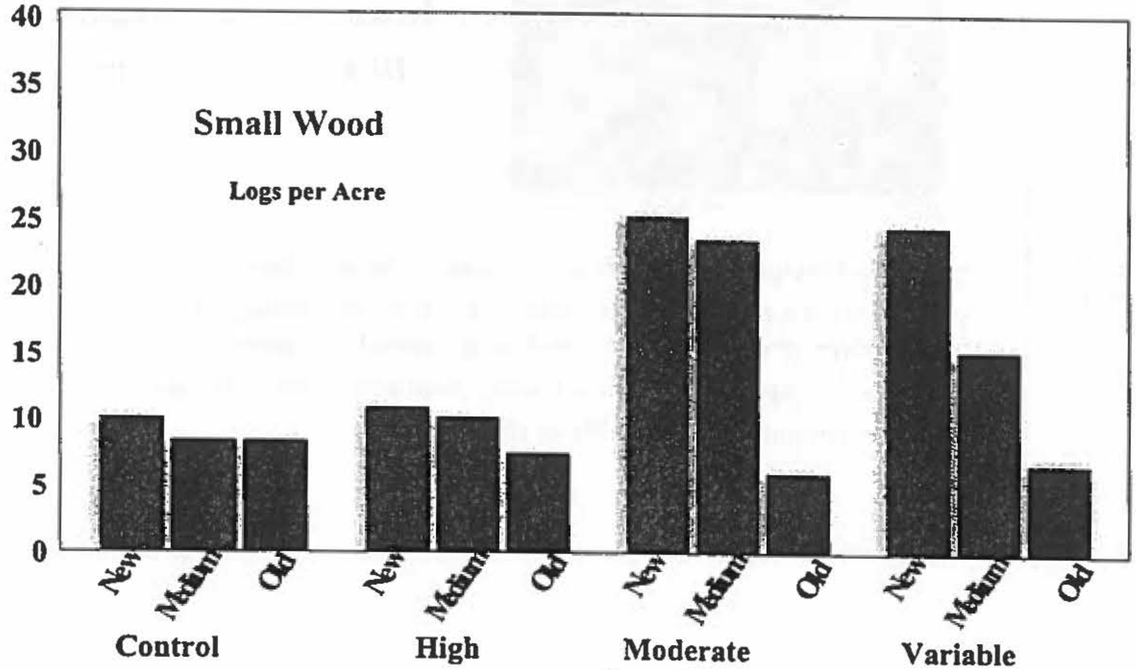
Large wood are logs with large end diameters >10".

Small wood are logs with large end diameters <10".

New logs are in decay classes 1 and 2.

Medium-aged logs are in decay class 3.

Old logs are in decay classes 4 and 5.



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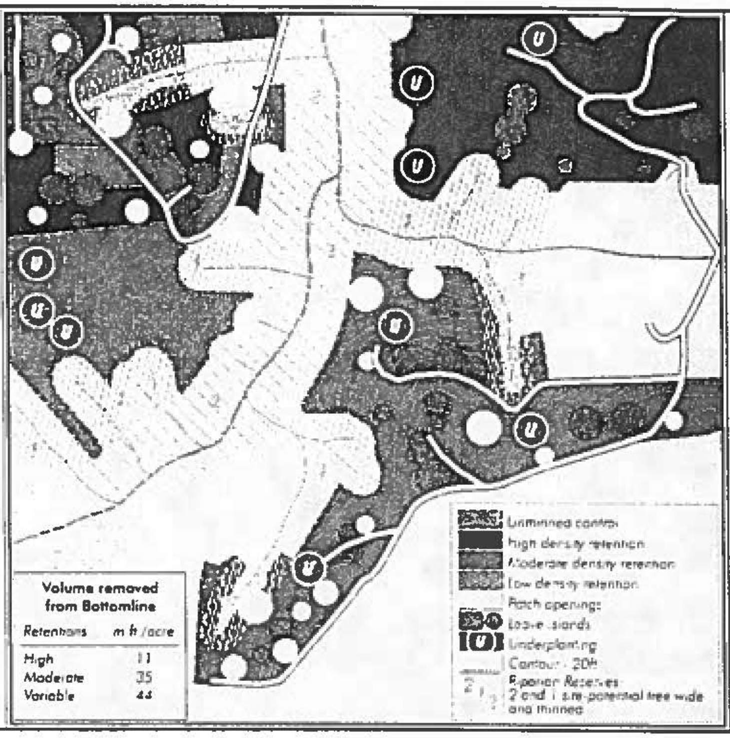
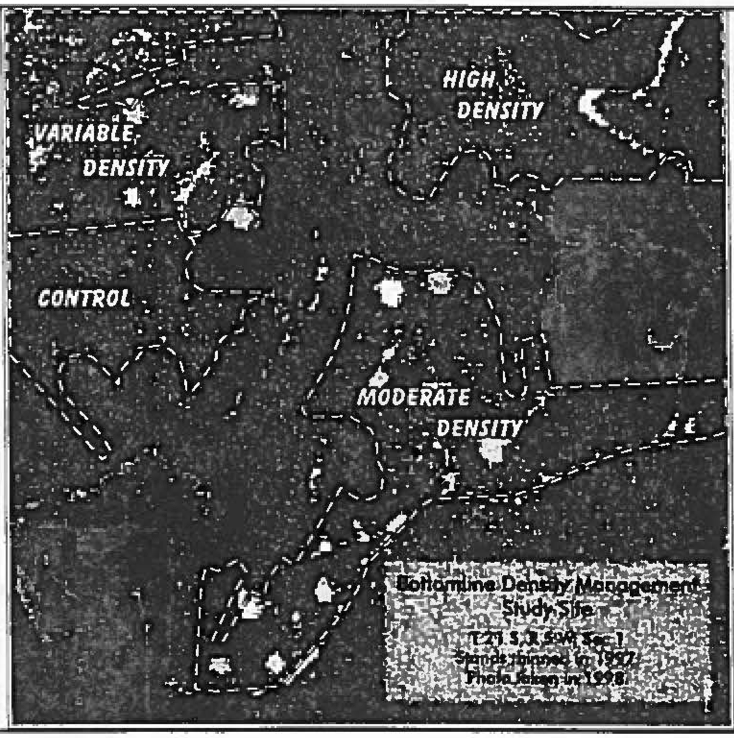


Volume removed from Bottomline

Retentions	m ft /acre
High	11
Moderate	35
Variable	44

②



Bottomline Density Management Study Site

T.27 S., R. 5W, Sec. 1
Stands thinned in 1997
Photo taken in 1998

①

Integrated Components of the Density Management and Riparian Studies

- Stand Dynamics: John Tappeiner, Charley Thompson and Kathleen Mass-Hebner USDI BLM, Oregon State University
- Aquatic Animals and Habitat: Deanna Olson, USDA FS, PNW Research Stn.
- Microsite and Microclimate: Samuel Chan, USDA FS, PNW Research Stn.
- Arthropods and the Riparian Zone: Andy Modenke, Oregon State University
- Bryophytes and Lichens: Pat Muir: Oregon State University

②

Ecology and Management of Headwater Forests (Objectives)

- Characterize the ecological attributes of headwater forests
- Develop methodologies for inventory and monitoring of headwater forests
- Evaluate the ecological roles, opportunities and consequences of silviculture and different buffer strategies in headwater forests.

③

Goals

- Increase our knowledge on the roles of silvicultural manipulation of forest stands to promote stand structure and species complexity in upland and riparian-associated areas.
- Increase stand diversity and structural stability to enhance effectiveness and ability of riparian areas to provide critical riparian and aquatic functions and processes.
- Improve understanding of multiple thinning entries to meet green tree retention management and diversity objectives.
- Evaluate buffers, leave islands, green tree retention, and their spatial distribution as refugia, structural and biological links between riparian areas, headwater forests and uplands.

④

Riparian Silviculture

- Build and enhance connectivity between the riparian areas and uplands including focus on the role and opportunities of silviculture in the management of headwater forests.
- Silvicultural opportunities to enhance function, stability, dynamics, and complexity of forest stands within and on the edges of riparian management zones.
- Silvicultural applications, e.g., for developing a gradient in stand density ("feathered buffers") from streamside into upland stands needs to be explored as an alternative to fixed width buffers with sharply defined edges.
- Tradeoffs between short and long term changes .

⑤

Expectations

Control: development of late-successional characteristics is expected to be much slower than in the other treatments, and will occur through natural processes only.

High Density: will produce some vertical structure but the canopy is expected to close rapidly, which will slow down any further development.

Moderate Density: is expected to develop both vertical and horizontal structure, but development also is expected to slow as the canopy closes.

Variable Density: is expected to maximize the rate and amount of both vertical and horizontal structural development.

⑥

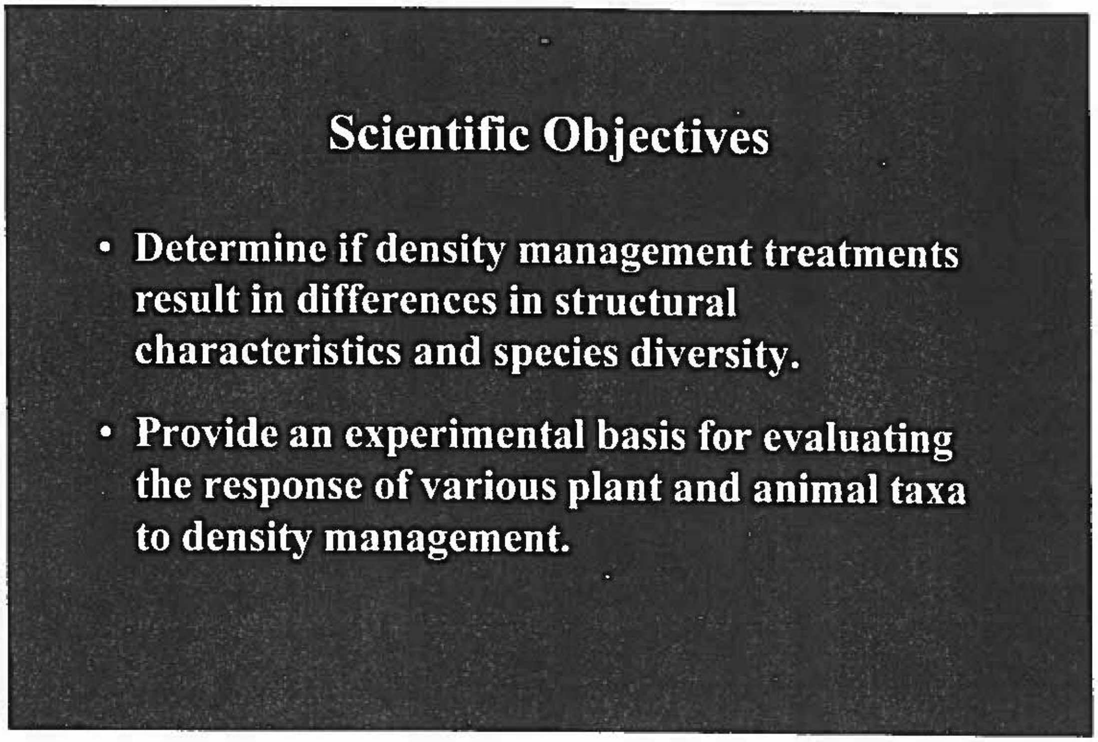
Overarching Questions for the Density Management and Riparian Buffer Studies.

? Can active forest density management within young managed stands, 40 to 50 years old, accelerate the development of late-successional forest conditions?

? Can a variety of silvicultural treatments on an operational scale effectively increase both stand structural and species diversity?

? How can silvicultural treatments in riparian zones and adjacent upland areas balance multiple resource objectives, such as wood production, sensitive species protection and critical riparian functions and processes?

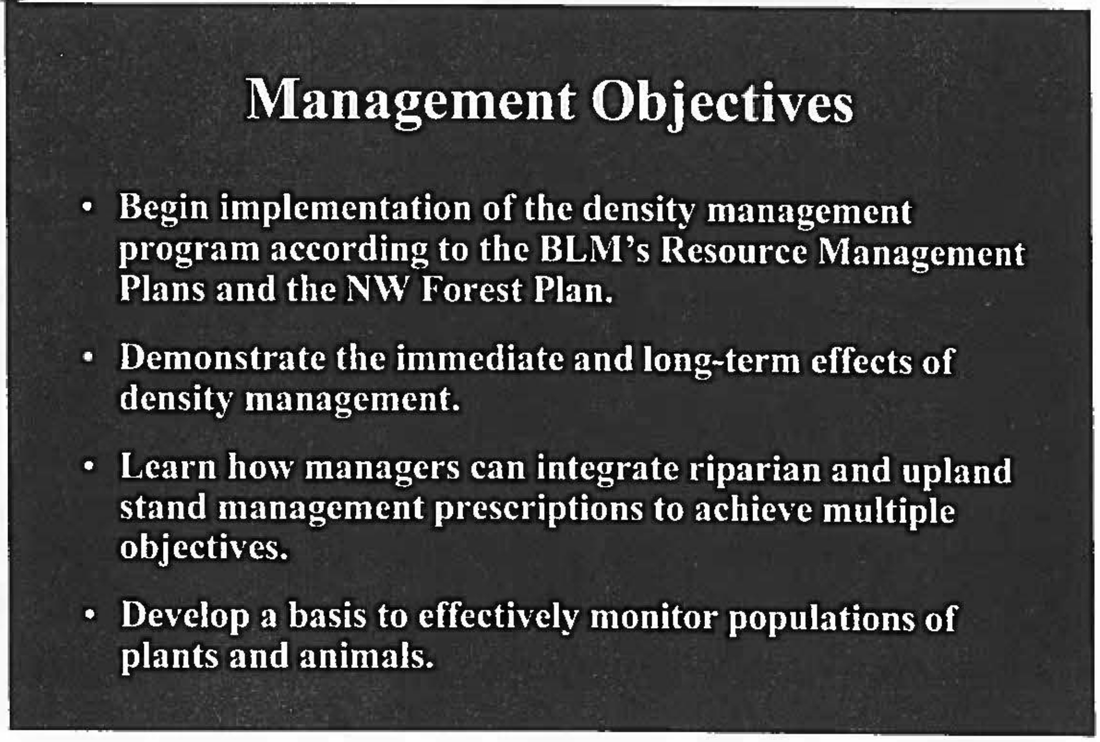
⑦



Scientific Objectives

- Determine if density management treatments result in differences in structural characteristics and species diversity.
- Provide an experimental basis for evaluating the response of various plant and animal taxa to density management.

⑧



Management Objectives

- Begin implementation of the density management program according to the BLM's Resource Management Plans and the NW Forest Plan.
- Demonstrate the immediate and long-term effects of density management.
- Learn how managers can integrate riparian and upland stand management prescriptions to achieve multiple objectives.
- Develop a basis to effectively monitor populations of plants and animals.

⑨

Microclimate Considerations

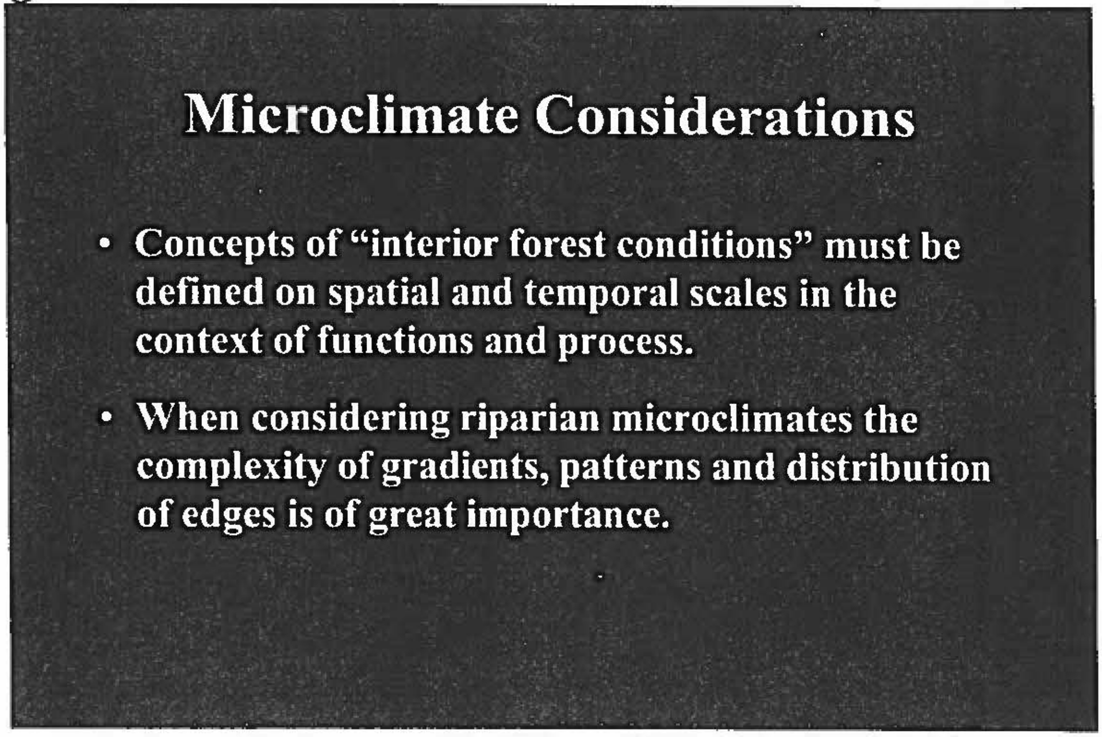
- The relevance of microclimates must be considered in the context of physical and ecological functions and processes
- Microclimates are often described and often "managed" at a stand or small stream reach scale.
- The mosaic of microclimates associated with patterns in the landscape (drainage, watershed) should first be considered

⑩

Microclimate Considerations

- Our knowledge of the interactions between the drivers of microclimate (macroclimate, vegetation, geomorphology, topography) with microclimate is still limited.
- Our understanding of interactions that arise from different patterns of microclimate such as evaporation and convection is limited.

⑪



Microclimate Considerations

- Concepts of “interior forest conditions” must be defined on spatial and temporal scales in the context of functions and process.
- When considering riparian microclimates the complexity of gradients, patterns and distribution of edges is of great importance.

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Appendix F
Additional Material – Microclimate and Stream Temperatures

Workshop -

MICROCLIMATIC FACTORS INFLUENCING STREAM TEMPERATURE

Sherri Johnson - OSU

A. Introduction to Theory -Factors influencing stream temperatures
  - a. Driven by solar inputs
  - b. Lags and timing of responses
- 2. Microclimate and interactions
  - a. Evaporation
  - b. Convection
  - c. Conduction
  - d. Re-radiation
- 3. Movement of water - complication from lake studies
  - a. Length of time of exposure to microclimates

B. Studies - examining theory on the ground and predicting effects of forest harvest
- 1. Difficult to individually examine factors because all responding to solar and temp dependent
- 2. Shading and air temp
  - a. Bedrock reach
    - (i) chosen to control for inputs of gw or tribs
    - (ii) reduction of incoming solar to stream
    - (iii) but limited change in air temperatures under shade due to mixing of air over larger areas than that shaded
  - b. Energy balance
    - (i) understanding factors controlling stream temp in 200m reach
    - (ii) without solar inputs - decrease in stream temperature
    - (iii) George Brown's formula based on solar inputs and surrogates for surface area - 1°C unaccounted for during full sun and same 1°C decrease without solar suggests other factors of influence
  - c. Air temp still higher - but stream temp decreased

- 3. Correlations and scaling
  - a. Questions: in the literature
    - (i) air temp controls stream temp??
    - (ii) elevation controls stream temp?
  - b. Relationships among: Air - Water - Soil temperatures - GW temps
    - (i) all responding to solar
  - c. Spatial scaling
    - (i) extrapolation from climate stations to riparian sites
      - proximity to site - variability over short distances
    - (ii) elevation - watershed area- gw temp - air temp - gradient - width - volume or Q
    - (iii) Forest science project - Humboldt (Lewis et al. 2000)
      - Lack of correlation for air temp from climate stations at

distance

- d. Temporal scaling
  - (i) Hourly, daily, seasonal, annual
  - (ii) Sullivan and Adams
    - Monthly and annual correlations are strongest for air& water
    - not mechanistic
  - (iii) Sinokrot and Stefan (93)

C. Harvest effects and predicting effects of forest harvest

- 1. Clearcutting through riparian
  - a. HJA studies - Johnson and Jones 2000
  - b. Alsea studies - Ice in prep, Brown
  - c. Changes in max - but also min
    - (i) re- radiation countered by increased soil temps
  - d. COPE - Current data examined using physically based models - Brown, Heat Source, SS temp - Rob Tanner masters project, FE pub
- 2. Recovery over time
  - a. depends on site
  - b. HJA -Alsea - ~15 yrs - riparian species different
  - c. Beschta and Taylor 1988 - suggested ~15-20 yrs
- 3. Recovery over distance through intact forest - revisit later
- 4. Partial harvest effects ??
  - a. Changes in incoming solar, wind, humidity, soil temp, air temp

D. Other microclimatic effects

- 1. Substrates - conduction
- 2. WS 3 alluvial reach - revisit
- 3. Energy budget for same length reach - not acct for decrease in temps
- 4. Effects of travel time - ways to measure
- 5. Increases in minimums over summer

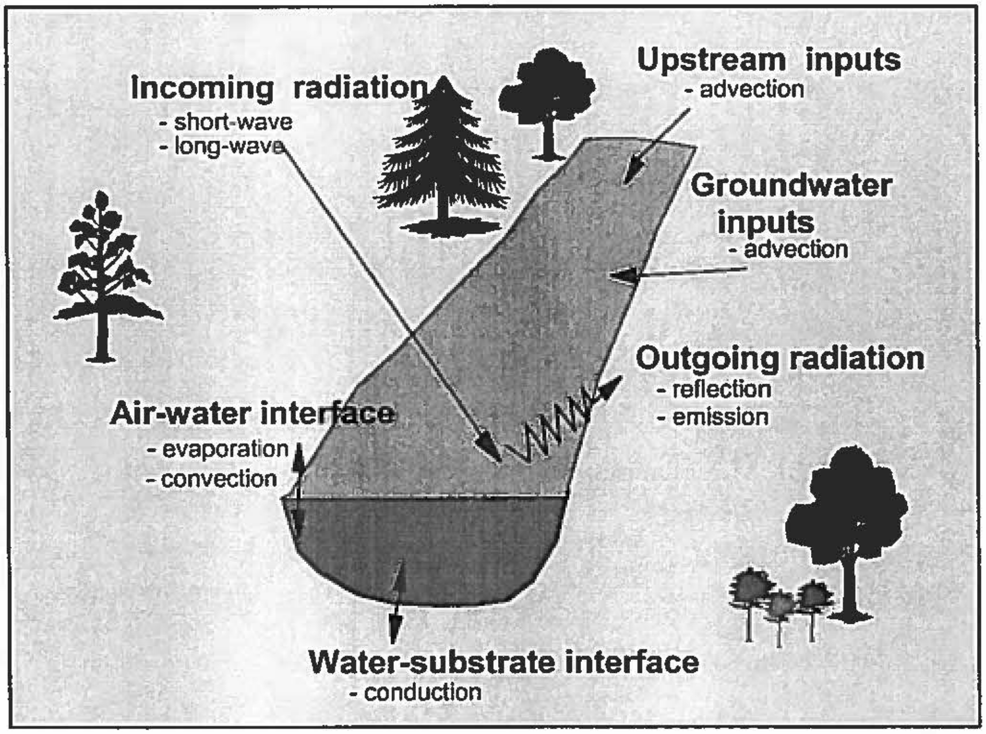
E. Scaling up from site studies

- 1. Landscape linkages
  - a. How point processes fit into landscape dynamics
  - b. HJA studies
- 2. Uncertainty and variability
  - a. Temperature recovery downstream of harvest ?
  - b. Zwieniecki and Newton 1999 - assume longitudinal trends are consistent among basins, which is not borne out by other studies
- 3. Regional trends
  - a. East side- west side
  - b. Site specific differences
    - (i) sources of water - initial temperatures
    - (ii) length of time of exposure
    - (iii) Climatic differences

- RH, wind,, air drainage patterns

CMER Workshop: Microclimatic influences on stream temperature

Sherri L. Johnson
Oregon State University



Incoming radiation
- short-wave
- long-wave

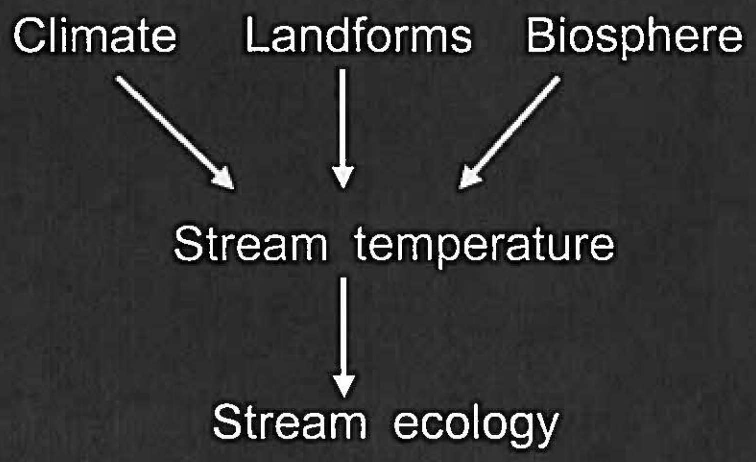
Upstream inputs
- advection

Groundwater inputs
- advection

Outgoing radiation
- reflection
- emission

Air-water interface
- evaporation
- convection

Water-substrate interface
- conduction



Climate Landforms Biosphere

Stream temperature

Stream ecology

Scaling of observations

Spatially variable microclimates

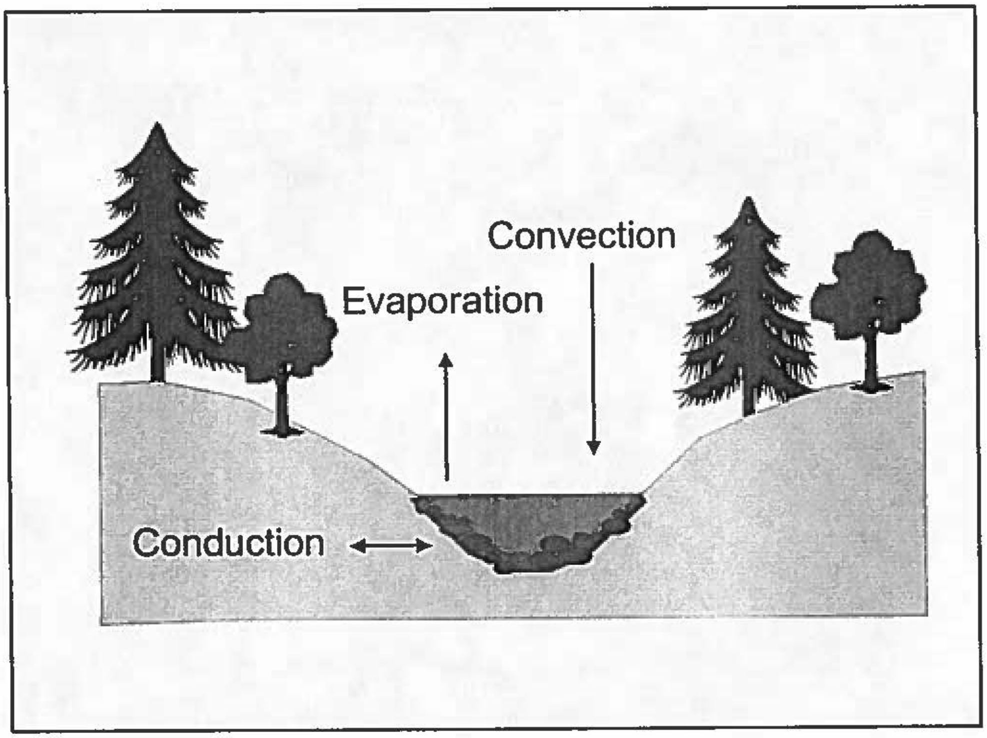
and

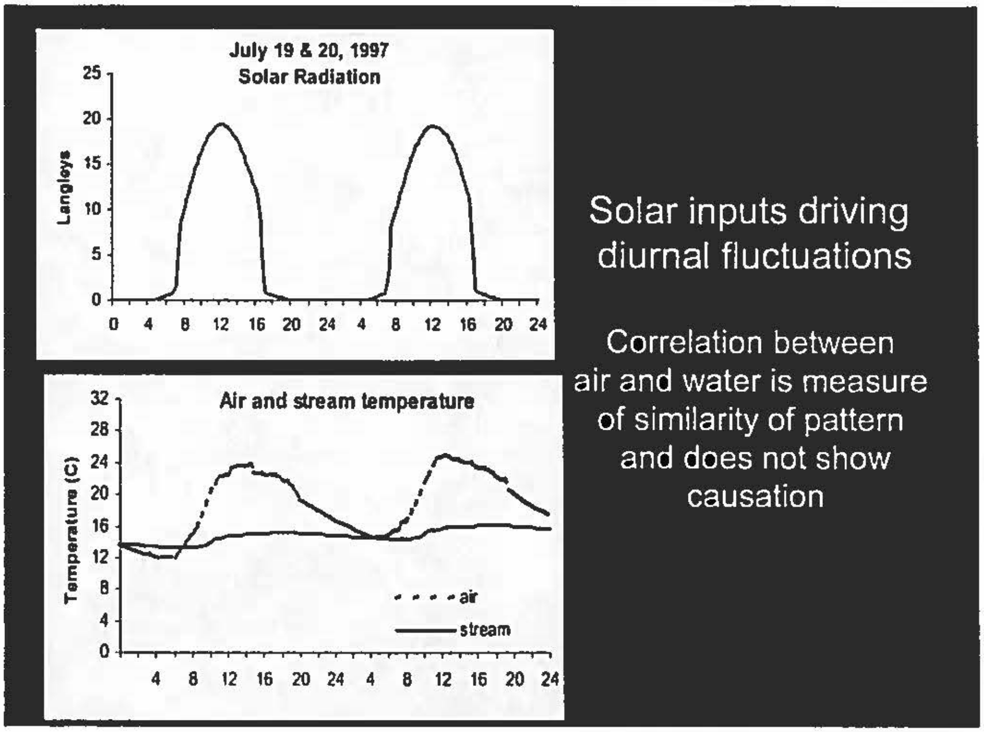
Temporally variable data

- Multiple factors influence stream temperatures
- Microclimatic factors are highly variable over short gradients

Air temperature influences?

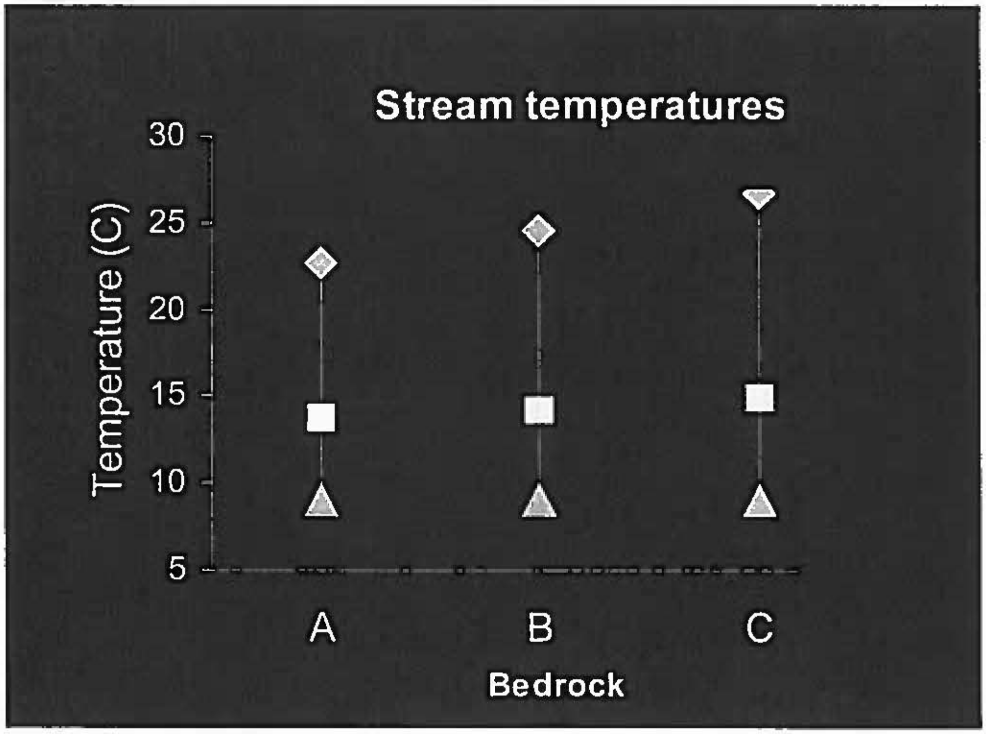
- Solar drives temperature dynamics of soil, air, water
- Difficult to separate effects of solar inputs from air temperature responses to those solar inputs





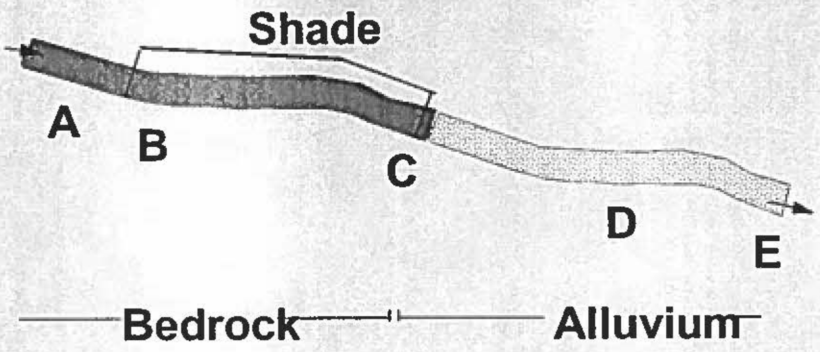
Solar inputs driving diurnal fluctuations

Correlation between air and water is measure of similarity of pattern and does not show causation



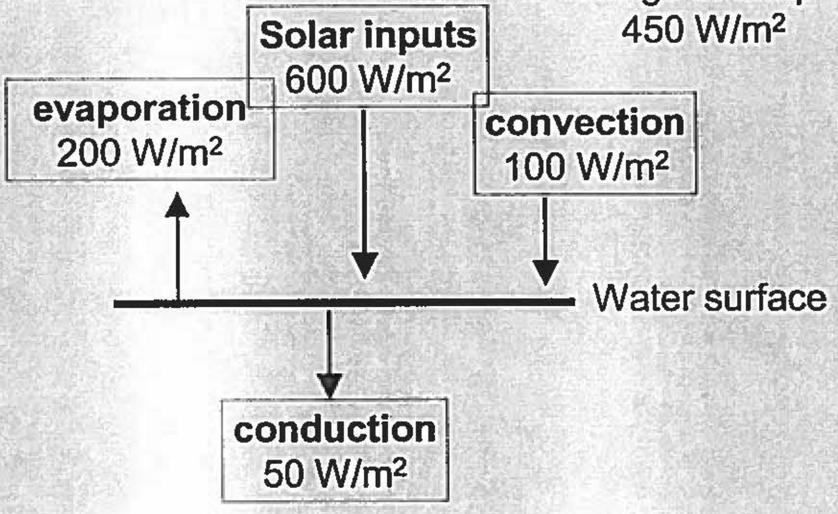
Watershed 3

1964 & 1996 Debris flows:
scoured to bedrock and deposited alluvium



Bedrock Reach: 4°C increase

change in temp =
450 W/m²

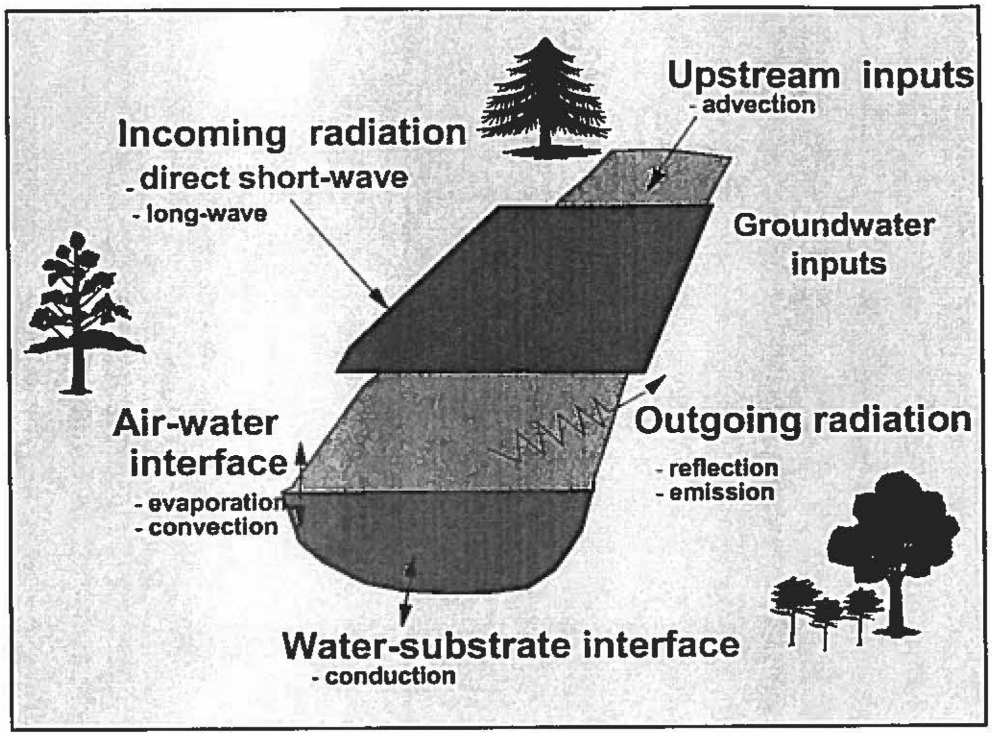

Solar inputs
600 W/m²

evaporation
200 W/m²

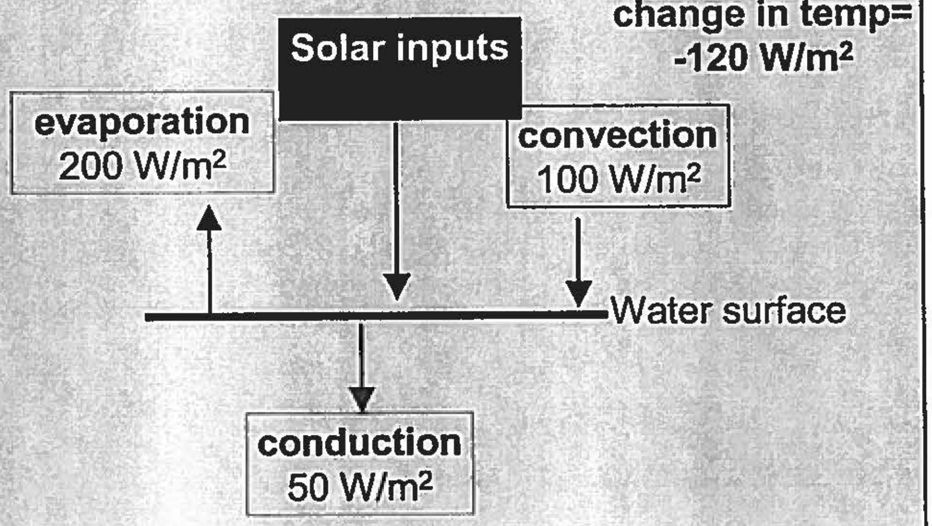
convection
100 W/m²

Water surface

conduction
50 W/m²



Bedrock Reach: 1^{0}C decrease



change in temp= -120 W/m^2

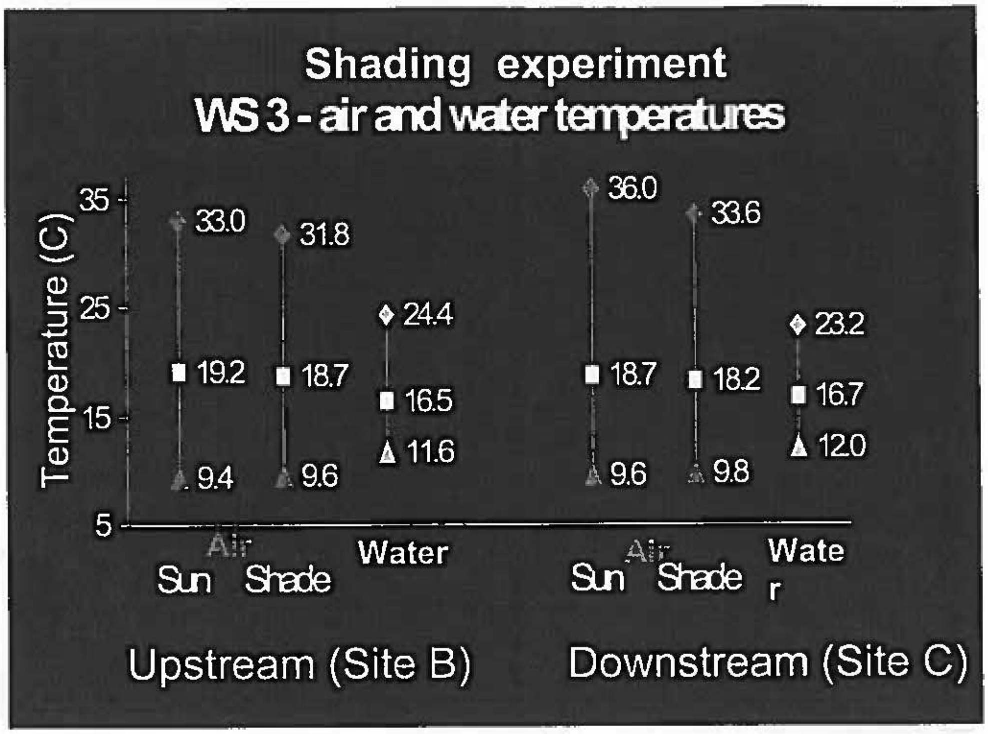
Solar inputs

evaporation 200 W/m^2

convection 100 W/m^2

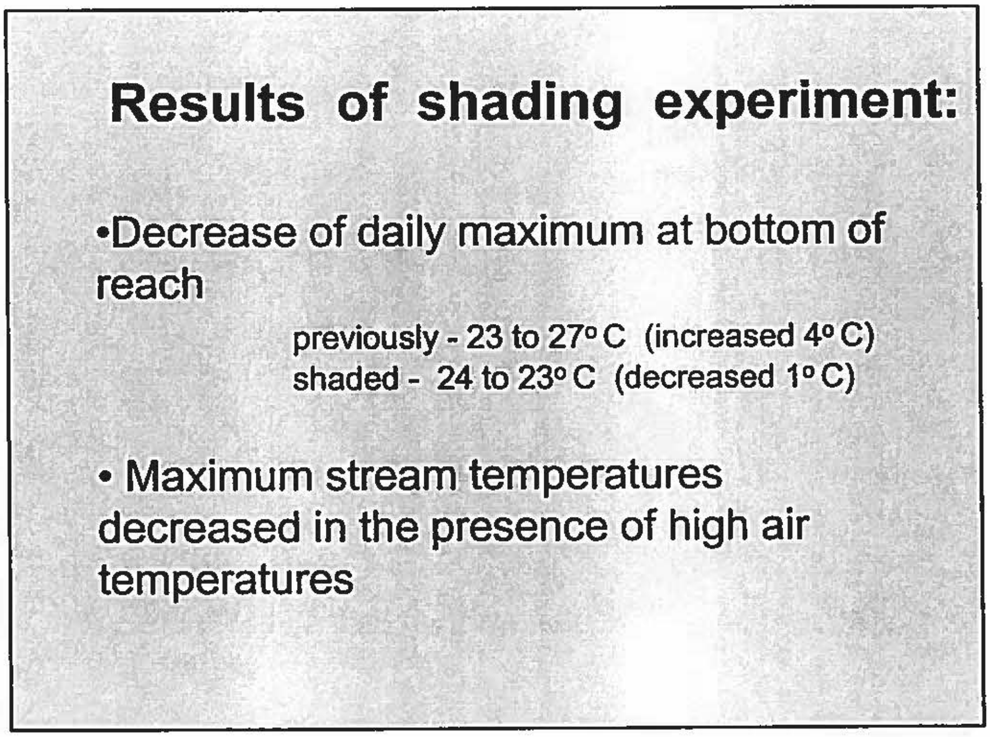
Water surface

conduction 50 W/m^2



Shading experiment
WS 3 - air and water temperatures

Upstream (Site B) Downstream (Site C)



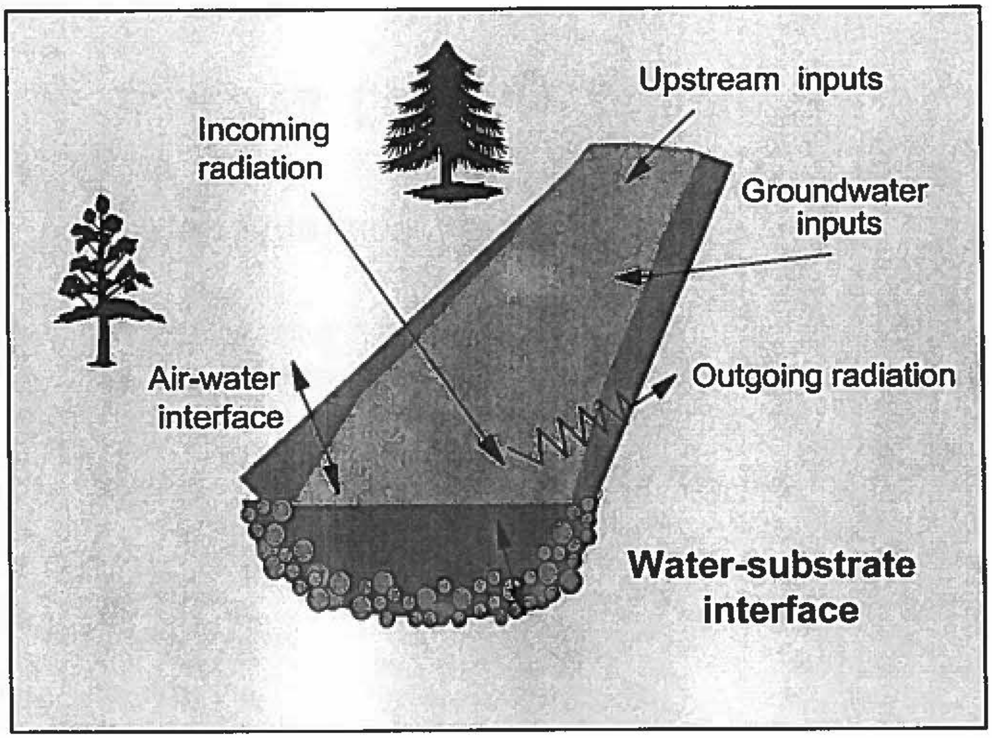
Results of shading experiment:

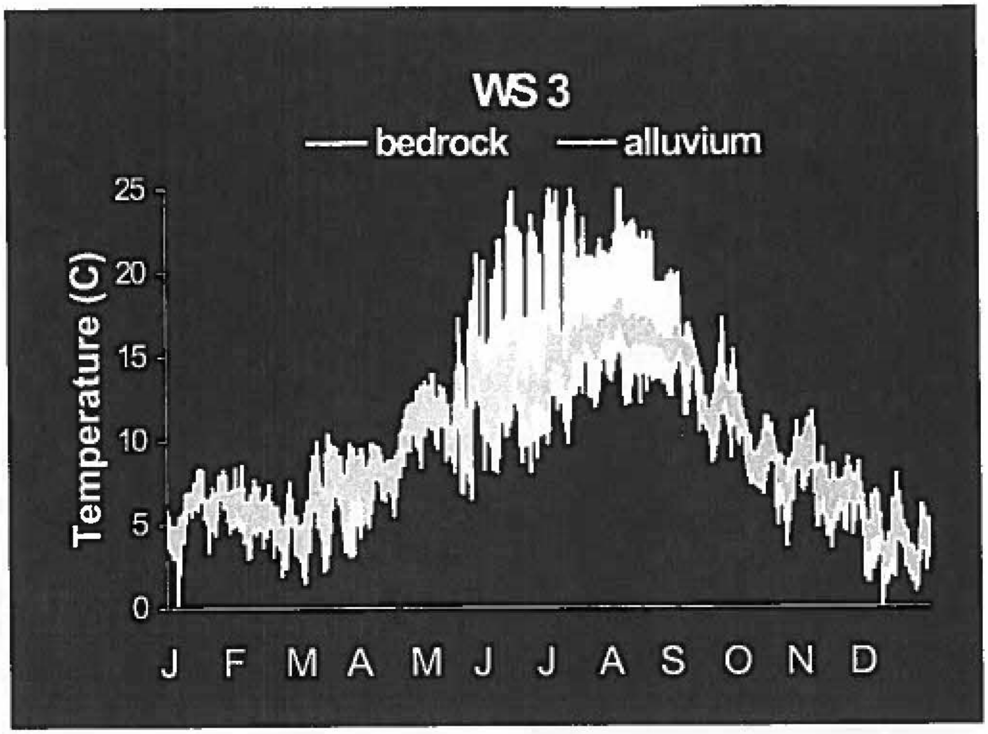
- Decrease of daily maximum at bottom of reach
  previously - 23 to 27° C (increased 4° C)
  shaded - 24 to 23° C (decreased 1° C)

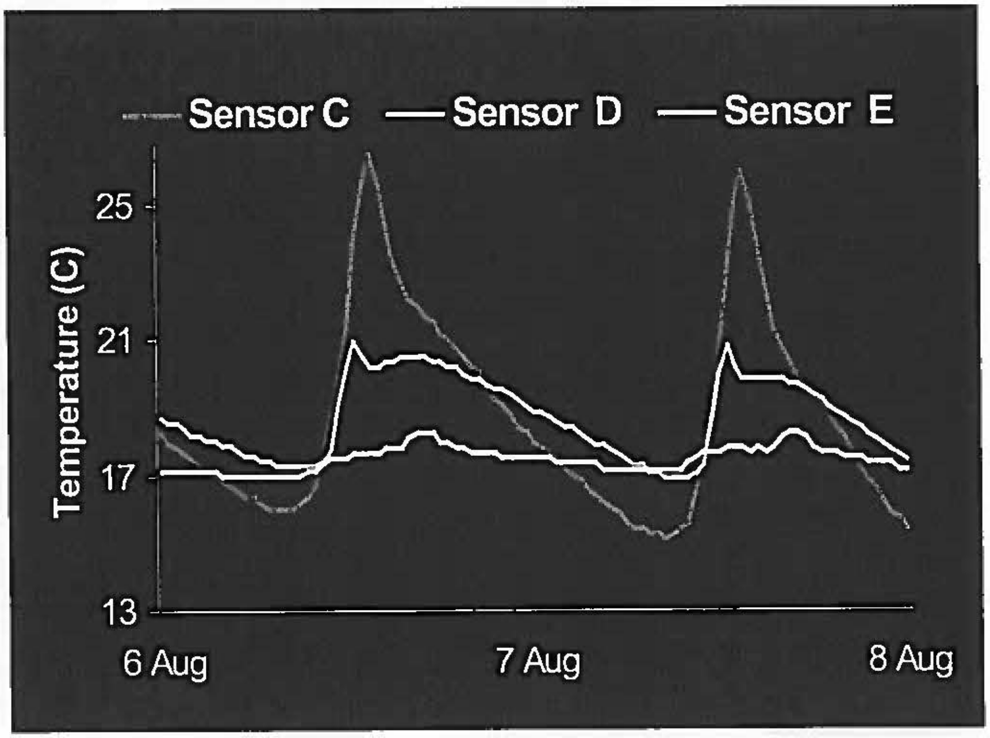
- Maximum stream temperatures decreased in the presence of high air temperatures

Conduction influences?

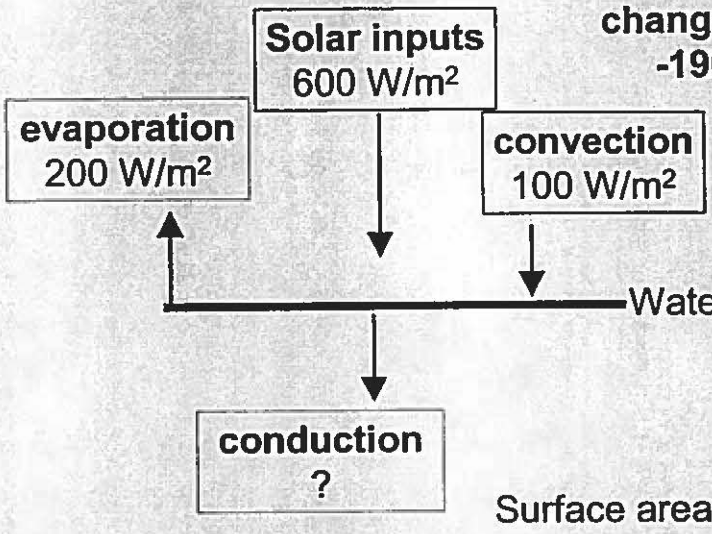
- Heat transmitted from warmer areas to cooler areas
- Rates of conduction (rock/soil) are much greater than rates of convection (air)
- Much is not known about the microboundary layers and flow rates of hyporheic zones and rates of conduction through this zone




WS 3
bedrock
alluvium
Temperature (C)
25
20
15
10
5
0
J
F
M
A
M
J
J
A
S
O
N
D


Sensor C
Sensor D
Sensor E
Temperature (C)
25
21
17
13
6 Aug
7 Aug
8 Aug

Alluvial reach: 10^0C decrease



change in temp = -1900 W/m^2

Solar inputs
600 W/m^2

evaporation
200 W/m^2

convection
100 W/m^2

Water surface

conduction
?

Surface area = 260 m^2
Subsurface area = 13020 m^2

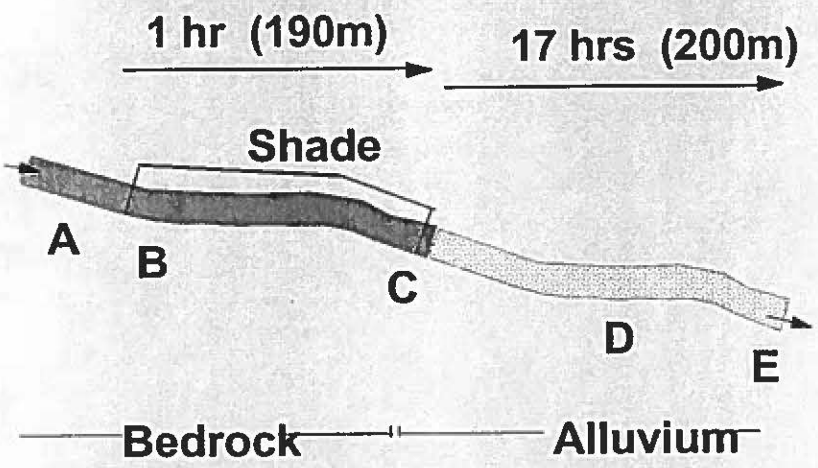
Alluvial Reach

Potential mechanisms for decrease of maximum temperature and narrowing of diurnal ranges:

- Conduction with large surface area of subsurface alluvium
- Mixing with large volume of stored subsurface water
- Delays in transport lead to mixing of hot daytime and cool nighttime water

Watershed 3

Median water travel time:



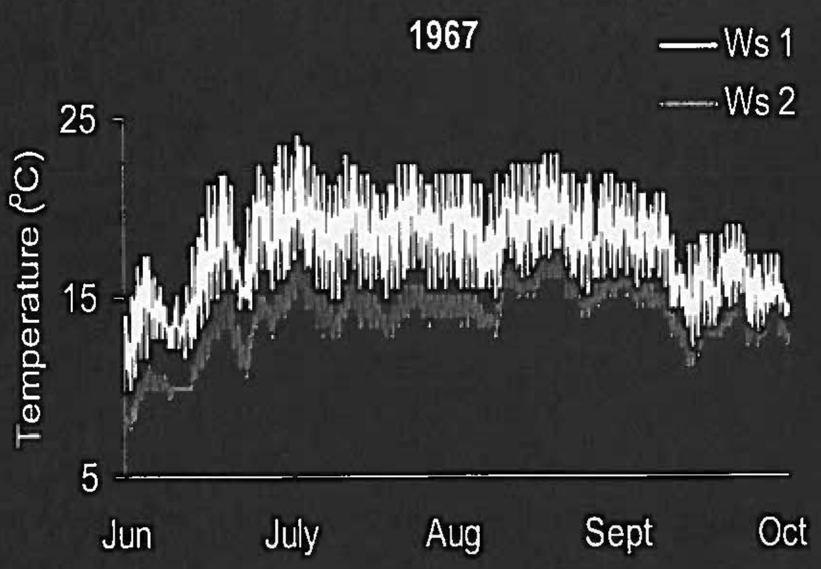
Water velocity rates through two reaches:

differences among methods

	bedrock	alluvium
flow meter	0.20 m/s	0.15 m/s
leading edge dye	0.10 m/s	0.02 m/s
median transport	0.05 m/s	0.003 m/s

Effects of forest harvest on stream temperatures

(Johnson and Jones, CJFAS, 2000)



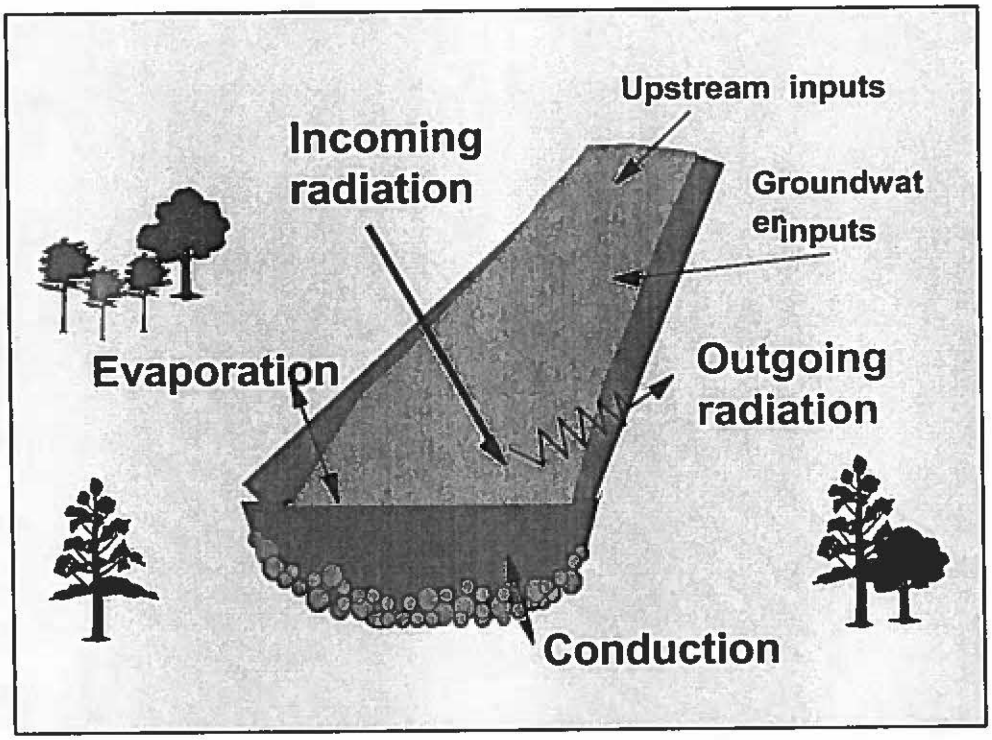
Effects of forest harvest

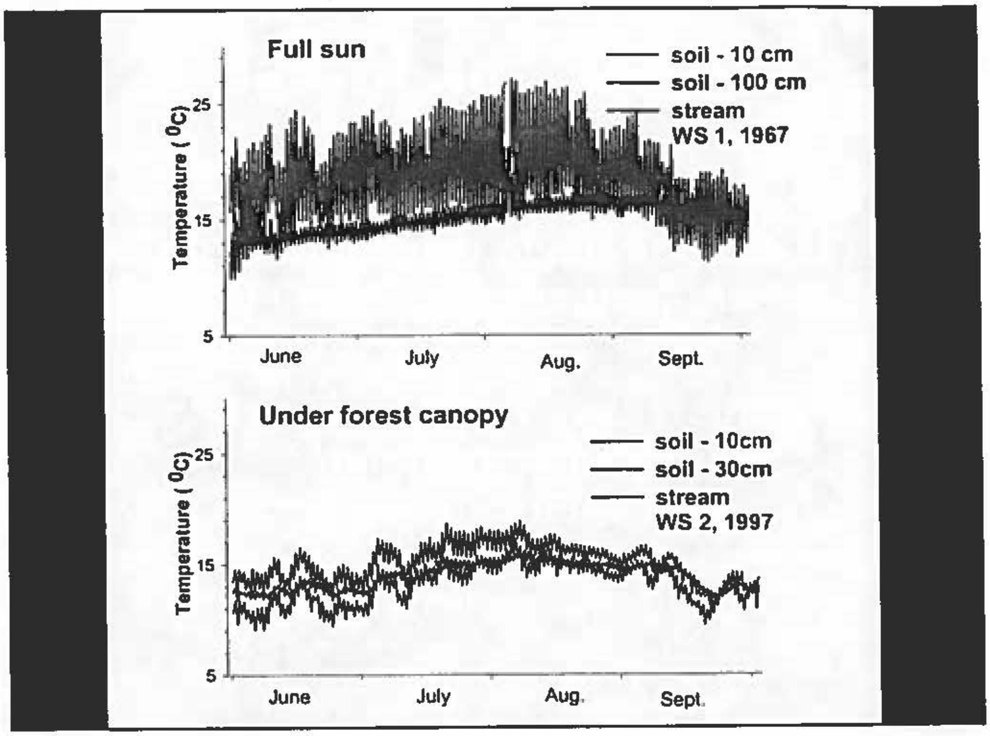
Another early study of effects of clearcutting and patchcutting on stream temperature - Alsea Basin

Findings:

- increases in maximum
- increases in minimum

but other studies suggest decreases in minimum following canopy removal - why?





Recovery of stream temperatures after forest harvest

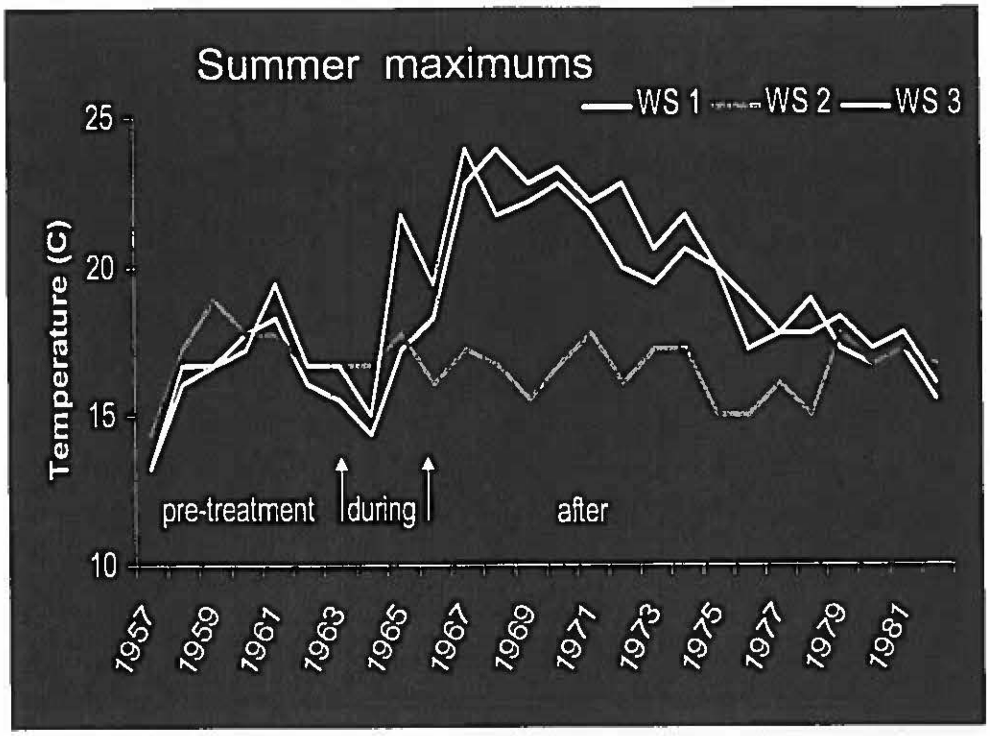
Beschta and Taylor 1988

predicted recovery in ~15-20 years

Alsea Basin studies

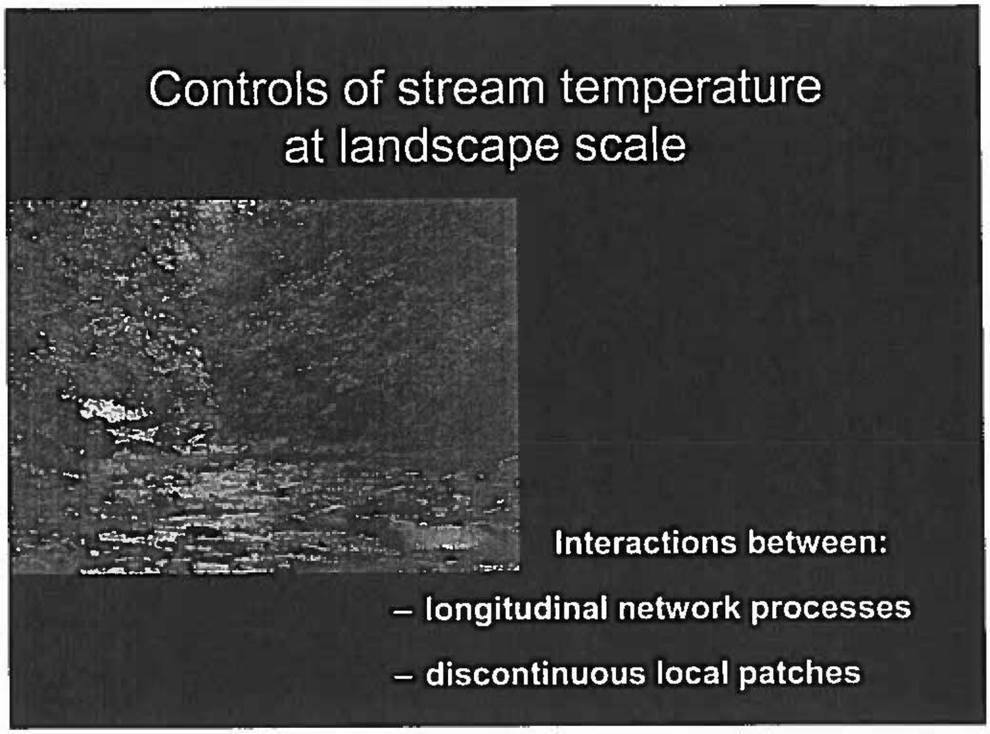
Brown and Krygier 1970 - noted trend within 5 yrs

Ice in press - return to pre-treatment levels



Uncertainties

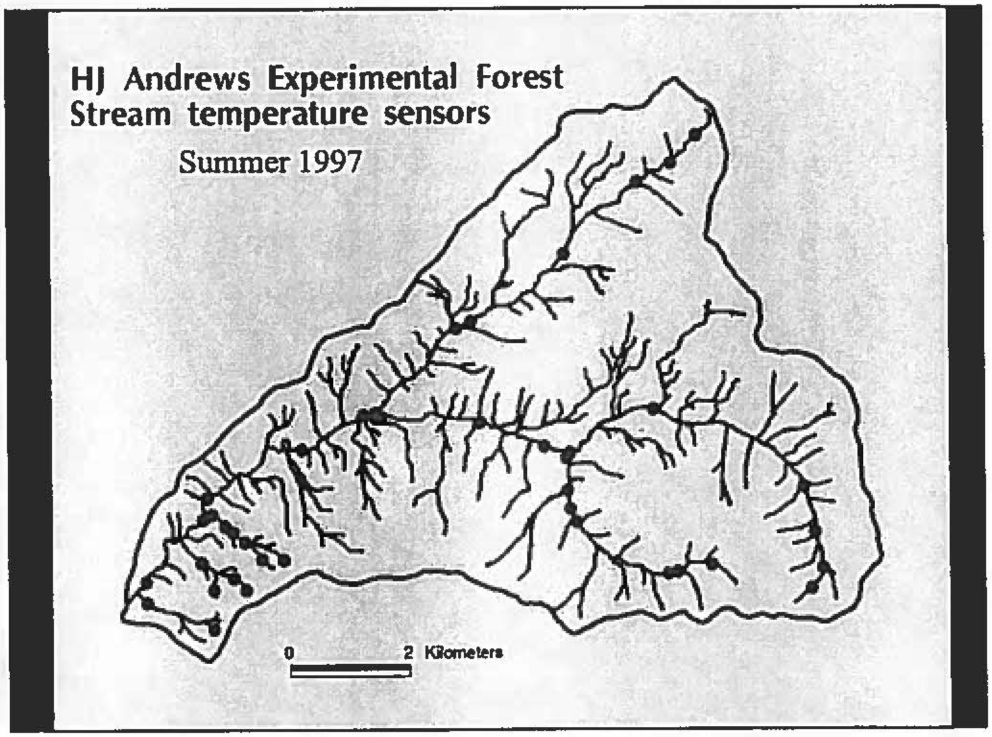
- **Effects of riparian thinning?**
  few studies of current harvest practices and stream temperature responses
- **Downstream temperature recovery?**
  few studies of harvest effects downstream



Controls of stream temperature at landscape scale

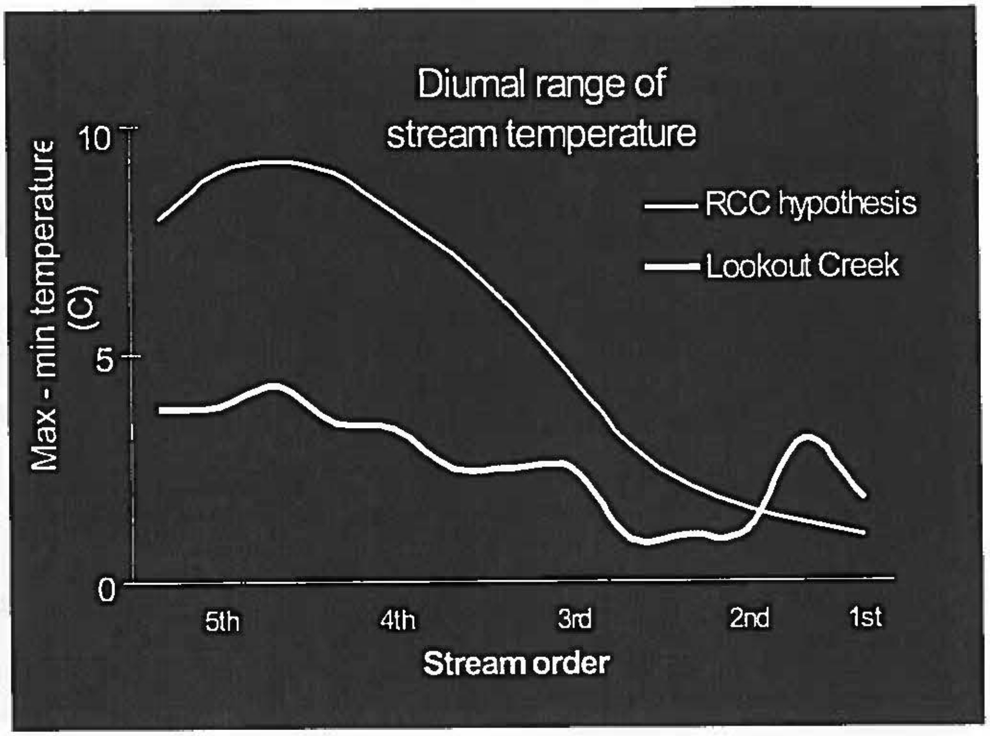
Interactions between:

- longitudinal network processes
- discontinuous local patches



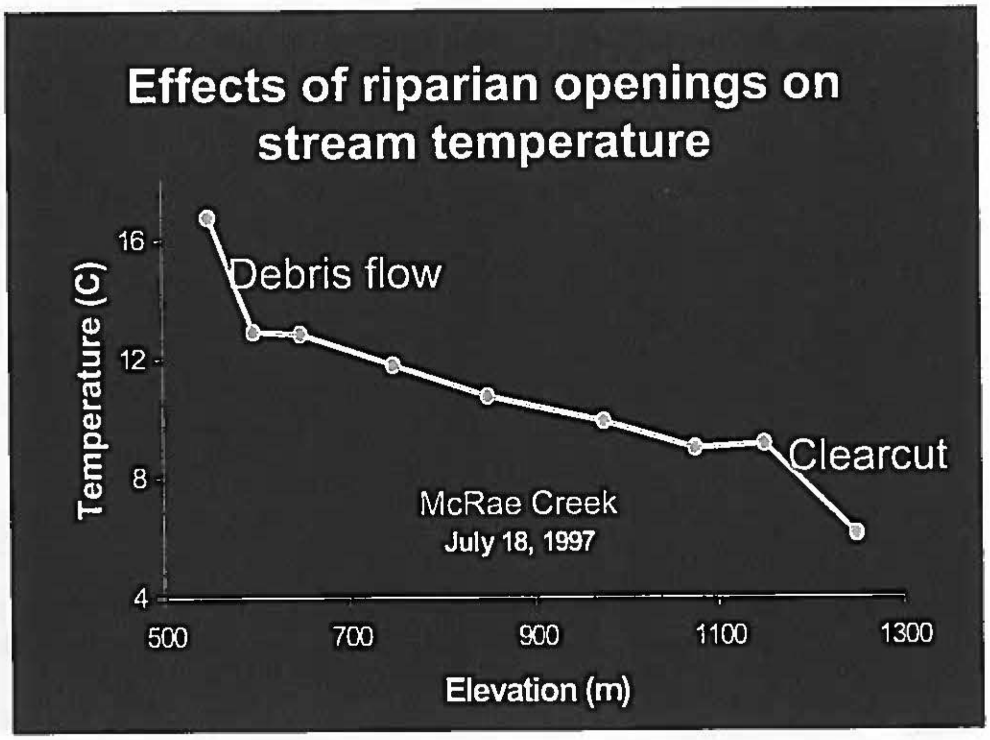
HJ Andrews Experimental Forest
Stream temperature sensors

Summer 1997



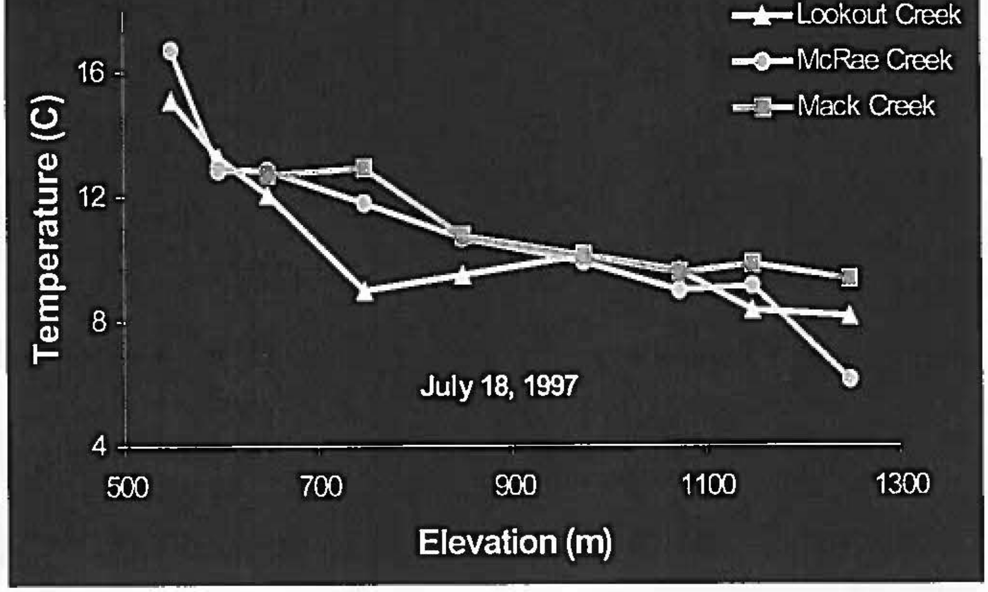
Diurnal range of stream temperature

Effects of riparian openings on stream temperature

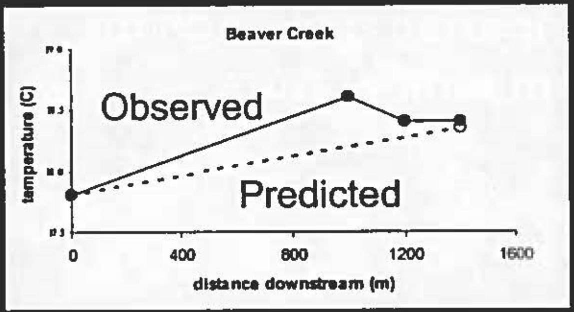


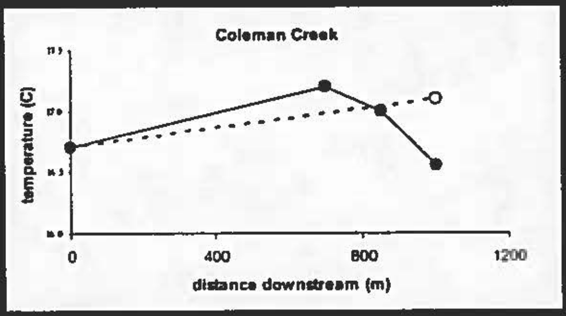
McRae Creek
July 18, 1997

Longitudinal variation
maximum stream temperatures



Zwieniecki and Newton 1999



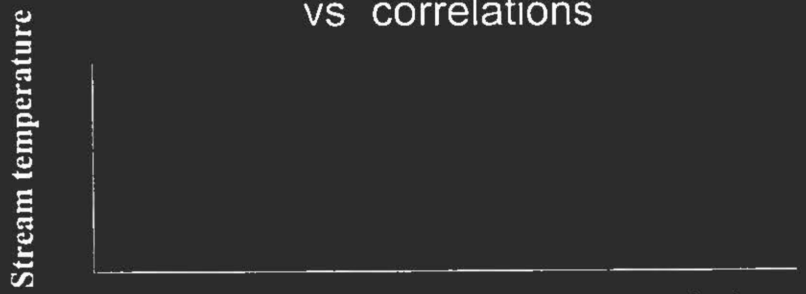


Observed versus predicted warming trends below harvested units

But longitudinal trends are variable

Spatial dynamics

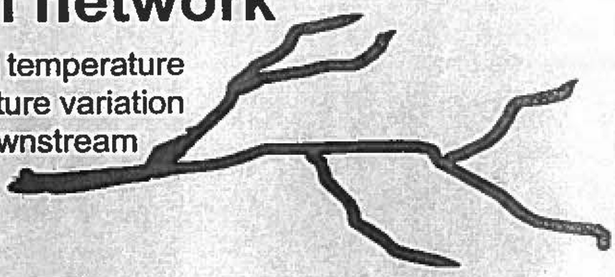
Drivers of stream temperature
vs correlations



low	**Elevation**	*high*
high	**Discharge**	*low*
wide	**Stream width**	*narrow*
deep	**Stream depth**	*shallow*
large	**Watershed area**	*small*
warmer	**Air temperature**	*cooler*

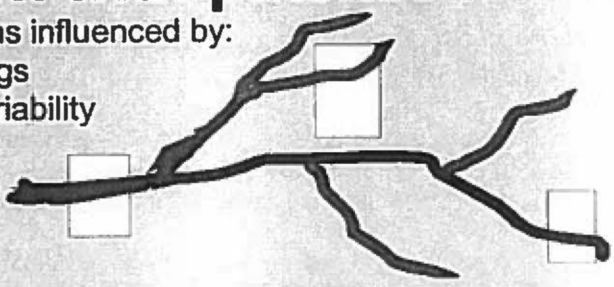
Stream network

Increased maximum temperature
and diurnal temperature variation
with distance downstream



Network with patches

Longitudinal patterns influenced by:
- riparian openings
- geomorphic variability



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Steve Mcconnell

From: Lynn Doremus
Sent: Tuesday, December 04, 2001 6:29 PM
To: Steve Mcconnell
Subject: Re: stream temp workshop report

Steve- The scope of work looks fine. I would add to the rationale a statement about the need for a more clear expression of what the information presented at the workshop was, and what the technical discussion was regarding the information presented (both the points of agreement and the points of disagreement), and the outcome. Outcome being what it was that was decided in terms of what direction to go in next, i.e. what were the processes that needed further work or study, and what the actions were defined to be taken to address that need?

In a more informal tone, I would suggest toning down the insinuations about the incompetence of the previous document author. B.S. degree, spelling errors, "Recorder not having a background..." etc. I don't know who will be reading this, or the background on how it was decided this should read, but the meaning will come across without the direct references to the previous document. In my humble opinion, leaving a little of that to the reader's discretion also is a matter of professional courtesy.

Thanks for the option to comment on it. And, I look forward to seeing the new document that will derive from your effort!

-llyn
----- Original Message -----
From: Steve Mcconnell <SMcconnell@nwifc.org>
To: Lynn Doremus <ldoremus@nwifc.org>
Sent: Thursday, November 29, 2001 11:34 AM
Subject: stream temp workshop report

Hi Lynn,

At the last CMER meeting, additional funding was found to get technical editing for the stream temp workshop report you reviewed earlier this fall. I wrote a scope of work for this project (attached). Current plans are for the contract details to be finished by next Monday (Dec. 3), work to begin shortly thereafter, and the edited draft (final copy) finished by Dec. 31. The contractor we are working with is Steve Fairweather, of Mason, Bruce and Girard, Inc. in Portlant. Please let me know if you have any comments on this scope of work. Thanks again for editing an earlier draft of this and providing us your comments.

Steve McConnell
Silviculturist
Northwest Indian Fisheries Commission
6730 Martin Way E.
Olympia, WA 98516-5540
Phone: (360) 438-1181, ext. 389
FAX: (360) 753-8659
www.nwifc.wa.gov

<<scope of work.doc>>

From: HITCHENS, DAWN (DNR)
Sent: Thursday, August 14, 2008 11:15 AM
To: Hunter, Mark (DFW)
Subject: RE: Question about Summary Report CMER/RSAG Temperature Workshop 2001

Hi Mark-

Okay, thank you for this. May I have a copy of the appendices?

Thanks.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

-----Original Message-----
From: Mark Hunter [mailto:HUNTEMAH@DFW.WA.GOV]
Sent: Thursday, August 07, 2008 2:08 PM
To: HITCHENS, DAWN (DNR)
Subject: Re: Question about Summary Report CMER/RSAG TemperatureWorkshop 2001

This does appear to be the final RSAG consensus draft. It's a good thing you have a copy, because I don't. I believe I have most of the Appendices listed at the end of the Executive summary. RSAG rewrote parts of the executive summary drafted by the contractor in 5/01, but other made no changes.

Mark Hunter

Mark A. Hunter
Major Projects Section Manager, Habitat Program Washington Department of Fish and Wildlife
1111 Washington Str, 5th floor
Olympia WA 98501-1091

Mailing address
600 Capitol Way N
Olympia WA 98501-1091

email huntemah@dfw.wa.gov
Phone 360-902-2542
Fax 360-902-2946

>>> "HITCHENS, DAWN (DNR)" <DAWN.HITCHENS@dnr.wa.gov> 08/05/2008 10:19 AM >>>
Hi Mark -

I am checking in with you about the attached summary report. Do you

know if this is the final version? Any help you can provide with this question is greatly appreciated.

Thank you.
Hope your summer is going well.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

<<Stream-TEMP_workshop_final_with_exec_summary.doc>>

From: CRAMER, DARIN (DNR)
Sent: Friday, August 08, 2008 7:02 AM
To: HITCHENS, DAWN (DNR)
Subject: RE: Question about Summary Report CMER/RSAG Temperature Workshop 2001

Yes we should - Go through and accept all changes (if there are any more), get a copy of the appendices from Hunter and edit the Appendices section on page iv to read that the appendices are available from DNR upon request. Thanks Dawn.

-----Original Message-----
From: HITCHENS, DAWN (DNR)
Sent: Thursday, August 07, 2008 2:42 PM
To: CRAMER, DARIN (DNR)
Subject: FW: Question about Summary Report CMER/RSAG Temperature Workshop 2001

Darin -

Some feedback about the document Doug Martin inquired about. It is attached for your reference. So, shall I finalize it, assign a CMER # & get this loaded on the website?

Thanks.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

-----Original Message-----
From: Mark Hunter [mailto:HUNTEMAH@DFW.WA.GOV]
Sent: Thursday, August 07, 2008 2:08 PM
To: HITCHENS, DAWN (DNR)
Subject: Re: Question about Summary Report CMER/RSAG TemperatureWorkshop 2001

This does appear to be the final RSAG consensus draft. It's a good thing you have a copy, because I don't. I believe I have most of the Appendices listed at the end of the Executive summary. RSAG rewrote parts of the executive summary drafted by the contractor in 5/01, but other made no changes.

Mark Hunter

Mark A. Hunter
Major Projects Section Manager, Habitat Program Washington Department of Fish and Wildlife
1111 Washington Str, 5th floor
Olympia WA 98501-1091

Mailing address
600 Capitol Way N

Olympia WA 98501-1091

email huntemah@dfw.wa.gov
Phone 360-902-2542
Fax 360-902-2946

>>> "HITCHENS, DAWN (DNR)" <DAWN.HITCHENS@dnr.wa.gov> 08/05/2008 10:19 AM >>>
Hi Mark -

I am checking in with you about the attached summary report. Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.

Thank you.
Hope your summer is going well.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

<<Stream-TEMP_workshop_final_with_exec_summary.doc>>

HITCHENS, DAWN (DNR)

From: Mark Hunter [HUNTEMAH@DFW.WA.GOV]
Sent: Thursday, August 07, 2008 2:08 PM
To: HITCHENS, DAWN (DNR)
Subject: Re: Question about Summary Report CMER/RSAG TemperatureWorkshop 2001

Attachments: Mark Hunter.vcf

Mark
inter.vcf (262

This does appear to be the final RSAG consensus draft. It's a good thing you have a copy, because I don't. I believe I have most of the Appendices listed at the end of the Executive summary. RSAG rewrote parts of the executive summary drafted by the contractor in 5/01, but other made no changes.

Mark Hunter

Mark A. Hunter
Major Projects Section Manager, Habitat Program Washington Department of Fish and Wildlife
1111 Washington Str, 5th floor
Olympia WA 98501-1091

Mailing address
600 Capitol Way N
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email huntemah@dfw.wa.gov
Phone 360-902-2542
Fax 360-902-2946

>>> "HITCHENS, DAWN (DNR)" <DAWN.HITCHENS@dnr.wa.gov> 08/05/2008 10:19 AM >>>
Hi Mark -

I am checking in with you about the attached summary report. Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.

Thank you.
Hope your summer is going well.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

<<Stream-TEMP_workshop_final_with_exec_summary.doc>>

HITCHENS, DAWN (DNR)

From: HITCHENS, DAWN (DNR)
Sent: Tuesday, August 05, 2008 10:20 AM
To: Mark Hunter
Subject: Question about Summary Report CMER/RSAG Temperature Workshop 2001

Attachments: Stream-TEMP_workshop_final_with_exec_summary.doc

Hi Mark –

I am checking in with you about the attached summary report. Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.

Thank you.
Hope your summer is going well.
Dawn Hitchens
Contract Specialist
Forest Practices Division
902-1388

Stream-TEMP
rkshop_final_

HITCHENS, DAWN (DNR)

From: HITCHENS, DAWN (DNR)
Sent: Friday, June 27, 2008 2:12 PM
To: steve@ucut-nsn.com
Subject: Question about a Final version of a report

Attachments: Stream-TEMP_workshop_final_with_exec_summary.doc

Hi Steve –

Doug Martin found this version of the following report as attached:

> Summary Report CMER/RSAG Temperature Workshop – 2001, *Prepared for* RSAG – the Riparian Scientific and Advisory Group, and CMER – the Cooperative Monitoring, Evaluation, and Research Committee Olympia, Washington. *Prepared by:* EDAW, Inc. Seattle, Washington. Final Proceedings Report – February 2002

Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.
Thank you.
Dawn Hitchens
Contract Specialist
Forest Practices Division
360-902-1388

Stream-TEMP
rkshop_final_

From: HITCHENS, DAWN (DNR)
Sent: Friday, June 27, 2008 2:12 PM
To: steve@ucut-nsn.com
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Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.
Thank you.
Dawn Hitchens
Contract Specialist
Forest Practices Division
360-902-1388

Stream-TEMP
kshop_final_

HITCHENS, DAWN (DNR)

From: CRAMER, DARIN (DNR)
Sent: Friday, June 27, 2008 10:19 AM
To: HITCHENS, DAWN (DNR); SCHIEBER, JEFF (DNR)
Subject: FW: Report?
Importance: High

Dawn/Jeff:

Do we have a .PDF of the report referenced below?

Darin D. Cramer
Adaptive Management Administrator
Forest Practices Division
WA Dept of Natural Resources
(360) 902-1088

From: Douglas Martin [mailto:doug@martinenv.com]
Sent: Friday, June 27, 2008 9:59 AM
To: CRAMER, DARIN (DNR); Nancy Sturhan; Sally_Butts@fws.gov
Subject: Report?

Darin and co-chairs,

Where is this report? I cannot find it on the web site. Please direct me or provide a pdf. Thanks

Doug

Summary Report CMER/RSAG Temperature Workshop – 2001, *Prepared for* RSAG – the Riparian Scientific and Advisory Group, and CMER – the Cooperative Monitoring, Evaluation, and Research Committee Olympia, Washington. *Prepared by:* EDAW, Inc. Seattle, Washington. Final Proceedings Report – February 2002

Douglas Martin
Martin Environmental
2103 N 62nd Street
Seattle, WA 98103
(206) 528-1696

HITCHENS, DAWN (DNR)

From: HECKEL, LINDA (DNR)
Sent: Monday, October 27, 2008 3:27 PM
To: HITCHENS, DAWN (DNR)
Subject: FW: [cmer] conference call information for the CMER meeting tomorrow

may not get the stuff from Steve tomorrow – FYI.

---

rom: Steve [mailto:Steve@ucut-nsn.org]
ent: Monday, October 27, 2008 11:21 AM
o: HECKEL, LINDA (DNR)
ubject: RE: [cmer] conference call information for the CMER meeting tomorrow

hanks Linda,

may opt to phone in as it looks like a meeting I planned to attend on Wednesday is not going to happen. Hopefully I will find ıat out for sure later today. I'll get back to you to let you know for sure and to make a new plan to deliver the Stream Temp /orkshop materials if it turns out that I will not be delivering these to you tomorrow.

teve

---

rom: cmer-bounces@mailman2.u.washington.edu [mailto:cmer-bounces@mailman2.u.washington.edu] **On Behalf Of** HECKEL, INDA (DNR)
ent: Monday, October 27, 2008 9:31 AM
o: cmer@u.washington.edu
ubject: [cmer] conference call information for the CMER meeting tomorrow

ireetings:

Ve will be out at the DNR/DOC Conference Room A tomorrow. I have set up a conference call if you would like to call ı:

hone # is 360-407-3780, PIN is 465651#

have also set up video in the DNR Olympic Region and DNR Northwest Region.

you have any questions, please let me know.

hank you.

inda A. Heckel

orest Practices Division

Vashington Department of Natural Resources

)lympia, WA

360) 902-1399

nda.heckel@dnr.wa.gov

From: HITCHENS, DAWN (DNR)
Sent: Friday, October 17, 2008 8:42 AM
To: 'Steve'
Subject: RE: Question about a Final version of a report

Hi Steve –

Thank you for replying to this request for information. I indeed would appreciate you sending me the hard copies of the appendices & the electronic files of the editing for this report.

Thank you, this is very helpful.
Dawn Hitchens
Contract Specialist
Forest Practices Division
360-902-1388

From: Steve [mailto:Steve@ucut-nsn.org]
Sent: Monday, October 13, 2008 2:41 PM
To: HITCHENS, DAWN (DNR)
Cc: Douglas Martin (E-mail)
Subject: RE: Question about a Final version of a report

Hi Dawn,

Yes this is the final version. I noticed that on the 5th page of the report (p. iv) there is a note about where copies of the appendices (referred to but not included in the report) can be found. Both people identified (Heather Rowton, WFPA and Mark Hunter, WDFW) have moved on from CMER and the Adaptive Management Program. I have hard copy of these appendices. Do you want them for your file for this project? If you do put this on the website, it would probably be appropriate to identify a current contact for these and have them on hand should anyone request these materials. Mark Hunter may have electronic files of these but may also no longer have these at all, not be terribly motivated to search for them or any number of other possible responses. I assume that it would be difficult to access records that Heather Rowton may have had as she is even more removed from the AMP than is Mark. But, in both cases that is just me making assumptions and by calling them or contacts where they worked you may be able to get electronic files of these appendices. And again, I am happy to provide you with the hard copy versions I have.

I managed the contract for the editing done by Steve Fairweather of Mason, Bruce and Girard for this report (PSC 02-144) and still have computer files that pertain to that contract. Please let me know if you would like to have these for your records and I will send those also.

Hope this is helpful.

Steve

From: HITCHENS, DAWN (DNR) [mailto:DAWN.HITCHENS@dnr.wa.gov]
Sent: Friday, June 27, 2008 2:12 PM
To: Steve
Subject: Question about a Final version of a report

Hi Steve –

Doug Martin found this version of the following report as attached:

> Summary Report CMER/RSAG Temperature Workshop – 2001, *Prepared for* RSAG – the Riparian Scientific and Advisory Group, and CMER – the Cooperative Monitoring, Evaluation, and Research Committee Olympia, Washington. *Prepared by:* EDAW, Inc. Seattle, Washington. Final Proceedings Report – February 2002

Do you know if this is the final version? Any help you can provide with this question is greatly appreciated.

Thank you.

Dawn Hitchens

Contract Specialist

Forest Practices Division

360-902-1388

<<Stream-TEMP_workshop_final_with_exec_summary.doc>>

HITCHENS, DAWN (DNR)

From: HITCHENS, DAWN (DNR)
Sent: Wednesday, October 15, 2008 9:01 AM
To: CRAMER, DARIN (DNR)
Subject: FW: Question about a Final version of a report

YI -

awn Hitchens
ontract Specialist
orest Practices Division
02-1388

---

rom: Steve [mailto:Steve@ucut-nsn.org]
ent: Monday, October 13, 2008 2:41 PM
o: HITCHENS, DAWN (DNR)
c: Douglas Martin (E-mail)
ubject: RE: Question about a Final version of a report

i Dawn,

es this is the final version. I noticed that on the 5th page of the report (p. iv) there is a note about where copies of the ppendices (referred to but not included in the report) can be found. Both people identified (Heather Rowton, WFPA and Mark unter, WDFW) have moved on from CMER and the Adaptive Management Program. I have hard copy of these appendices. Do ou want them for your file for this project? If you do put this on the website, it would probably be appropriate to identify a urrent contact for these and have them on hand should anyone request these materials. Mark Hunter may have electronic files f these but may also no longer have these at all, not be terribly motivated to search for them or any number of other possible esponses. I assume that it would be difficult to access records that Heather Rowton may have had as she is even more removed om the AMP than is Mark. But, in both cases that is just me making assumptions and by calling them or contacts where they orked you may be able to get electronic files of these appendices. And again, I am happy to provide you with the hard copy ersions I have.

managed the contract for the editing done by Steve Fairweather of Mason, Bruce and Girard for this report (PSC 02-144) and till have computer files that pertain to that contract. Please let me know if you would like to have these for your records and I ill send those also.

ope this is helpful.

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rom: HITCHENS, DAWN (DNR) [mailto:DAWN.HITCHENS@dnr.wa.gov]
ent: Friday, June 27, 2008 2:12 PM
o: Steve
ubject: Question about a Final version of a report

i Steve –

oug Martin found this version of the following report as attached:

Summary Report CMER/RSAG Temperature Workshop – 2001, *Prepared*

for RSAG – the Riparian Scientific and Advisory Group, and CMER – the Cooperative Monitoring, Evaluation, and Research Committee Olympia, Washington. *Prepared by:* EDAW, Inc. Seattle, Washington. Final Proceedings Report – February 2002

o you know if this is the final version? Any help you can provide with this question is greatly appreciated.

hank you.

awn Hitchens

ontract Specialist

orest Practices Division

60-902-1388

<Stream-TEMP_workshop_final_with_exec_summary.doc>>