Forests, Insects & Pathogens and Climate Change:

Workshop Report

Forests, Insects & Pathogens and Climate Change: Workshop Report

Prepared for

Western Wildlands Threat Assessment Center
3160 NE Third St, PO Box 490
Prineville, OR 97754

Prepared by

Sarah J. Beukema, Donald C.E. Robinson, and Lorne A. Greig
ESSA Technologies Ltd.
1765 West 8th Avenue, Suite 300
Vancouver, BC V6J 5C6

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Executive Summary

This report summarizes the results of a workshop held June 26-28, 2007 in Portland, Oregon. The meeting was sponsored by the Western Wildlands Threat Assessment Center, with the goal of finding useful approaches to thinking about and preparing for the impacts of climate change on western forests and their insect and pathogen systems.

Participants agreed that **things will change**. Most vegetation communities will not simply migrate from one location to another. Instead, many communities will be completely new, with new combinations of trees, understory plants, insects, and pathogens. At the same time it is important to bear in mind that **we are not going to completely lose all forests and all vegetation**. New plant communities will organize themselves and replace trees that are unable to adapt to new climates. New communities could include current tree species, other tree species (*e.g.*, hardwoods or strongly dispersing species from warmer areas) or could become dominated by grass and shrub species.

When we contemplate making predictions about what could happen under alternative climate change scenarios, our thinking needs to incorporate a wide variety of topics that will affect what species and communities will be present in different locations. These topics include:

- water-use efficiency;
- Range and genetic adaptedness of species provenances;
- the wide variety of spatial and temporal scales found in natural systems;
- interactions among plant hosts and their insect and disease agents; and
- phenological patterns and other forms of synchronized relationships that evolve between species in response to climate signals.

After working in subgroups studying selected ecosystem change under two GCM climate scenarios, the participants enumerated gaps in both knowledge and research (see Section 2 for a complete listing). Two broad knowledge gaps are the role of water in tree health, and the direct role of climate on insects and pathogens. It was also noted that a lack of funding creates a major gap in the research that is necessary to bridge the many knowledge gaps that were identified by the different working subgroups. Participants were also concerned about the large body of climate change literature. This literature, which includes the effects of climate change on living things, is growing at a pace that is difficult for most scientists to keep pace with.

The concluding plenary discussion made some general recommendations for model developers and users. All model developers (or development groups) need to re-evaluate their existing models in light of climate change. Model users need improved access to different types of models, whether they be small-area mechanistic-process models, empirical-statistical models or large area detailed spatial models. The issue of incompatible model scales also needs to be addressed. At one extreme are models that need a stream of daily climate information at a point scale, while GCMs typically produce monthly output over a spatial scale of one degree. Finally, completely new models may be necessary to solve new or emerging problems.

As a result of the workshop, WWETAC staff heard about how climate change may affect certain ecosystems; how insect and disease specialists think about the impacts of those changes, and about the knowledge, research, and modelling needs that surround the topic. The information and ideas expressed at the workshop will be applied in WWETAC cooperative projects, additional workshops to address knowledge, research and modelling needs, and could lead to the establishment of a center to provide literature reviews and summaries relevant to the study of climate change impacts on forest ecosystems and their insects and pathogens.

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Acknowledgements

We thank the participants listed in the appendix made time to attend, and who contributed the ideas and opinions that made the workshop a success. In particular, we thank the five speakers who offered their expertise through the following background talks:

Name	**Affiliation**	**Title**
Ron Neilson	PNW	Climate change simulations – Possibilities and Predictions Across Multiple Scales: Global, North America and the West
Jeff Hicke	U Idaho	Mountain Pine Beetle and Climate Change Predictions and Challenges
Paul Hennon	PNW	Lessons from Yellow-Cedar Decline: Predicting Paradoxes in a Warming Alaska
Craig Allen	USGS	Pinyon-Juniper Ecosystems and Recent Mortality
Tom Swetnam	U of Arizona	Interannual and Interdecadal Climatic Variability: Implications for Understanding Climate Change Patterns

We give special thanks to Bridgett Naylor (WWETAC), who prepared the summary climate data and maps, and who ensured that each group was provided with the means to view this information. Finally, we express our thanks to the staff at Ron Nielson’s lab who provided the climate data and assisted Bridgett with its conversion to ArcGIS format.

1. Background and Context

Forest managers and planners have historically relied on observations and lessons from the past in order to help plan for the future. In a world in which the average climate is assumed to be stationary, unusual events are usually considered anomalies and are sometimes discounted, ignored or forgotten. Yet within the current planning horizon, environmental conditions are predicted to change significantly in many areas. These changes will have an impact on the geographic ranges of some plant species, on their insect and pathogen complexes, and on the interactions between host and pathogen. In some areas our current ideas about “normal” ecosystem behaviour will change, and we will see more unusual events.

One of the difficulties with these changes is that for the most part, we do not know how to predict their full impacts: past experience of climatic variation may not be an adequate guide to future system behaviour. There are few models or tools which quantify how ecosystems might change, particularly those that include insects and pathogens. In many cases, we are not even sure what the changes will be. Although the emerging concepts of resilience, panarchy and system reorganization may be qualitatively helpful, their quantitative application is still undeveloped.

The workshop began with a number of thought provoking presentations about observed and simulated impacts of climate change on terrestrial vegetation, but the main work of the two-and-a-half day meeting was a series of “thought exercises”, one in a plenary session and the three in subgroups. In each of those discussions we tried to focus on the mixture of climate, biology and social aspects that will likely interact in novel ways over the next century. As described in more detail below, we qualitatively and subjectively examined four different ecosystem types in light of two contrasting sets of climate change predictions over a 100 year period. Participants were given a set of questions to stimulate their thinking[1]. They were then asked to discuss what they thought could be the impacts of the climate change scenario on the current vegetation and on the insects and pathogens that either are a current part of each ecosystem, or that could become a part of the ecosystem in the future. They were also to identify key issues and research needs. Each subgroup was charged with providing a summary of their discussions of five different topic areas:

- the current state of the ecosystem and how it might be changing in the absence of climate change;
- the predicted potential state of the ecosystem under climate change;
- past history of the ecosystem (if relevant to current or future states);
- knowledge gaps or research needs; and
- tools or models.

At the conclusion of the subgroup sessions, each group prepared and presented a verbal summary report about the current state of the ecosystem, what could occur in each ecosystem as the climate changes, what knowledge gaps exist, what questions need to be asked when preparing risk assessments, and how the science of risk assessment can be advanced through conceptual and simulation models.

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[1] These questions are found in Appendix C

2. Ecosystem Discussions

During the workshop we discussed the four different ecosystem-site complexes shown in Figure 1. Three are in the western US: Pinyon-Juniper, Spruce-Fir, Eastside Cascades Ponderosa Pine. The fourth ecosystem, Northern Boreal, is in British Columbia.

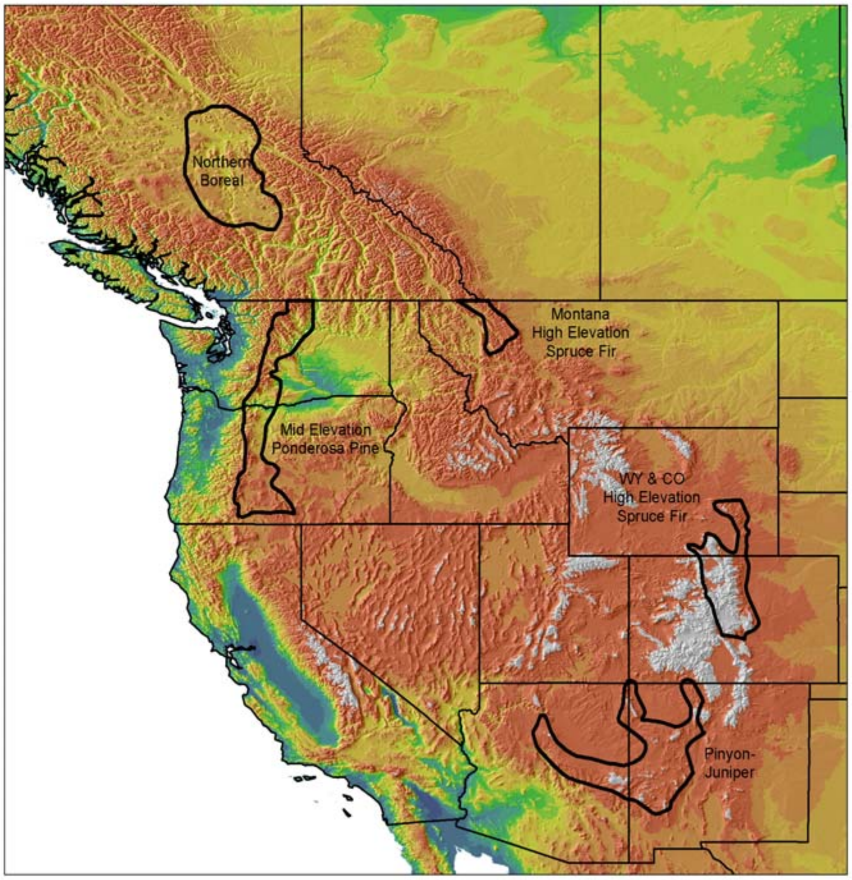

Figure 1. Western North America, showing the boundaries and locations of the four ecosystem types used for the workshop. Lower elevations are shown in blue, grading through yellow and red to the highest elevations in white.

The first ecosystem, Pinyon-Juniper, was discussed in a plenary session. Using the Pinyon-Juniper discussion as a template, the participants were then assigned to smaller subgroups to discuss the remaining three systems. In a concluding plenary session, each group then presented a summary of their discussions using five topic areas to structure their thinking and reporting:

- the current state of the ecosystem and how it might be changing in the absence of climate change;
- the predicted potential state of the ecosystem under climate change;
- past history of the ecosystem (if relevant to current or future states);
- knowledge gaps or research needs; and
- tools.

2.1 Pinyon-juniper

The pinyon-juniper ecosystem was chosen for the opening plenary discussion because it was thought to be a relatively straight-forward system that could be discussed by the entire group to give a sense of the ways that we might think about potential ecosystem changes. Craig Allen (Bandelier National Monument, Los Alamos, NM) presented an overview of the ecosystem, providing the group background to this ecosystem and to the recent problems of widespread pinyon dieback, laying a foundation for the discussion of this system.

Ecosystem overview

The pinyon-juniper ecosystem is geographically large and highly variable. While the system is called "Pinyon-Juniper" (and these are its key vegetation types) it was noted that the two species do not necessarily occur together, and that more is known about pinyon than juniper. Thus, the discussion focussed on pinyon, which is affected by drought, insects (such as *Ips*), and pathogens. Drought is the key driver of the system, with *Ips* being more successful at attacking the drought-stressed trees. Cheatgrass is also invading the system regardless of drought, and this is changing the impact of fire on the landscape.

Climate change

There was not enough time in the plenary session to explore the detailed mapped monthly precipitation and temperature data. Thus, the group made its predictions based on Craig Allen's presentation and on the graphed point data provided in the briefing document[2].

Climate is thought to drive drought stress through the joint effects of decreased precipitation and increased temperature. It is assumed to drive insect life cycles via temperature, with increasing temperatures leading to more insect generations in a year. Climate could also influence pathogens through precipitation.

The change in timing of precipitation, with rain coming earlier in the growing season, could be beneficial to grasses early in summer. However, the lack of rain later in the summer could increase fire risk because there would be abundant dry vegetation coupled with hotter temperatures.

Retrospective

The ecosystem is one in which history provides important information which will help attempts at future prediction. Records show that there have been longer droughts in the past, although past droughts are thought to have resulted in less mortality and vegetation continues to cover the area today. The current and projected drought is hotter than those of the past, however, and the system has already experienced higher mortality levels than in previous droughts.

In the very recent past, novel disturbances include chaining and grazing. Together, these have had a large impact on the type and amount of understory vegetation that is currently present.

Looking back 10,000 years ago, the area did not support either pinyon or juniper. Instead, the area was covered by ponderosa pine and oaks, highlight the idea that that systems can change over time in the absence of anthropogenic effects, and that whatever happens, some vegetation will be there in the future, even if it does not include pinyon.

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[2] The Briefing Document is included as Appendix C.

Knowledge needs and gaps

The group was asked what types of information they would need in order to make predictions about the impacts of insects and pathogens, and produced a detailed list with many types of data:

- mean annual precipitation;
- degree days greater than 5 degrees;
- degree days less than 0 degrees;
- hours of leaf wetness;
- consecutive days without precipitation during the growing season;
- very dry periods (*i.e.*, periods that have precipitation levels that are two standard deviations below normal levels);
- daily minimum and maximum temperature;
- relative humidity;
- suddenness of temperature change preceded by constant temperature;
- lightning strikes;
- fall precipitation (impacts survival of regeneration, recharges soil water);
- weather sequences (*e.g.*, a low temperature that follows days of high temperatures); and
- climate information in time series that are in synchrony with fire/bug/other models (*e.g.*, providing daily rain and temperatures if that is what a model calls for).

The participants were also asked to suggest areas in which we need more knowledge about the *interaction* between climate variables and insects or pathogens. A summary of these includes:

- Does temperature affect the number of *Ips* generations, emergence time, and survival?
- How will changes in precipitation affect root pathogens?
- How are other insects affected by temperature and precipitation (*e.g*. saw fly, Prescott scale beetle, tip moth)?
- Interactions between moisture, soils, and pathogens (*e.g.*, fog, water patterns, north/south slope differences.
- What are the thresholds at which drought will kill a tree?
- What does it take for *Ips* to kill a tree?
- What does it take to grow a stand (microscale effects on regeneration)?

2.2 Spruce-fir

Ecosystem overview

The spruce-fir ecosystem type differs from the others in that it spans Montana, Colorado, Arizona and New Mexico. The forests differ in each of these locations: In Montana, the ecosystem is relatively large contiguous areas of Spruce-Fir forests with a maritime climate. Colorado's forest distribution is similar to that of an archipelago. Contrasting these are the systems of Arizona and New Mexico which are distributed in small "islands" on mountain peaks, with a more continental climate. These southern forests are at the edge of their ecological range and may be a warm analogue of future conditions for the spruce-fir forests further north. Generally, temperature and precipitation have increased at higher elevations in the past 30 years. This may be an early indicator for the coming changes under climate change.

There are a large number of biotic and abiotic disturbances in spruce-fir systems. Abiotic disturbances include wind, ice storms, avalanche, and fire. Biotic disturbance agents include a wide range of insects and pathogens:

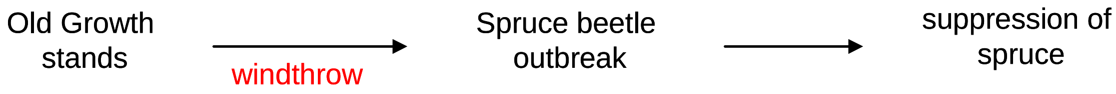
- spruce beetle;
- western balsam bark beetle;
- mountain pine beetle;
- Douglas-fir beetle (*Scolitins*);
- geometrids (loopers);
- aphids and adelgids;
- white pine blister rust;
- broom rust;
- annosus and other root diseases;
- needle pathogens;
- heart rot pathogens;
- defoliating insects (budworm, tussock moth); and
- mistletoe.

In the Spruce-fir ecotype, fires tend to have a long interval return time and to be stand replacing. Currently the extent of fires has been greater and there is a longer fire season relative to historical conditions. Fires in these forests also tend to be related to the presence of lodgepole pine.

Drivers of disturbance

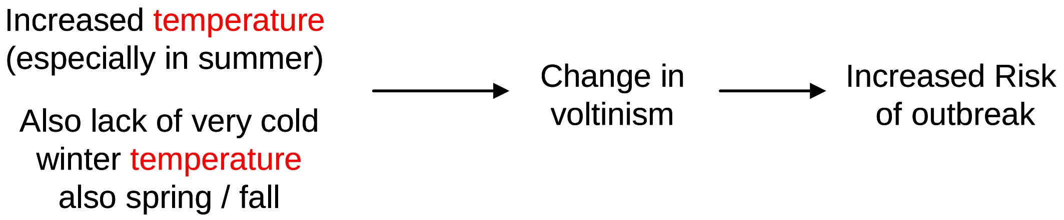
The subgroup looked at each of the major disturbance agents and tried to determine how they worked: what were the drivers for each agent and which of these was climate related. For each disturbance agent, links to climate-related triggers are highlighted in red.

Spruce beetle



Outbreaks of spruce beetle are driven by temperature in combination with abiotic disturbance such as windthrow (which may also be climate related).

Bark beetles

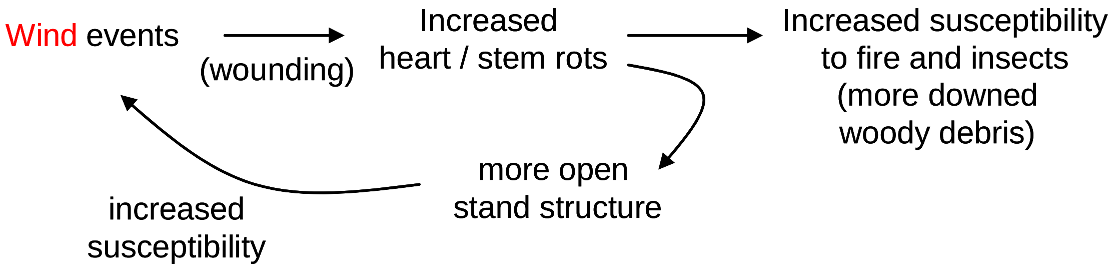


The seasonal change in temperature pattern is critical for bark beetles. Shifts in snow pack affect beetle dynamics via the changes this causes in the condition of the host trees.

White pine blister rust

Any change in climate that increases fire frequency will leads to increased *Ribes* and increased white pine blister rust. Increased summer precipitation would lead to increased spore production on *Ribes* and to increased blister rust as well.

Heart & stem rots



Needle pathogens

For sexually reproducing needle pathogens, the timing of the host and pathogen phenology is critical to their interaction. There is a possibility for decoupling of the phenology with changes in climate. In contrast, those needle pathogens that reproduce asexually are not at risk for this decoupling. Both types will do better with higher spring precipitation and increased temperatures.

Geometrids

There have been several recent outbreaks of species thought to be relatively innocuous. These outbreaks are associated with *warm late autumn* and *warmer winter temperatures*. Outbreaks are possibly a direct temperature impact on the insect life cycle, but the actual cause and effect is unknown. The host condition and interactions with other organisms may also be important factors. There is concern that the range of these species could extend northward under climate change.

Root disease

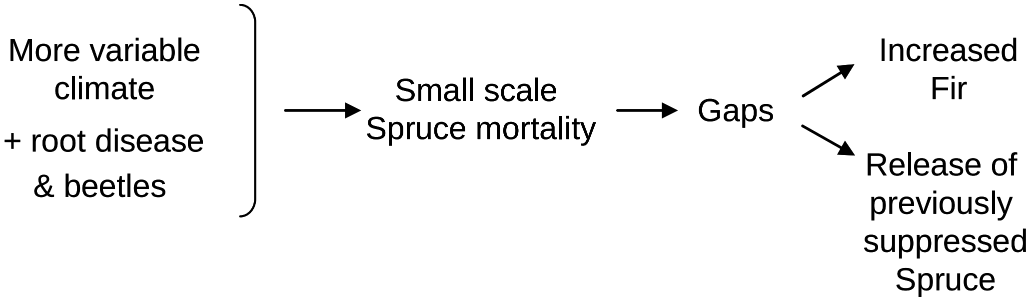
Root disease leads to increased tree stress which in turn leads to increased susceptibility to other pathogens. The strength of effect depends on mix of species present. The climate influence is in relation to the condition of the host. For example, if the host is weakened due to drought, it will be more susceptible to root disease.

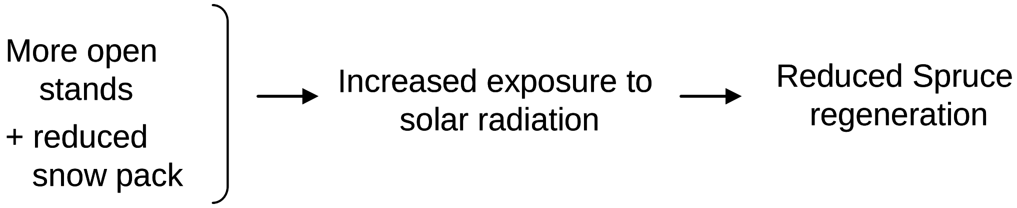
General observations of effects of disturbance agents

Due to their shorter generation time, insects and pathogens may be able to adapt to climate change more quickly than their hosts. Generalists may be the “winners” in these systems. Specific disturbance agents can lead to changes in the potential for regeneration and succession. The pattern of inter-annual variation in climate may be very important in determining the interactions between biotic disturbance agents and hosts. For example, a pattern of high inter-annual variability (one-year cycles of dry/wet or warm/cold) would lead to very different outcomes than would cycles with at five-year periodicity.

Hypotheses

1) If increased climate variability were to be expressed as relatively rapid cycling between warm/cool or wet/dry (or both) it might lead to increased frequency of small scale disturbances and increased heterogeneity in stand structure





2)

Climate change

The subgroup compared the two extremes of the climate scenarios provided for the workshop, using the year 2100 predictions in both models (MIROC and CSIRO) in relation to each other and to the year 2000 conditions, for both Montana and Colorado. Data for the south end of the Spruce–Fir range were not available.

It is important to note that the subgroup participants felt strongly that they needed to see forecasts for a series of continuous years (*e.g.* over a five year period) rather than for an individual year. They felt that their conclusions would be different if the sample year examined was an “anomaly” relative to other years, or was representative of typical conditions in other years near 2100.

Montana

Both models predicted a similar increase in precipitation for the Montana spruce-fir site, while they had significant differences in the temperature predictions. The mean summer temperature in the base year (2000) was 10°C (for the single location chosen for the illustrations), while for 2100, CSIRO predicted 14°C and MIROC predicted 19°C.

Under both these predictions, the spruce-fir forest type would be expected to persist with potential increases in disease and pest problems and likely increases in fire. Whitebark pine would be expected to be absent from these forests and limber pine would be expected to do better than at present. Fungi would be expected to do very well and there would be more frequent MPB outbreaks. A longer fire season would be expected with increased fire problems for the entire spruce-fir system in general, and on lodgepole pine sites in particular. The increased fire activity would also lead to an increase in alternative hosts for rusts.

Colorado

In Colorado, the models' predictions differed for both precipitation and temperature. The CSIRO model predicts a small increase in precipitation, while the MIROC predicts a small decrease. The CSIRO model predicts very little change in temperature at the elevations of the spruce-fir forest type. It predicts a much greater temperature increase at elevations below the present spruce-fir zone, which could have implications for the spruce-fir zone. In contrast, the MIROC model predicts substantially warmer temperatures in the spruce-fir zone

Under the MIROC predictions the spruce-fir system would be expected to be gone. Limber pine and whitebark pine might not survive at the lower elevations but may be the winners at higher elevations. We would also expect a faster population growth of insects and fungi. Under the CSIRO predictions, the spruce-fir system will likely still exist, with some changes in species composition.

Both Locations

This group had access to another source of data: a figure which showed increases in temperature by latitude and elevation (Figure 2). This figure indicates that at latitudes currently occupied by this ecosystem (around 40° N latitude), there will be relatively high mean annual temperatures (3-3.5° C). In addition, the increases in mean annual temperature will be greater at the higher elevation sites compared to lower elevation sites (note the overlapping of the white line and the red band at +40 on the latitude axis). The group was very concerned about the consequences suggested by the results in this figure. Overall, the group felt that the tree species in the spruce–fir forest type may not be well adapted to such large fluctuations in climate conditions.

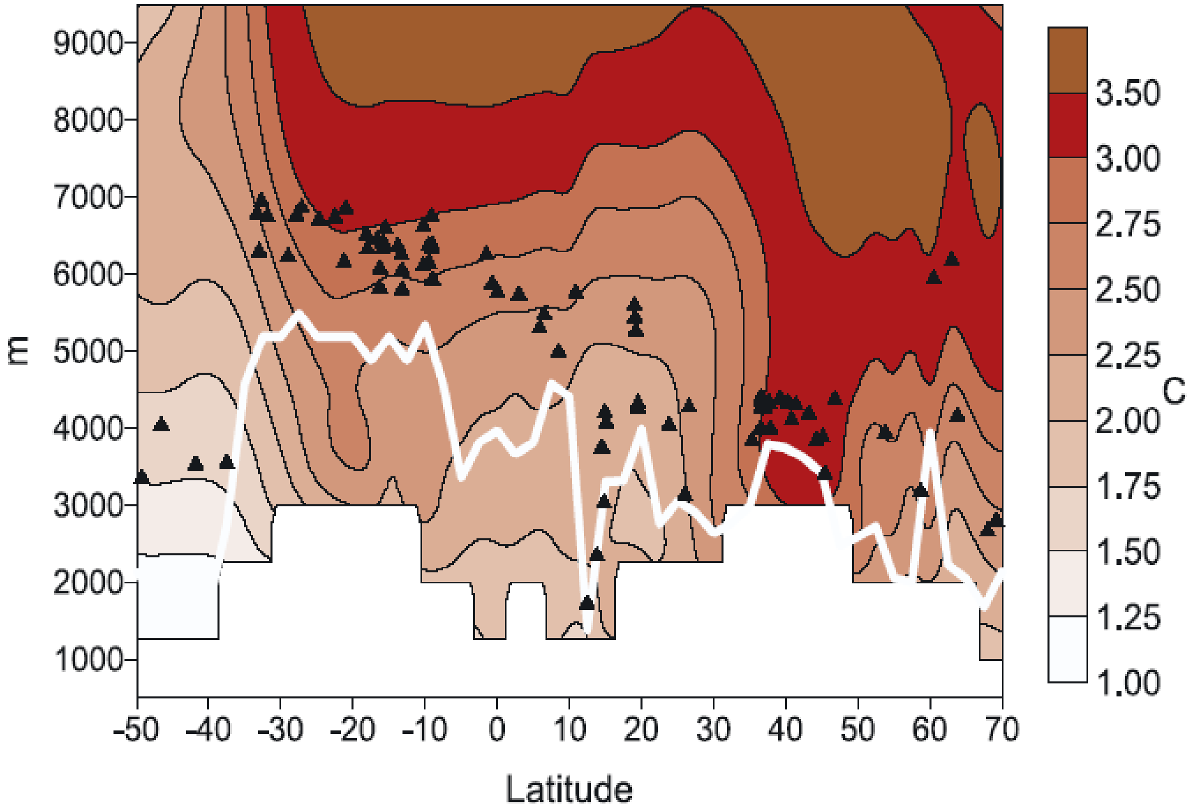


Figure 2. Predicted mean temperature change under the doubled CO_2 scenario from 7 GCMs, from Bradley et al. (2004)[3]. The white line shows the approximate ridge line of the Rocky Mountain/Andes ranges. At 40° north latitude and 3000m elevation, the figure shows predicted summer temperature increases in the 3.0 to 3.5° C range.

Knowledge gaps

The subgroup participants identified the following knowledge gaps:

- There is a poor understanding of the adaptability of species that are currently at lower elevations (*e.g.* Douglas-fir, ponderosa pine). Thus, there is uncertainty about the potential for succession.
- What is the water balance threshold that leads to direct mortality?
- Change in growth over time in response to altered climate?
- Drivers of "new" insects that will become threats? (thought to be temperature for some, but this is a hypothesis)
- Effect of climate change (changes in temperature & precipitation) on host defensive systems.
- Allocation of carbon between growth and production of defensive compounds as the climate changes.
- Will increased temperature lead to decoupling of the insect – fungi symbiosis?

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[3] Bradley, R.S., Keimig, F.T. and Diaz, H.F. 2004. Projected temperature changes along the American cordillera and the planned GCOS network. Geophys. Res. Lett. **31**:L16210.

Tools & models

The subgroup participants identified the following gaps:

- More complete vegetation inventory is needed.
- Need to identify locations / conditions that would be suitable as refugia for preferred species.
- Need to understand the rate of change in climate drivers relative to the life cycles of the various organisms – hosts vis-à-vis pests
- Need work on how to scale up fine scale models to coarser scales.
- Need work on how to move from single species models to functional group models
- Need to think about what is the right scale to address different questions.

2.3 East Cascades ponderosa pine

Ecosystem overview

The group chose to look at a broader system than just what was indicated on the map. The map shows a very narrow ponderosa pine area, but the group felt that what happens on the larger region is also important and that this context helps to define what happens in the selected area.

Vegetation

This ecosystem is dominated by ponderosa pine with different species present at different elevations. Across the system the species mix is dependent on water, soil type, temperature, and elevation. Beginning from higher elevations and going down, some of the other common species that are present on the site are:

- lodgepole pine (dry, cool sites);
- true firs and Douglas-fir (wetter sites);
- larch; and
- juniper.

The understory vegetation on these sites is likely to be one or more of the following (again dependent on elevation and moisture):

- ocean spray;
- service berry;
- buck brush;
- manzanita;
- sage/bitter brush; and
- native grasses/cheatgrass.

Insects and pathogens

A wide variety of insects and pathogens are found in the system and are listed below:

- bark beetles: mountain pine beetle, western pine beetle, *Ips*, *Valens*, root insects;
- defoliators: Douglas-fir beetle, tussock moth, budworm, pine engraver, larch case bearer;
- other insects: Pandora moth, pine whites;
- other insects that feed on seeds, cones, and regeneration;
- dwarf mistletoe;
- root diseases: annosus, *Armillaria*, black stain, blue stain;
- rusts, gall rusts;
- needle/foliar diseases (*e.g.*, *Elytroderma*);
- decay fungi; and
- seed fungi.

Other disturbances

This system is highly altered from its condition in the early 1900s. Land-use change and urbanization have become very important, especially at lower elevations and along existing roads. With this urbanization has comes an increase in ozone and air pollution which have a negative impact on the trees. These changes are expected to continue at a relatively high rate, independent of climate change.

Fire patterns have also changed over the last century. In the early 1900s the main natural disturbance was low severity fire. These fires were then suppressed beginning later in the 20th century, which has allowed many other tree and plant species to thrive, and therefore has changed the structure of the forests. Fire size and severity are expected to increase even without a changing climate.

Animals play a large role in affecting regeneration success in this ecosystem. For example, rabbits and rodents feed on seeds while porcupines and ungulates feed on the regenerating trees.

Climate change

Both models indicate that this area will experience warmer, drier summers and warmer winters. Precipitation patterns will change, with the snow line becoming much higher and less precipitation falling as snow. Summers are likely to be drier than they are currently.

The area of ponderosa pine will expand up the elevation gradient. Currently, its high-elevation range is mostly limited by competition. Climate change will remove some of the tree species that are currently more successful and will allow the ponderosa pine to colonize those areas.

There will be more insect activity. Increasing temperatures will help bark beetles to expand to have more generations per year. Mountain pine beetle may disappear from the system, but will be replaced by some other bark beetle such as southern bark beetle or one of the five bark beetles currently operating in Mexico.

There will likely be more pathogen-related mortality. It is thought that temperatures influence pathogens, and that increasing temperatures will increase pathogen activity. However, little is known about this relationship, making it a major knowledge gap.

Changes in climate will bring surprises and may destabilize some existing relationships. In this system the larch case bearer, a non-native insect, has been controlled through the use of parasites. Recently however, the larch case bearer population is increasing, and it is thought that the warmer temperatures are affecting the insect and the parasites differently so that the parasites can no longer control the insect's population.

One way to think about the overall changes in insect behaviour is to track the data in the insect surveys. If summarized over time, these are likely to show that the endemic levels of insects are rising significantly, and becoming close to the current epidemic levels, as shown in Figure 3.

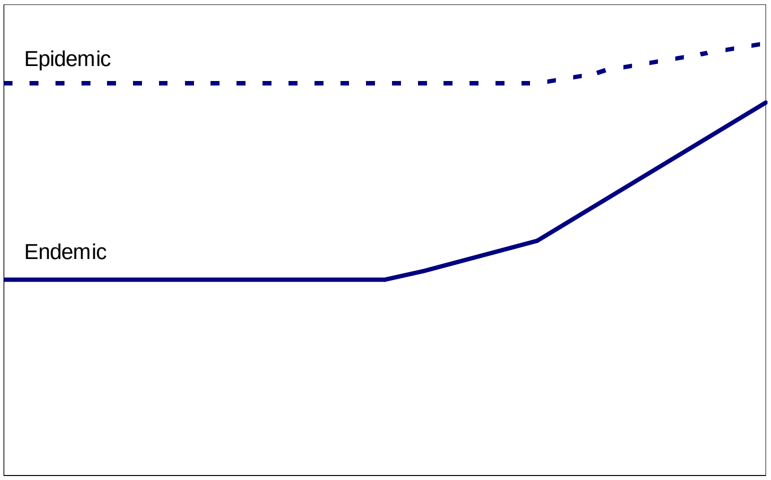

Figure 3. Total levels of endemic insects are expected to rise over time under a warming climate.

The warming and drying trend predicted under the climate change scenarios will also increase the likelihood of fires. These fires will be larger and more severe, especially at higher elevations. There will be fewer trees regenerating after a fire due to increased severity (fewer trees surviving), increased size of the fire (more of the area further from seed sources), and increased regeneration mortality from higher insect and pathogen activity. Eventually, much of the currently forested areas will convert to predominantly brush lands with buck brush and cheat grass.

While fires will likely cause the greatest immediate change on the overall structure of the forest, insects will have large impacts on selected species. The more time before the first large fire, the more likely it is that there will be insect outbreaks, which could kill huge areas of a given species. For example, a bark beetle outbreak could kill pines; a larch case bearer output could kill larch; or tussock moth could kill Douglas-fir. Any of these outbreaks becomes more likely as insect populations increase and trees experience more stress.

Finally, the subgroup noted the role of volcanoes as a source of major change in these systems. Volcanoes are independent of climate change, but what regenerates afterwards will be a function of the new climate.

Knowledge gaps

A summary of the knowledge gaps that were identified by this group are:

- phenological relationships among trees and fungi, mistletoe and micro-organisms;
- pathogens: current distribution and range;
- pathogens: minimum and maximum temperature preferences and response to extremes;
- knowledge of insects and pathogens from outside the area such as Mexican bark beetles and various Asian insects;
- relationship between insects and their predators;
- relationships between climate, insects, and the insects’ parasites (*e.g.*, climate, larch case bearer, and the parasite of the larch case bearer);
- genotypic variability and plasticity of host;
- synergies between fire, insects, and pathogens; and

- management actions in the face of no-analog vegetation systems and climate change that can address all the issues in this area: wildland urban interface, threatened and endangered species, and carbon sequestration.

Tools & models

The main resource that this group identified as being useful would be a tool/website/database that could make GCM output available to meet local needs. GCM data is usually global, or at some other very large scale and needs to be downscaled to specific locations at different spatial scales. With such a tool, users involved in planning at the forest or the watershed would have better access to relevant data. In addition, climate data should come from a variety of the existing scenarios, models, and downscaling techniques. Finally, the data must be easy to download so others doing modelling or planning can use common GCM information and assumptions as part of their plan development.

All models that use biological integrators (*e.g.*, site index) will need to be revised. For example, FVS is based on the assumption of static site index or other similar measures which are now changing. VDDT and other succession models are also based on historical assumptions about states and disturbances. All these basic assumptions are likely to change over the next 100 years and few of these assumptions can be easily incorporated into the models. Thus, there will need to be more dynamic vegetation and climate sensitivity in VDDT, Landsum and other successional-class models.

There is a need for coupled hydrology and disturbance models which use climate information. This will become especially important as precipitation patterns change (coming as rain rather than snow, coming at different seasons, or at different amounts) and as the vegetation on the landscape is altered.

2.4 Northern boreal

Ecosystem overview

The current landscape is dominated by lodgepole pine, but there are significant amounts of spruce, subalpine fir, Douglas-fir, aspen and birch as well. Following disturbance, the subsequent species composition of the forest depends on the kind of disturbance: fire favors retention of lodgepole pine, while other disturbances favor species mixtures. Seed source, however, is also important during regeneration.

Many different disturbance agents currently operate on the landscape. The main ones are mountain pine beetle, fire, spruce beetle, and western balsam bark beetle. Others include:

- foliar diseases such as *Dothistroma*
- insect defoliators (2 year cycle budworm)
- minor bark beetles (*Ips*)
- stem rusts such as *Comandra*
- root diseases such as *Tomentosus*
- heart rots (*Phellinus*)

Other insects and diseases are thought to be moving into the boreal system. Although they are either not yet present or are not currently causing concern, they are expected to become more common in the future, independent of the changing climate. Some of these include:

- black stain
- *Armillaria*
- Swiss needle cast
- European spruce beetle
- understorey shrubby plants

Climate change

Under future climate change scenarios, adaptation of both tree species and their disturbance agents becomes important. Trees adapt slowly, with selection operating over the multi-decadal reproductive time frame. Changes in fitness – either through selection or through the migration of more fit types – is slow compared to the life cycles of many of their pests. Disturbance agents such as insects and some fungal diseases can change very quickly, on an annual basis. The underlying genetic knowledge about the trees and their disturbance agents is important, and not always well known.

The subgroup felt that climate change will affect both the allocation of resources within individual trees, and their phenology. These phenological changes could play an important role in affecting the trees' susceptibility to different insects or diseases.

In the short term, the impact of mountain pine beetle will reduce the amount of pine in these forests and wetter sites will show an increase in spruce. As the forest moves from being pine-dominated to spruce-dominated, the incidence of mountain pine beetle will decrease and there will be increases in the levels of *Tomentosus* root disease and spruce beetles.

The group noted that some predictions of the future ecosystem indicate that parts of the boreal ecosystem could become much more dominated by shrubs, which could suppress forest regeneration.

Forest management practices will also need to change under new climate. Forest managers will need to consider the forest characteristics they want to manage for. Also, to minimize the risk of catastrophic losses (due to a lack of understanding about basic biological interactions), they will likely want to ensure that they have a variety of tree species across the entire the landscape.

History

Little is known about this ecosystem from the older palaeographic records. There are reconstructions of *Dothistroma* over the past two centuries, as well as long term reconstructions of mountain pine beetle and fire history.

Knowledge gaps

The subgroup identified the following areas that require better information:

- Good plot and inventory data on where host and disease are currently.
- Good monitoring of different disturbance agents.
- More models that incorporate meteorological data.
- Improved spatially explicit climate prediction at the daily scale. Many insects and pathogens (*e.g.*, *Dothistroma*) are very sensitive to daily patterns in temperature and precipitation.
- More information about the role of changes in CO_2 and precipitation (and whether it is rain or snow) in tree, insects, and pathogen survival, growth, susceptibility, and interactions.

Tools & models

Some of the tools that the group thought would be useful were:

- Good retrospective databases.
- A revival of FIDS (Forest Insect and Disease Survey – a national program that used to be in place in Canada).
- Improved mapping tools that would allow users to get continuous monthly five-year average profiles of temperature and precipitation by point or area. These averages would be for both historical and future scenarios.
- Individual climate sensitive models of agents.

3. Summary

On the final day of the workshop the participants were asked to summarize what they had learned about the systems: how they might change, how to think about those changes, general knowledge gaps, and modeling needs.

General messages

Participants had two clear messages. The first message was that **things will change**. In many areas there will be more stressed trees, increased insect and pathogen activity, more native and non-native invasive species (plants, insects, pathogens), and an increase in fires. Trees adapt slowly, while insects and pathogens can adapt more quickly. During this extended period of adjustment, future **endemic** levels of insects and diseases resemble current **epidemic** disturbances. Given the anticipated rate of change, it is unlikely that existing systems will just migrate from one place to another.

Some ecosystems will be completely new: new communities of tree and plant species, with different suites of insects and pathogens. If forests do remain on a particular site, similar functional types of insects and pathogens will likely remain, although they may be different species. For example, mountain pine beetle may become rare in some pine forests, but would likely be replaced by a species better-adapted to the future climate, which would perform a similar functional role as MPB does today. Similarly, current root diseases and defoliators may become rare or absent, and be replaced by similar functional agents that may themselves be absent or rare today.

Such changes could come about through a cascade of interactions. For example, an insect outbreak might result in a widespread loss of pine species, with subsequent regeneration to spruce-dominated forests. Such new forest structures could then become a more widespread substrate to a root disease like *Tomentosus*, which is currently more restricted.

Finally, there may be geographic regions that are particularly at risk to more extreme changes in future climate. One example of this possibility is the region around 40^o North latitude and 3000 ft elevation (see Figure 3), where annual changes in excess of 3^o – well above continental averages – may take place.

To anticipate these changes and perhaps learn in advance of them, we may be able to learn from ecosystems on other continents that may already have climatic features and ecosystem structures similar to those which are anticipated in western North America.

Secondly, it is important to bear in mind that species have survived large climate changes before (*e.g.*, during the medieval warming period). **We are not going to completely lose all forests and all vegetation**. In some areas, current species may continue to exist, while in others, the same species may disappear. Although a particular species such as whitebark pine might disappear from some locations, it might become more widely distributed in another part of its geographic range. In all cases, something will come in to replace maladapted trees. It could be other tree species (*e.g.*, hardwoods, or species from warmer areas) or grasses and shrubs.

Areas of uncertainty

When we try to predict what will happen in the future under different scenarios of climate change, we need to think about a wide variety of topics that will affect what species will be present in different locations. Some of these topic areas are:

- **Water-use efficiency –** How can trees best respond to the amounts and timing of precipitation, and which of the species that are present on a site or nearby sites will be able to adapt to the new moisture levels.
- **Genetics** – While there may be trees of the same species distributed across a wide range of ecosystems, they are all genetically different, and beneath the homogeneity of the species-label, there is a finer structure of locally adapted genomes. Thus, even though a species may grow in warmer and colder areas for example, the trees that are growing in the colder areas may not be genetically capable of surviving warmer weather.
- **Scales** – We need to think across spatial, ecological, organism, and genetic scales.
- **Interactions and Synchrony** – The relationships that create sustainable ecosystems are very important. We need to think about what conditions will hold (*e.g.*, cheat grass will probably continue to do very well), what relationships will break down (*e.g.*, the timing between bird migrations and peak populations of the insects that they feed on; between fungi or insects and their hosts), and what new components are immigrating from outside the system (*e.g.*, other tree, insect and pathogen species). These components and their interactions will have a profound impact on whether the system will undergo dramatic change, or the how the system will change. For example, if the synchrony between birds and insects breaks down, even if a tree species can survive the new climate, it may be decimated from insect outbreaks. Likewise, synchronous relationships between seed fungi and their hosts; or larch case bearers and their hosts, may be upset by climate change.

Knowledge gaps

As part of each ecosystem discussion, participants compiled a list the knowledge and research gaps that they considered the most relevant to their ecosystem. These more detailed lists are enumerated in Section 2 of this report, as part of the discussion for each ecosystem. The concluding plenary discussion identified some additional general knowledge gaps.

The first general knowledge gap concerns **the role of water** in tree health. Although water is obviously necessary, there are gaps in detailed species-level knowledge about how much water trees really need for survival, and at what level lack of sufficient water causes trees to become stressed.

A second general gap is the **direct role of climate on insects and pathogens**. While some relationships (*e.g.*, the role of temperature in creating multivoltine insect cycles) are understood for some species, the direct effects of climate are not well known for the pathogens and many of the insects that are part of every ecosystem. For example, what is the impact of increased precipitation on pathogens? The interaction between these two kinds of knowledge and the impacts of indirect effects (*e.g.*, water-stressed trees being more susceptible to insect attack) will play a crucial role in the future of the forests.

The third information gap concerns **the large body of literature**. The number of published papers pertaining to climate change and the effects of climate change on living things is growing at a pace that is difficult for most scientists to keep pace with. The group felt that it would be very useful to have a resource that could serve as a clearing house for the synthesis of current and recent literature. This would allow scientists to educate themselves and broaden their understanding of the range of climate issues without being swamped with details. It was also noted that knowledge of the literature from other countries such as those in Eastern Europe can be very valuable because their approaches may be different than in North America and provide additional insights and information. Finally, older literature could be reassessed from a different view-point to see what information about climate change impacts may be present. For example, studies of trees grown in pots may give information about what trees do when stressed.

Finally, it was noted that a **lack of funding** is a major impediment to finding answers or more information about many of the knowledge gaps that were identified by the different groups.

Modeling needs

The concluding plenary discussion made some broad recommendations for model developers.

First, **model developers** (or development groups) need to re-evaluate existing models in light of climate change. Many models, including all those that use biological integrators, will need to be revised to some degree. Under a changing climate, the assumptions on which they are based will no longer hold. Developers will need to first decide which aspects, drivers, or indicators of climate change should be incorporated into their model. They then need to decide how to modify their models to incorporate these aspects of climate change.

Model users need improved access different types of models, whether those are small-area mechanistic-process models, empirical-statistical models or large area detailed spatial models. Each works at different scales and has been designed to answer or inform different problems. Users also noted that their ability to make predictions about climate change impacts were limited by having single simulations of future conditions at single years: 2050 and 2100. They stated that they find ongoing multiple years of (daily) climate records necessary, to gain a sense of the impact to the forest-insect-pathogen systems.

Incompatible model scales emerged as a key unsolved problem facing climate and ecosystem modellers. At the time scale, the insect and pathogen specialists at the workshop repeatedly pointed out their need for daily-resolution (sometimes within-day) data on temperature and precipitation, sequences or changes in daily sequences of temperature and precipitation, and the form of the precipitation. In contrast, GCMs generally predict monthly climate measures. Daily weather (temperature and precipitation) are beyond current GCM models, and can be the key to the phenology of epidemic outbreaks. At the spatial scale, many models require information at for a forest or a stand within a landscape. In contrast, GCMs generally predict at a half-degree modelling cell size, that with some effort can be downscaled to a 5km grid.

When the inputs are reversed, there is a similar problem of allowing GCMs to be informed by vegetation and insect and pathogen models. Current global vegetation models are currently much simpler than the research models developed for insect and pathogens. GCMs generally cannot use information at a fine spatial or temporal scale.

The key to solving these related problems will be to discover the key simplifications that will bridge these very different temporal and spatial scales.

Completely new models may be necessary to solve new or emerging problems. For example, one subgroup pointed out that there is a need for coupled hydrology and disturbance models which use climate information. This will become especially important as precipitation patterns change and as the vegetation on the landscape is altered. New disturbance models may be necessary to help understand and predict changes in the new forest complexes.

Providing guidance

One important question that was explicitly not addressed in detail at the workshop was what kind of guidance to provide to forest managers. This question is its own complex topic. The guidance that forest managers need depends on their goals for the system (*e.g.*, to maximize timber, maintain existing ecosystem structure, maintain the presence of a forest, maintain habitat for an endangered species, maximize carbon sequestration, *etc.*) At the end of the workshop, we had a brief discussion of this topic in plenary. Some preliminary suggestions were:

- Start planting species that will be adapted for the predicted climate to ensure that they will be there.
- Ensure that a variety of species is planted. Monocultures are less likely to survive because they can encourage large scale insect or pathogen outbreaks (*e.g.*, MPB in BC or western white pine in the US).
- Plant trees that fill a niche, but are less susceptible to known (*i.e.*, already in the system) or probable (*i.e.*, coming from outside the current system) insects and disease.

All participants agreed that this topic area is huge and needs additional thought and discussion. Thus, all the preceding suggestions could actually be framed as questions, so they are possibilities that can be thought about further before passing them to a manager.

Next steps

This workshop was likely the first of many concerned with forests and climate change. In this workshop WWETAC staff learned more about how climate change will affect certain ecosystems, how people other experts think about those changes, and about the many knowledge, research, and modeling needs. WWETAC staff will take the information that they have learned here and will apply it in various possible ways:

- Set up cooperative projects between WWETAC and other scientists to help address some of the knowledge or research needs. (*e.g.*, Susan Frankel’s suggestion to run a similar workshop just discussing current state of knowledge of the impact of climate on pathogens);
- Hold a workshop to discuss climate and management models in the national forests;
- Consider setting up a center that provides reviews and summaries of current and past literature about impacts of climate change on forest ecosystems.

Appendix A: Workshop Participants

Name	Affiliation	Contact	Group
Bov Eav	PNW	beav@fs.fed.us	
Jerry Beatty	WWETAC	jbeatty@fs.fed.us	
Terry Shaw	WWETAC	cgshaw@fs.fed.us	
Becky Kerns	WWETAC	bkerns@fs.fed.us	
Judith Haigler	WWETAC	jhaigler@fs.fed.us	
Bridgett Naylor	WWETAC	bnaylor@fs.fed.us	
Alan Ager	WWETAC	aager@fs.fed.us	
Bill Hubbard	WWETAC	whubbard@uga.edu	
Don Robinson	ESSA	drobinson@essa.com	
Sarah Beukema	ESSA	sbeukema@essa.com	
Lorne Greig	ESSA	lgreig@essa.com	
William Hargrove	EFTAC	whargrove@fs.fed.us	NB
Kathy Lewis	UNBC	lewis@unbc.ca	NB
Paul Hennon**	PNW	phennon@fs.fed.us	NB
Rona Sturrock	PFRC	rsturrock@pfc.forestry.ca	NB
Jeff Hicke**	U Idaho	jhicke@uidaho.edu	NB
Bill Jacobi	CSU	william.jacobi@colostate.edu	NB
Jeff Stone	OSU	stonej@science.oregonstate.edu	NB
Harry Kope	BC Forests	Harry.Kope@gov.bc.ca	NB
Drew McMahan	RMRS	dmcmahan@fs.fed.us	NB
Susan Frankel	PSW	sfrankel@fs.fed.us	PP
Don McKenzie	PNW	donaldmckenzie@fs.fed.us	PP
Nick Crookston	RMRS	ncrookston@fs.fed.us	PP
Chris Fettig	PSW	cfettig@fs.fed.us	PP
Jane Hayes	PNW	jhayes@fs.fed.us	PP
Rebecca Kennedy	PNW	rebeccakennedy@fs.fed.us	PP
Ron Nielson**	PNW	rneilson@fs.fed.us	SF
Eric Smith	FHTET	elsmith@fs.fed.us	SF
Barbara Bentz	RMRS	bbentz@fs.fed.us	SF
Linda Joyce	PSW	ljoyce@fs.fed.us	SF
Ellen Goheen	USFS/R6	egoheen@fs.fed.us	SF
Brian Geils	RMRS	bgeils@fs.fd.us	SF
Tom Swetnam**	U of A	tswetnam@ltrr.arizona.edu	SF
Ken Brewer	RSAC	kbrewer@fs.fed.us	SF
Ann Lynch	RMRS	alynch@fs.fed.us	SF
Catherine Parks	PNW/LaGrande	cparks01@fs.fed.us	SF

NB = Northern boreal subgroup
PP = Eastside cascades ponderosa pine subgroup
SF = High elevation spruce fir subgroup
** Plenary speakers
Craig Allen (USGS, craig_allen@usgs.gov) participated on June 26th via phone.

Appendix B: Invitation to Workshop

Greetings:

You are invited to participate in a workshop focused on climate change and insect and pathogen interactions, June 26 - 28, likely in Portland Oregon. The Western Wildland Environmental Threat Assessment Center will be hosting this small, focused, working workshop.

The goals of the workshop are to:

- Explore and advance the state-of-the science for the integrated analysis and prediction of climate change and native and exotic insect and pathogen processes for risk assessment across multiple spatial and temporal scales.
- Develop a RD&A strategy to advance synergistic analysis in the context of risk assessment.
- Facilitate development of tools to assess and quantify climate change and native insects and pathogen synergistic effects on natural resources and ecosystem services at scales relevant for forest management and planning.
- Produce a series of rapid threat assessments focused on the interaction of climate change and insect and pathogen threats to western wildands.

This email is a “heads-up" and for some of you a date correction for the Workshop. More information will be forthcoming with workshop and hotel details. Please let us know if you are able to attend by April 1.

RSVP to: jhaigler@fs.fed.us. Please contact Terry Shaw (cgshaw@fs.fed.us) or Becky Kerns (bkerns@fs.fed.us) if you have questions regarding the workshop.

We look forward to your participation!

Sincerely,

/s/Jerry Beatty
Director
541.416.6583

/s/Charles G. “Terry” Shaw
Chief Scientist
541.416.6600

/s/Becky Kay Kerns
Research Ecologist
541.416.6602

Western Wildland Environment Threat Assessment Center
USDA Forest Service, Pacific Northwest Research Station
3160 NE 3rd Street
Prineville, OR 97754
http://www.fs.fed.us/pnw/WWETAC/index.shtml

Judith L. Haigler
Program Coordinator
Western Wildland Environmental Threat
Assessment Center (WWETAC)
3160 NE Third Street
Prineville, OR 97754
(541) 416-6618

Appendix C: Workshop Briefing Document

Climate Change, Insects, Pathogens and Forests Workshop Briefing Document

Workshop Goals

The workshop has three goals:

- Explore and advance the state-of-the science for the integrated analysis and prediction of climate change and native and exotic insect and pathogen processes for risk assessment across multiple spatial and temporal scales.
- Discuss current tools used to assess and quantify climate change, insects and pathogens, and synergistic effects on natural resources and ecosystem services at scales relevant for forest management and planning.
- Assist WWETAC in developing a collaborative RD&A strategy for risk assessment that includes the interaction of climate change and insect and pathogen threats to western wildlands.

We think it would be premature to try to develop or modify any tools or models at this workshop. Our focus will be to develop conceptual ideas that will be useful for doing risk assessments in the face of climate change. **WWETAC will then use this information to develop a RD&A strategy, program of work, and fund proposals using concepts and collaborations developed at this workshop.** The workshop activities are described in more detail below.

Overview

Forest management and planning has always relied on observations and lessons from the past in order to help plan for the future; unusual events are usually considered anomalies and frequently discounted or ignored. Yet within the current planning horizon, environmental conditions are now predicted to change significantly in many areas. This change will have an impact on the geographic ranges of different vegetation species and on their insect and pathogen complexes. In some areas our current ideas about “normal” ecosystem behaviour will change, and we will see more “unusual” events.

One of the difficulties with these changes is that for the most part, we do not know how to predict their impacts: past experience may not be an adequate guide to future system behaviour. There are only limited models or tools which quantify how ecosystems might change, particularly those that include insects and pathogens. In many cases, we are not even sure what the changes will be. Although the emerging concepts of resilience, panarchy and system reorganization may be qualitatively helpful, their quantitative application is still undeveloped.

We are keeping future tool development in mind, but we understand that we are still learning about asking the right questions. In this workshop we want to keep our eyes on the mixture of climate, biological and human aspects that will all interact over the coming years. For this reason we will be looking at two story lines created by the Intergovernmental Panel on Climate Change (IPCC), each representing a contrasting high level scenario of global human activity over the coming century. Each IPCC scenario is simulated with one of two Global Circulation Models (GCMs): MIROC and CSIRO. The two models were selected because one is thought to be more sensitive to precipitation, while the other more sensitive to temperature.

The main work of the meeting will be a series of "thought exercises" in a plenary session and then in subgroups. We will examine four different ecosystem types in light of two sets of climate change predictions over the next 100 years. Participants will be given a set of questions that may help their thinking, and asked to discuss what they think could be the impacts of the changing climate on the current vegetation and on the insects and pathogens that either are a current part of each ecosystem, or that could become a part of the ecosystem in the future. Each subgroup will also be given a charge – a set of responses that each group will be asked to briefly summarize in the closing plenary session. At the end of these discussions, we hope to have learned more about the current state of the ecosystem, what could occur there as the climate changes, what knowledge gaps exist, what questions need to be asked when doing risk assessments for other ecosystem types, and how the science of risk assessment can be advanced through conceptual and simulation models.

Climate Scenarios

As part of the brainstorming exercises we will be doing, you will be able to overlay current and future climate simulation maps with other spatial information such as current ecosystem boundaries and topography at different scales, *etc*. We used two scenarios of future climate: the CSIRO and the MIROC GCM simulations of the **B1** and **A2** IPCC futures, respectively. We chose these combinations of models and scenarios from the available suite in order to create strongly contrasting predictions. In these scenarios, the B1 future (as modeled by CSIRO) has lower CO_2 emissions and less change in global mean temperature, while the A2 combination (as modeled by MIROC) is the opposite. For reference, current atmospheric CO_2 concentration is approximately 380 ppm.

> **The B1 storyline** and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives. Atmospheric CO_2 is stable at around 550 ppm in 2100. (IPCC 2001)
>
> **The A2 storyline** and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. Atmospheric CO_2 is still increasing at around 850 ppm in 2100. (IPCC 2001)

The results of the two simulation climate scenarios have been downscaled from the GCM half-degree grid scale to a 5 minute (approximately 8 km) scale using PRISM (thanks to Ron Nielson's MAPPS team at PNW). The simulated data provide us with four pieces of monthly data at 5 minute (approximately 8 km) resolution: minimum/maximum temperature and minimum/maximum precipitation. Using the current and future simulations for the 4 ecosystems, we have produced summary and map information for selected time periods. Summary information is included in this document, but because of the enormous amount of available information, we do not provide detailed maps here. Instead, we will have one laptop for each sub-group with the climate data available for viewing and querying by combining elements in GIS (Table 1). Additional variables can also be calculated using these data.

Table 1. Simulated climate data available for each sub-group at the 5 minute scale (approx. 8 km).

Simulated Climate Time Periods	Ecosystems	Variables
Historical: 1901, 1950, 2000	Northern Boreal	Monthly Minimum Temperature
CSIRO: 2050, 2100	Eastside Cascades	Monthly Maximum Temperature
MIROC: 2050, 2100	Spruce Fir (2 examples)	Monthly Maximum Precipitation
	Pinyon-Juniper	Monthly Maximum Precipitation

Ecosystems

To focus the discussion, we chose the four different ecosystems shown below, to examine in greater depth. We expect that many of the issues and strategies raised in the study of these systems will be applicable elsewhere, and you should not feel constrained by these illustrative systems if you feel that there are important principles to be learned and shared from other settings.

Although the four ecosystems were chosen for a variety of reasons, all are thought to be either experiencing substantial change or are under the threat of substantial change. First, we wanted to ensure that we had one relatively well-understood system so that we could test our scenario analysis approach as a group. We also wanted ecosystems that might be experiencing a complex of potential driving issues: pathogens, insects, elevation, drought-stress, *etc.* During our workshop scoping session it was suggested that we pick our study ecosystems based principally on the magnitude of predicted climate change: those whose climates are expected to change the most, or those in which the two IPCC scenarios give very different predictions. While these ideas have merit, we were constrained by data availability and time, and did not take this approach explicitly.

In addition to the expertise that you bring, we will have available literature and reports (some general, some specific to the ecosystem) to provide additional background on current ecosystem status, host/insect/pathogen dynamics, temperature or precipitation sensitivity, and other related information. We recognize that the vegetation that is in these sites today may not be well suited to the climate in 2100, that past experience may not be a good predictor of the future, and that we may not be able to predict the exotic plants, insects and pathogens that may become part of the system. Part of the goal of the workshop is to explore possibilities, determine what questions we need to be asking about these systems, and see what information gaps there may be.

We will start the process by discussing the pinyon-juniper system as a plenary group. Once we are all comfortable with the process and have made any necessary adjustments, we will break into three sub-groups. Each sub-group will be assigned one of the other systems. Note that each person has already been assigned to a group (see Participant List at the end of this document).

Southwestern Pinyon Juniper Woodlands

Pinyon pine and various juniper species are among the most drought-tolerant trees in western North America, and pinyon-juniper ecosystems characterize lower tree lines across much of the West. Although pinyon-juniper woodlands appear to be expanding in some areas, possibly due to fire exclusion or cessation of Native American fuel wood harvesting, they are clearly water-limited systems. At fine scales, pinyon-juniper ecotones are sensitive to feedbacks both from environmental fluctuations and existing canopy structure that may buffer trees against drought to some degree. However, severe multi-year droughts periodically cause dieback of pinyon pines, overwhelming any local buffering.

Dieback of both ponderosa pine and pinyon pine occurred during and before the 20th century, but the current dieback is unprecedented in its combination of low precipitation and temperatures indicative of global warming. Global warming is the predisposing factor, and pinyon pine mortality and fuel accumulations are inciting factors. Drought stress in pinyon pine has also expressed itself through increased susceptibility to attack by pinyon *Ips* beetles. Ecosystem change, possibly irreversible, comes from large-scale severe fires that lead to colonization of invasive species that further compromise the ability of pinyon pines to re-establish.

(from the draft SAP report, Joyce et al.)

Reading List

Acrobat copies of these documents may be found here:

ftp://ftp.essa.com/pub/essa/ClimateChangeWorkshop/

Documents are organized by ecosystem name.

Allen, C.D. 2007. Cross-scale interactions among forest dieback, fire, and erosion in northern New Mexico landscapes. Cross-scale interactions and spatial heterogeneity: consequences for system dynamics. Ecosystems. *In press:* ***Hardcopy only; please do not copy or distribute***.

Allen, C.D. and D.D. Breshears. 1998. Drought-induced shift of a forest/woodland ecotone: rapid landscape response to climate variation. Proceedings of the National Academy of Sciences, U.S.A. **95**:14839-14842.

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Gray, S.T., Betancourt, J.L., Jackson, S.T. and R.G. Eddy 2006. Role of multidecadal climate variability in the range extension of pinyon pine. Ecology **87**:1124–1130.

Mueller R.C., Scudder C.M., Porter M.E., Trotter III R.T., Gehring C.A., and T.G. Whitham. 2005. Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. Journal of Ecology **93**:1085-1093.

Romme, W. and many others. 2007. Historical and modern disturbance regimes of Piñon-Juniper vegetation in the western U.S. Colorado Forest Restoration Institute and The Nature Conservancy. 16pp.

Seager, R. and many others. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science **316**:1181-1184.

Shaw, J.D., Steed, B.E. and L.T. DeBlander. 2005. Forest Inventory and Analysis (FIA) annual inventory answers the question: what is happening in Pinyon-Juniper woodlands? J. For. **Sept**:280-285.

Swetnam T.W. and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate **11**:3128-3147.

Wilcox, B.P., Breshears, D.D. and C.D. Allen. 2003. Ecohydrology of a resource-conserving semiarid woodland: effects of scale and disturbance. Ecological Monographs. **73**:223-239.

http://www.fs.fed.us/r5/spf/fhp/fhm/aerial/pinyon/pinyon-mortality.shtml

Northern Boreal

Lodgepole pine (*Pinus contorta var. latifolia*) is widely distributed across western North America, often forming nearly monospecific stands in some locations. Lodgepole pine is the principal host of the mountain pine beetle (*Dendroctonus ponderosae*), and monospecific stands are particularly vulnerable to massive mortality during beetle outbreaks.

Recent beetle outbreaks have caused extensive mortality across millions of hectares, with large mature cohorts (age 70-80 yr) contributing to widespread vulnerability. Warmer temperatures facilitate bark beetle outbreaks in two ways. First, drought stress makes trees more vulnerable to attack and secondly, insect populations respond to increased temperatures by speeding up their reproductive cycles (*e.g.* to 1-year life cycles. Warming temperatures would be expected to exacerbate these already devastating outbreaks northward and even eastward across the continental divide, but even at current levels of recent mortality lodgepole pine ecosystems may be poised for significant changes. Warmer temperatures in combination with the greater flammability of dead biomass associated with beetle mortality sets up ecosystems for extensive species conversion following stand-replacing fires, plus a favorable environment for the establishment of species adapted to warmer temperatures, for example interior Douglas-fir or even ponderosa pine. In northern BC (the area of focus for this workshop) the region has also experienced unprecedented outbreaks of *Dothistroma* needle cast disease, which might be related to climatic changes..

(from the draft SAP report, Joyce et al.)

Reading List

Acrobat copies of these documents may be found here:

ftp://ftp.essa.com/pub/essa/ClimateChangeWorkshop/

Documents are organized by ecosystem name.

Campbell, E.M., Alfaro, R.I. and B. Hawkes. 2007. Spatial distribution of mountain pine beetle outbreaks in relation to climate and stand characteristics: a dendroecological analysis. J. Integr. Plant Biol. **49**:168-178.

Hicke, J.A., Logan, J.A., Powell, J. and D.S. Ojima. 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. J. Geophys. Res. III, G02019 (found under the general reading list section).

McCullough, D.G, Werner R.A. and Neumann, D. 1998. Fire and insects in northern and boreal forest ecosystesm of North America. Annual Review of Entomology, 43: 107-127

Logan, J. and Powell, J.A. 2001. Ghost forests, global warming, and the Mountain Pine Beetle (Coleoptera: Scolytidae). American Entolomologist **47**:160-172.

Woods, A., Coates, D. and A. Hamann. 2005. Is an unprecedented *Dothistroma* needle blight epidemic related to climate change? BioScience **55**:761-769.

High Elevation Spruce Fir

Spruce fir forests occur throughout higher elevations of BC and the western US. They are often relatively steep areas dominated by Engelmann Spruce and subalpine fir. In areas where fire is frequent, lodgepole pine can also dominate. Winters are usually long and cold, with soils remaining frozen for much of the year. In wetter parts of this system, a high snow pack can provide water for the short growing season. Fire and spruce beetle are currently the two main disturbance agents in this system.

Warmer temperatures could affect the type of precipitation that is falling in the winter, perhaps leading to more rain and less snow, which could impact the summer water availability. Warmer temperatures could also increase the likelihood and severity of fires, which could change the species mix on the landscape. Spruce beetles will be affected by species shifts, host availability and the possibility of increased survival or reproductive capability. As well, additional beetle species such as mountain pine beetle may be able to take advantage of warmer winters to attack lodgepole pine in this system.

Reading List

Acrobat copies of these documents may be found here:

ftp://ftp.essa.com/pub/essa/ClimateChangeWorkshop/

Documents are organized by ecosystem name.

Bebi, P. Kulakowski, D. and T.T. Veblen. 2003. Interactions between fire and spruce beetles in a subalpine Rocky Mountain forest landscape. Ecology **84**:362-371.

BC Ministry of Forests. 1998. The ecology of the Engelmann spruce – subalpine fur zone. 6pp

Hansen, E.M. and B.J. Bentz. 2003. Comparison of reproductive capacity among univoltine, semivoltine and re-emerged spruce beetles (Coleoptera: Scolytidae) Can. Entomol. **135**:697-712.

Kulakowski, D, Veblen, T.T. and P. Bebi. 2003. Effects of fire and spruce beetle outbreak legacies on the disturbance regime of a subalpine forest in Colorado. J. Biogeography **30**:1-12.

Romme, W.H. Clement, J., Hicke, J., Kulakowski, D., MacDonald, L.H., Schoennagel, T.L. and T.T. Veblen. 2005. Recent forest insect outbreaks and fire risk in Colorado forests: a brief synthesis of relevant research. Colorado Forest Restoration Institute and others. 24pp.

Eastside Cascades Ponderosa Pine

Ponderosa pine occupies a narrow band on the eastern flanks of the eastern Cascade Mountains, with the band increasing in elevation moving from north to south. Ponderosa pine is often found on coarse-textured soils, where annual precipitation ranges from 350 to 850 mm. These forests have undergone dramatic physiognomic changes in the last 100 years. Once open and park-like, historical fire regimes consisted of very frequent (<25 year mean fire-free interval) to frequent (26-75 year mean fire-free interval) low intensity fires. Decline in the overall extent of eastside old-growth ponderosa pine forest can be attributed to changes in natural disturbance regimes (fire exclusion/suppression), livestock grazing, selective logging of old fire-resistant trees, and extensive road building

Effects of climatic variability on tree growth and forest productivity can be pronounced in forests near the lower tree line, which are typically sensitive to variations in annual precipitation. Warmer winter and spring temperatures in the region are expected to reduce winter snowpack accumulations, shift the winter snowline to higher elevations, and melt snow earlier in the spring. Warmer summer temperatures are expected to increase evaporative demands, which may or may not be offset by higher winter and spring precipitation. At lower elevations, reductions in snowpack will lower the amount of winter precipitation that is stored for soil water recharge in the spring and could increase the severity and duration of summer soil moisture deficits, reducing growth and increasing the risk of fire. Dry forests in the eastern part of the region are projected to expand in response to increased winter precipitation, with increases in vegetation carbon or leaf area also exceeding 50% in some locations (this paragraph summarized from Mote et al., 2003).

(adapted from Franklin and Dryness 1988; Youngblood et al. 2004, Spies et al. 2006, Mote et al. 2003).

Reading List

Acrobat copies of these documents may be found here:

ftp://ftp.essa.com/pub/essa/ClimateChangeWorkshop/

Documents are organized by ecosystem name.

Hessburg, P.F., Agee, J.K. and J.F. Franklin. 2005. Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. Forest Ecology and Management **211**:117-139.

Hessburg, P.F., Mitchell, R.G. and G.M. Filip. 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 pp.

Lehmkuhl, J.F., Hessburg, P.F., Everett, R.L., Huff, M.H., and R.D. Ottmar. 1994. Historical and current forest landscapes of eastern Oregon and Washington. Part I: Vegetation pattern and insect and disease hazards. Gen. Tech. Rep. PNW-GTR-328. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 88 pp.

Spies, T.A., Hemstrom, M.A., Youngblood, A. and S. Hummel. 2006 Conserving Old-Growth Forest Diversity in Disturbance-Prone Landscapes. Conservation Biology **20**:351-362.

Youngblood, A., Max, T., Coe, K. 2004. Stand structure in eastside old-growth ponderosa pine forests of Oregon and northern California. Forest Ecology and Management **199**:191-217.

Charge to Subgroups

The charge to each subgroup is to explore the climate change and insect and disease interactions for each of the assigned ecosystems with the eventual goal of identifying key issues and advancing or facilitating model and tool development for simulations. Participants should explore multiple lines of thoughts and possibilities using the questions and topics provided (provided on the next pages) as a starting point. They should keep in mind that there are two climate change scenarios to consider, and determine what additional questions we need to be asking about these systems or about climate change and system change in general, and see what information gaps there may be and how research can address these.

Each subgroup will have an assigned note taker, facilitator, laptop with climate simulations, projector and access to copies of the key overview papers for the ecoregion. We have tried to arrange the groups based on disciplinary expertise and to maximize a range of perspectives. Each sub-group should appoint a speaker for the final plenary session. This speaker will present the group summary, and there will be time for further discussion. A template for the sub-group summary is provided in the next section.

Template for Subgroup Summaries

Using the following list of questions as a guide, please provide a short verbal and written summary (you can use the laptops and create a Word or PowerPoint file) with key points for the plenary main discussion for each of the major topical areas:

- Ecosystem Overview
- Climate Change Interactions
- Looking In the Rear View Mirror
- Tools for Simulation and Story Telling
- Knowledge Gaps and Research Needs
- Other (if applicable)

Questions

The scientific literature on the impacts of a changing climate on insects, pathogens and their hosts begins in earnest in the early 1990s with the pathologists, but to some it is a relatively novel concept. We want to encourage the development of ideas about the linkages between climate, insects, and pathogens in forested ecosystems that may help land managers be better prepared for change and surprise. Although there may be existing research to help the brain-storming, we also want to encourage ideas that may not yet be tested or that may be ideas from other problem domains.

To help with this we have created a set of questions under several general topics. These questions are not meant to be exhaustive or even be completely answered. They are deliberately general (although in some cases we have provided examples) and are simply meant to stimulate thinking and generate ideas.

Ecosystem Overview

- What are the major host species (or groups) of concern?
- What are the major insect/pathogen/host species (or groups) of concern?
- Are there keystone species or relationships in this system?
- Are there known exotics either already in the system, or anticipated to be in the system soon?

Climate Change (CC) Interactions

- How will CC likely affect the **host species** in the ecosystem?
    - Is the host at the edge of its range? Will CC make it more or less likely to occur in this system?
    - Will CC alter patterns in water availability (*e.g.*, more in the winter and less in the summer)?
    - Will CC cause new or changing stresses (*e.g.*, less winter cold injury from snow packs)?
    - Are there key thresholds to consider (could be species, landscape, system)?
    - Do the possible outcomes differ for the two climate scenarios?
- How will changes in climate affect **insects and pathogens** of the host?
    - *Consider:* increased over-wintering, more generations, earlier emergence, expanded or decreased range, changes to vectors, infection episode.
    - Are there key thresholds to consider?
    - Do you expect to see any host/pathogen/insect interactions disappear, or become more virulent?
    - Do the possible outcomes differ for the two climate scenarios (consider this throughout the exercise)?
- What are the climate cues that could make the **host** more susceptible or resistant to pathogens/insects?
    - *Consider*: increase in CO_2 could lessen food quality (nitrogen) for chewing insects; increased drought could increase tree stress and increase susceptibility to root diseases, cankers, other decay pathogens, or bark beetles.
- For each existing host/pathogen/insect system, how could the range of possible future climates alter the interaction? Consider:
    - Some insects require degree-days while trees also require light. If an insect emerges earlier because of degree-days alone, the tree may not yet provide a food source.
    - Stressed trees may be killed more easily but are also growing less well; could this affect the life history of insects or pathogens?
    - Stress and disease will cause increased mortality and open canopy structure. Could that cause a spiral of additional stress and disease?
    - The range of existing adjacent insects or pathogens could change.
- Are there existing significant invasive species or other biological perturbations in the ecosystem, or recent changes which might render the ecosystem more unstable?
- Do the future climate envelopes suggest that the host species will shift in latitude or elevation? Will this be through direct effects on the host or through change in host/insect/pathogen dynamics?
    - *Consider:* CO_2 effect and increased water use efficiency could offset some temperature increase and water stress; the past might not be a good guide.
    - Will shifts be through direct effects on the host or through changes in host/pathogen/insect dynamics?
- Do you foresee a decline syndrome such as the one suggested for Alaskan yellow-cedar?
- Do the differences in the scenario predictions make it impossible to set a management approach?
- What other disturbance processes would be important in this system, or might become more synchronized?

Looking In the Rear View Mirror

- If you were a pathologist, entomologist or very clever person, what signs might have alerted you to:
    - The 1915 arrival of white pine blister rust: international trading data? Movement of biological materials? Weather? Absence of a rust pathogen among the 5 needle pines.
    - The mid-1980's arrival of *SOD:* international trading data? Movement of biological materials? Changes in west coast weather?
    - Decline of white spruce in Alaska?
    - Pinyon-ponderosa pine mortality in the southwest?

- Are there lessons or principles to apply from the very long backward view to the Pleistocene and beyond?. Species assemblages may be quite different; the emergent self-organization of ecosystems following release and renewal.

Tools for Simulation, Prediction and Story Telling

- Are there existing models available to account for some of the climate change interactions described above? If so, what are they?
- Do you think existing models can be tweaked or developed, or are new tools needed? Think about whether or not the tools available can account for the interactions you have described above, and how they might be used with land management agencies (planning, project work, *etc*).
- For simulation purposes, could groups of insects, pathogens and/or hosts species be treated as groups rather than as species, *e.g.* defoliator bark beetles?
- How different were the predictions for each model (CSIRO and MIROC) and how did these differences influence the discussions or your interpretations of potential impacts?

Knowledge Gaps and Research Needs

- What are linkages/gaps between existing ecological/biological predictive tools and climate models?
- Based on your discussion, outline the major knowledge gaps and research needs. Include methods to approach or tackle these issues, existing challenges, barriers, *etc.*
- Where should we be putting energy and effort for predictive efforts with respect to climate change and insect and disease interactions?
- Can you define specific research topic areas that we could make important progress on in the next 1-2 years?
- What are longer-term issues that need to be resolved or where basic research is needed?

General Reading List

Acrobat copies of these documents may be found here:

ftp://ftp.essa.com/pub/essa/ClimateChangeWorkshop/

Documents are found in the General Reading folder.

Allen, C.D. and many others. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications **12**:1418-1433.

Bachelet, D., Nielson, R.P., Lenihan, J.M. and R.J. Drapek. 2001. Climate change effects on vegetation distribution and carbon budget in the United States. Ecosystems **4**:164-185.

Bachelet, D., Neilson, R.P., Hickler, T., Drapek, R.J., Lenihan, J.M., Sykes, M.T., Smith, B., Sitch, S. and K. Thonicke. 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles **17**:14-1–14-21.

Botkin, D.B., Saxe, H., Araújo, M., Betts, R., Bradshaw, R., Cedhagen, T., Chesson, P., Dawson, T., Etterson, J., Faith, D., Ferrier, S., Guisan, A., Skjoldborg Hansen, A., Hilbert, D., Loehle, C., Margules, C., New, M., Sobel, M. and D. Stockwell. 2007. Forecasting the effects of global warming on biodiversity. BioScience **57**:227–236.

Breshears, D.D. and C.D Allen. 2002. The importance of rapid, disturbance-induced losses in carbon management and sequestration. Global Ecology and Biogeography **11**:1-5.

Burdon, J.J., Thrall, P.H. and L. Ericson. 2006. The current and future dynamics of disease in plant communities. Annual Review of Phytopathology **44**:19–39.

Burkett, V.R. and many others. 2005. Nonlinear dynamics in ecosystem response to climate change: case studies and policy implications. Ecological Complexity **2**:357-394.

Choi, Y.D. 2007. Restoration ecology to the future: a call for a new paradigm. Restoration Ecology **15:**351-353.

Daly, C. 2006. Guidelines for assessing the suitability of spatial climate data sets. Int. J. Climatol. **26**: 707-721.

Fox, D. 2007. Back to the no-analog future? Science **316**:823-825.

Hicke, J.A., Logan, J.A., Powell, J. and D.S. Ojima. 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. J. Geophys. Res. III, G02019.

Levin, S.A. 2005. Self-organization and the emergence of complexity in ecological systems. BioScience **55**:1075-1079.

Loehle, C. and D. LeBlanc. 1996. Model-based assessments of climate change effects on forests: a critical review. Ecol. Mod. **90**:1-31.

Logan, J.A., Régnière, J. and J.A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. Front. Ecol. Environ. **1**:139-137.

Millar, C.I., Stephenson, N.L. and S.L. Stephens. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. App. In press.

Mote, P.W. and many others. 2003. Preparing for climatic change: the water, salmon and forests of the Pacific Northwest. Climatic Change **61**:45-88.

Oren, R. 2007. Responses of forests to atmosphere enriched with CO_2. Presentation to the 34th Annual Symposium of the Association of Graduate Students in the Biological Sciences. Toronto, Ontario. (Powerpoint).

Pascual, M. and F. Guichard. 2005. Criticality and disturbance in spatial ecological systems. Trends in Ecology and Evolution **20**:89–95.

Rehfeldt, G.E., Crookston, N.L, Warwell, M.V. and J.S. Evans. 2006. Empirical analyses of plant-climate relationships for the western United States. Int. J. Plant Sci. **167**:123-1150.

Saxon, E., Baker, B., Hargrove, W., Hoffman, F. and C. Zganjar. 2005. Mapping environments at risk under different global climate change scenarios. Ecology Letters **8**:53-60.

Spittlehouse, D.L. and R.B. Stewart. 2003. Adaptation to climate change in forest management. B.C. Journal of Ecosystems and Management.

Swetnam, T.W., Allen, C.D. and J.L. Betancourt. 1999. Applied Historical Ecology: using the past to manage for the future. Ecol. App. 9:1189-1206.

Thompson, J.N. 1998. Rapid evolution as an ecological process. Trends Ecol. Evol. **13**:329-332.

Invited and Confirmed Participants

Name	Affiliation	Contact	Group
Bov Eav	PNW	beav@fs.fed.us	
Jerry Beatty	WWETAC	jbeatty@fs.fed.us	
Terry Shaw	WWETAC	cgshaw@fs.fed.us	
Becky Kerns	WWETAC	bkerns@fs.fed.us	
Judith Haigler	WWETAC	jhaigler@fs.fed.us	
Bridgett Naylor	WWETAC	bnaylor@fs.fed.us	
Don Robinson	ESSA	drobinson@essa.com	
Sarah Beukema	ESSA	sbeukema@essa.com	
Lorne Greig	ESSA	lgreig@essa.com	
Ron Nielson**	PNW	rneilson@fs.fed.us	All
William Hargrove	EFTAC	whargrove@fs.fed.us	NB
Kathy Lewis	UNBC	lewis@unbc.ca	NB
Paul Hennon**	PNW	phennon@fs.fed.us	NB
Rona Sturrock	PFRC	rsturrock@pfc.forestry.ca	NB
Allen Carroll	PFRC	acarrollApfc.cfs.nrcan.gc.ca	NB
Jeff Hicke**	U Idaho	jhicke@uidaho.edu	NB
Bill Jacobi	CSU	william.jacobi@colostate.edu	NB
Jeff Stone	OSU	stonej@science.oregonstate.edu	NB
Harry Kope	BC Forests	Harry.Kope@gov.bc.ca	NB
Alan Ager	WWETAC	aager@fs.fed.us	PP
Bill Hubbard	WWETAC	whubbard@uga.edu	PP
Susan Frankel	PSW	sfrankel@fs.fed.us	PP
Don McKenzie	PNW	donaldmckenzie@fs.fed.us	PP
Nick Crookston	RMRS	ncrookston@fs.fed.us	PP
Chris Fettig	PSW	cfettig@fs.fed.us	PP
Jane Hayes	PNW	jhayes@fs.fed.us	PP
Rebecca Kennedy	PNW	rebeccakennedy@fs.fed.us	PP
Drew McMahan	RMRS	dmcmahan@fs.fed.us	PP
Eric Smith	FHTET	elsmith@fs.fed.us	SF
Barbara Bentz	RMRS	bbentz@fs.fed.us	SF
Linda Joyce	PSW	ljoyce@fs.fed.us	SF
Ellen Goheen	USFS/R6	egoheen@fs.fed.us	SF
Brian Geils	RMRS	bgeils@fs.fd.us	SF
Tom Swetnam**	U of A	tswetnam@ltrr.arizona.edu	SF
Ken Brewer	RSAC	kbrewer@fs.fed.us	SF
Ann Lynch	RMRS	alynch@fs.fed.us	SF
Catherine Parks	PNW/LaGrande	cparks01@fs.fed.us	SF

NB = Northern boreal subgroup
PP = Eastside cascades ponderosa pine subgroup
SF = High elevation spruce fir subgroup
** Plenary speakers
Craig Allen (USGS, craig_allen@usgs.gov) will participate on June 26th via net meeting.

Appendix D: Applications of GIS Climate Data to Forest Insects and Diseases

This Appendix provides more detail about the GIS-climate data that were prepared for the workshop and suggests other types of information that could be derived from it, along with questions and hypotheses that could be answered or studied using the data.

Background

Monthly data were prepared for the years 1900, 1950, 2000, 2150, and 2100. Years 1900 and 1950 represent historical conditions and year 2000 represents the current conditions. The future years were each taken from two different scenarios of future climate: CSIRO and MIROC GCM simulations of the B1 and A2 IPCC futures, respectively. We chose these combinations of models and scenarios from the available suite in order to create strongly contrasting predictions. In the scenarios, the B1-CSIRO future has lower CO_2 emissions and less change in global mean temperature, while the A2-MIROC combination is the opposite. For reference, current atmospheric CO_2 concentration is approximately 380 ppm.

> **The B1 storyline** and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives. Atmospheric CO_2 is stable at around 550 ppm in 2100. (IPCC 2001)
>
> **The A2 storyline** and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. Atmospheric CO_2 is still increasing at around 850 ppm in 2100. (IPCC 2001)

The results of the two climate scenarios were downscaled from the GCM half-degree grid scale to a 5 minute (approximately 8 km) scale using PRISM (thanks to Ron Nielson's MAPPS team at PNW). The simulated data provide us with three pieces of monthly data at 8 km resolution: **minimum and maximum temperature and cumulative precipitation.**

These four pieces of monthly-scale climate data can be laid over other spatial information such as current ecosystem boundaries, plant community boundaries, watersheds of various orders, or political and administrative boundaries (*e.g.*, state, county). In addition, other climate variables can be (and commonly are) derived from on these three pieces of data.

Types of Data

With the monthly information about temperature and precipitation, it is possible to calculate many other variables. One class of derived variables includes summaries spanning several months within a year:

- mean annual temperature and precipitation;
- average winter (November to February) temperature and precipitation;
- average summer (June to August) temperature and precipitation; and
- average growing season (April to September) precipitation.

Derived variables can also be based on the contrast between different months in the same year, or between the same month in different years or scenarios, such as:

- difference in temperature between August and January of the same year;
- difference in mean annual temperature or precipitation between different years;
- difference in minimum or maximum temperature or precipitation for a given month in different years; and
- difference in average winter or summer temperature or precipitation.
- ratio of average growing season temperature to average (or total) growing season precipitation

By judiciously combining the 36 annual estimates made by each GCM, a variety of new derived variables can be calculated. Including derived variables created through across-year contrasts provides the possibility of adding even more contrasts. Many of these derived variables were pre-calculated and available at the workshop.

Once calculated, any fundamental or derived variable can be mapped to show its spatial extent and landscape pattern. Such maps can also be coded using color groupings to highlight trends, thresholds, or significant relationships. For example, a map of differences can be colored so the users can easily distinguish between negative and positive values. In the case of contrasts across years, negative and positive changes can be highlighted. Alternatively, if there is an important threshold value (*e.g.*, a three degree increase in temperature), values could be colored such that they show two sets of area: those above the threshold and those below the threshold. Maps can also be queried to highlight specific types of information. For example, users can highlight all areas above a given elevation with a given maximum July temperature.

The monthly timescale of GCM output places an important constraint on the questions that can be explored, and some of important climate information which was requested at the workshop could not be derived. In particular, information about *daily trends*, such as consecutive days without precipitation or days in which a sudden change in temperature took place, is impossible to derive from the data set. For example, if the average monthly precipitation is 25mm, we do not know whether this amount falls in one day or is spread out over several days, or whether it falls as rain or snow or in some combination.

This temporal limitation is not just a problem of being unable to store huge amounts of intermediate GCM results at a finer time scales. Rather, it reflects the more fundamental temporal and spatial predictive problem of inferring climate variables at small scales where atmospheric turbulence and microclimatic effects become more important. Understanding the statistical properties of current weather may provide some guidance for making plausible conjectures at short time scales and small spatial scales, but may not provide definitive help under new climate regimes.

Some Sample Questions

Regardless of the limitations at the sub-month and sub-cell scale, the data can be used to explore many questions. Some examples are provided in this section.

1. How will freezing levels change? This has an impact on whether precipitation falls as rain or snow, which has an impact on tree survival and water patterns throughout the year.

   One way to look at the data to find out how freezing levels will change is to create several maps showing the minimum temperatures for each month for the base year and one or both future scenarios. These maps will show where, and in which months frosts will occur. By visually comparing maps, it will be possible to see if frost is occurring later in the year and occurring for fewer months. One thing that is not possible, however, is to see when or for how many days in the month the freezing occurs.

2. Will patterns of precipitation change? Will the precipitation be more or less, and will it come at a different time of year?

   This question can be approached several ways. One is to use monthly maps for the base year and for future climate scenarios. A second way is to use one or more maps with calculated differences, because in this case, we are not looking for an absolute number, but for relative amounts. The data sets prepared for the workshop already contains maps of change in summer- and winter-precipitation. Thus, one map already shows areas that have more or less precipitation for one season. If more precise timing is required, then a difference map for a single month could be used. For example, more rain in June may help the vegetation grow, but less rain in August may increase fire risk, especially when combined with increased June rain. Seasonal difference maps may not capture that, but monthly differences will.

3. Do temperature differences exceed a threshold? For example, suppose an increase in maximum temperatures of 3 degrees in the summer would have a significant impact on tree survival.

   As with precipitation, this type of map can be easily created using difference maps by temperature or season. If the temperature change is an important threshold, the map could be coded such that it showed only areas above or below the threshold.

4. Where will there be a summer temperature increase combined with a precipitation decrease?

   This information can be determined two ways. One is to create the two different maps (change in temperature and change in precipitation), and show them on top of each other, with the top layer using a transparent pattern. For example, increase temperature could be red, decrease could be blue while increased precipitation could be stripes and decreased precipitation could be dots. Then any areas that showed increased temperatures and decreased precipitation would be coded as dotted red areas. Alternatively, if there were a formula that could combine the temperature and precipitation change values in a way that was meaningful, one could create a new map with those calculated values.

Note that any information that is created using a map can also be exported to a file that can be read by a spreadsheet or database. Depending what variables are exported, other interesting graphs could be produced. For example, one could then look at changes in temperature stratified by elevation, or at minimum temperature over time at a single location.

Single Year Output vs. Multiple Year Output

There was concern at the workshop that the available data only represent single years (1900, 1950, 2000, 2050, 2100) and that there is no way of knowing whether that single year of simulated climate was representative of a typical or an atypical year.

Potential users need to bear in mind that exact climate predictions are impossible and that all scenarios represent single outcomes from a range of possibilities, initial conditions and random effects, and that no scenario result is expected to portray exactly what will actually happen in a future year. Faced with current GCM physical and computational limits, this is part of the reason for censoring short time-and space-scale results and for scaling at the month and half-degree scale. In principal it should be possible to sample from a range of future predictions at a given future year and location at the monthly and half-degree scale, but these results are computationally time-consuming to create and hard to obtain, should they exist. Moreover, they will continue to be time- and spatially-censored (so that they produce reasonably stable predictions), and may not produce the short-scale outputs that entomologists or pathologists would like to have.

Faced with this constraint, the most fruitful line of inquiry is to examine two or more contrasting scenarios. This allows us to pose questions that can be explored with current GCM outputs. Recognizing that the true future climate may be somewhere between such scenarios (*e.g.*, one showing greater change and another showing lesser change), scenario-based analyses can be used to explore the kinds of questions shown above. Thus, it matters little whether the sample year in one scenario is representative or atypical: the sample shows a possibility, and together, the two scenarios show an envelope of possibilities. For the moment, forest scientists must be content with the restrictions imposed by using this envelope and its limitations.