Annotated Bibliography: Suggested Readings for Bark Beetle Impacts in the Intermountain West: Redefining Post-disturbance Forests and Management Strategies
October 4th and 5th 2010
Hilton Garden Inn, Laramie, WY

Introduction

Forest herbivores impact stand structure and ecosystem process and services. Their role as agents of disturbance is normative, yet their population dynamics are currently shifting due to the indirect and direct effects of changes in temperature and precipitation. Disturbances are typically characterized by their spatial extent, intensity, return interval, severity, and predictability (Pickett & White, 1985). Presently there are unprecedented, both temporally and spatially, epidemics of native bark beetles throughout western North America. This has far-reaching consequences on ecosystem components such as forest structure, succession, watershed and biogeochemical processes, and politics and economics.

Specifically, the mountain pine beetle (*Dendroctonus ponderosae*) epidemics are occurring at greater intensity, and in locations not previously documented (Logan & Powell 2001). The mountain pine beetle is widely distributed across western North America and utilizes at least 12 native species of *Pinus* as hosts (Bentz et al. 2001). Forested systems, ranging from pinyon pine in the desert southwest to those found at high elevations and latitudes, are being severely impacted. The time frame of response to changing climate, however, is much shorter for the beetle (typically one year) than for their host forests (decades or longer).

Because this situation is novel, there are many aspects of ecosystem and disturbance dynamics that are beyond the scope of our current understanding. These unknown aspects include: 1) what role does climate change play in range expansion and or shifts of native bark beetles; 2) concepts of bark beetle genetics and the potential development of a host race; 3) individual host tree chemistry related to beetle life history, the role of multiple disturbance agents acting in combination; and 4) bark beetle life history traits related to temperature and host tree characteristics. Many of these topics are currently being addressed through research in progress and the introduction of these newly discovered concepts.

Articles (By Category and Date – Most Recent First)

Important definition:

Adaptive seasonality:

a. **Life cycle events occurring at appropriate times of year and in synchrony with cohorts and ephemeral resources, is a basic ecological requisite for many cold-blooded organisms. There are many mechanisms for synchronizing developmental milestones, such as egg laying (oviposition), egg hatching, cocoon opening, and the emergence of adult (Powell & Logan 2005).**
b. **The seasonal temperature pattern that enables beetles to complete their life cycle in one year and to synchronize adult emergence in order to overcome tree defenses.**

<u>Management</u>

1. **Hansen, E.M., Negron, J.F., Munson, A.S., Anhold, J.A. 2010. A retrospective assessment of partial cutting to reduce spruce beetle-caused mortality in the southern Rocky Mountains. West J. Appl. For. 25(2): 81-87.**

Context

Studies have been done that demonstrate the effectiveness of partial cutting on ponderosa and lodgepole pine stands in mitigating losses from the mountain pine beetle. This paper was written to explain studies done on spruce trees in the southern intermountain west to examine the feasibility of partial cutting as a management option for the minimization of beetle outbreaks in spruce stands.

Synopsis

This paper explains the methodology and results of studies done on spruce stands to examine the effectiveness of partial cutting as a management tool for minimizing bark beetle infestations. Scientists chose to study spruce stands that had been partially cut to various degrees prior to infestation and compared the results of their infestation to those of untreated/uncut stands within 2 km. The results revealed a significant reduction in beetle infestation in spruce stands that had been partially cut.

2. **Hays J. L., and Lundquist, J. E., comps. 2009. The Western Bark Beetle Research Group: a collaboration with Forest Health Protection – proceedings of a symposium at the 2007 Society of American Foresters Conference. U.S. Dept of Agriculture, Forest Service. PNW-GTR-784: 111-136. http://www.fs.fed.us/pnw/pubs/pnw_gtr784.pdf.**

Context

This report was compiled following a symposium held at the 2007 Society of American Foresters Convention in Portland, Oregon. The symposium covered a variety of topics that paralleled the goals of the Western Bark Beetle Research Group, including current knowledge about beetle responses to management and climate change, the interactions between fire and bark beetles as well as the ecological and socioeconomic impacts of bark beetle infestations. Also covered was the use of behavioral chemicals and a case-study concerning the potential risks posed by nonnative invasive bark beetles.

Synopsis

This report contains a variety of papers covering a range of bark beetle issues including management, interactions, and fire concerns.

Particularly relevant for our purposes are the McMillan and Fettig paper "Bark Beetle Responses to Vegetation Management Treatments," and the Gillette and Munson paper "Semiochemical Sabotage: Behavioral Chemicals for Protection of Western Conifers From Bark Beetles." The content of both papers focuses specifically on the management of bark beetles.

3. **Jenkins, Michael J. et al. 2008. Bark Beetles, Fuel, Fires and Implications for Forest Management in the Intermountain West. Forest Ecology & Management. 254. 1: 16-34.**

Context

This paper was written as a resource for management options to aid in the reduction of bark beetle impact in the intermountain west. Another goal of this paper is to help readers understand the relationship between bark beetle management, populations, fuels and fire hazard and behavior.

Synopsis

This paper discusses various fire regimes (fire risk, hazard and severity) among a variety of tree species, the ecology of various types of bark beetles, the impacts bark beetles have upon forest fuels, the relationship between fire behavior and stage of beetle infestation, strategies for managing bark beetle and the implications they carry for fuels and fire behavior, the implications management strategies have for bark beetles, and ideas for future research.

4. **Yeager, Ashley. 2008. Pop, Chirp, Bite, Crunch, Chew. Science News. 174. 5: 26-29.**

Context

This report was written after two researchers discovered the ultrasonic popping noises made by trees that are dehydrating, a result of beetle invasion.

Synopsis

Researchers are looking into the possibility that ultrasonic pops can be used in place of chemicals to communicate to bark beetles that a tree is full and they should search elsewhere for a place to lay their eggs. The idea came when it was discovered that trees infested with beetles make ultrasonic popping noises as their cells dehydrate.

5. **Raffa, Kenneth F., Aukema, Brian H., et al. 2008. Cross-Scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. Bioscience. 58. 6: 501-517.**

Context

This paper was written to explain the multi-level considerations that should be made when developing bark beetle management strategies. It explains the types of methods that are most effective under specific circumstances (tree stand type, level of outbreak – pre, during, post, etc.).

Synopsis

Specific to management, this paper explains the importance of considering the types of thresholds that have been surpassed in choosing management strategies. For example, a series of stand-level eruptions that will diminish once the fuel source – perhaps drought ridden trees – are consumed requires separate management

strategies from a landscape-scale eruption that continues even after drought and high temperature conditions are mitigated.

6. Louis, Halloin. 2003. Major Bark Beetles of the Intermountain West. Washington Department of Natural Resources. 1-18.

Context

This paper was written to provide a basic overview of bark beetles as well as some methods for improving forest resistance to bark beetle invasion and information specific to various species of bark beetles.

Synopsis

This paper explains the historical benefit of bark beetles, however as a result of human influence, many forests lack the necessary stand diversity that is so vital to their ability to resist bark beetle attacks. Consequently, we are faced with the current explosion of bark beetles in the Intermountain West. Along with providing management suggestions for reducing future outbreaks, this paper also includes information specific to the beetles that affect the Intermountain West and management suggestions for each one.

7. Logan, J.A., Regniere, J. & Powell, J.A. 2003. Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ. 1(3): 130-137.

Context

This review paper summarizes the state of knowledge, data, and modeled predictions of forest pest dynamics in relation to climate change for two reasons. The first reason was to illustrate the current and future impacts of climate change on forest resources. The second reason was to promote cooperation among researchers and managers to pool their current software tools, databases and models to monitor, evaluate and manage events.

The objectives of this paper were to evaluate specific forest pests and their associated hosts because of the substantial ecological, economic, and social impacts related to their changing population dynamics.

Methods critical to this study were a review of the: 1) methods used to assess the impact of climate change on insects; 2) databases required to build and test models; 3) available insect life cycle models based on temperature; and 4) quantitative models used to predict and evaluate outbreaks.

Major results from this research include:

1. Overall, the majority of assessments of pest species response to climate change indicate increased outbreak severity.
2. Insects will shift their distributions and increase outbreak intensity.
3. Models provide a way to evaluate future events.
4. Current high-resolution databases used to build models are improving and becoming more accessible.

The authors state that this study provides evidence that forest pests are valuable indicators for assessing climate change and the models currently available provide the building blocks for systematic assessments.

Synopsis

This review was not a breakthrough, but serves as an excellent resource for ecologically based empirical models of insect phenology and population dynamics, and reliable weather records for the western United States. In addition, this paper provides an excellent perspective of the inputs used to build many of the forest pest models.

Overall, this article was a substantive contribution to both climate change and bark beetle research.

8. Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., & Wotton, B.M. 2001. Climate change and forest disturbance. Bioscience. 51(9): 723-734.

Context

This review paper addresses the effect of climate change on forest disturbance, and the interactions of human-caused and naturally induced disturbances. The authors feel that the effects of climate change on forests will be expressed in alterations in disturbance regimes, due to the long-lived nature of trees.

Synopsis

The specific objectives of this paper were to first examine eight different disturbances and their influence on forest structure, composition, and function, and second, to examine the influence of climate change on the severity, frequency, and magnitude of these disturbances.

The methodological approach taken for this review paper includes a literature review of examples of disturbances in the United States in relation to two modeled climate scenarios from two GCMs, and a section about research needs. Considering the broad scope of this review paper, the 15 authors utilize a rather small number of peer-reviewed documents. This paper is one in a series by the forest portion of the National Assessment of Climate Variability and Change.

Major results from this research include:

1. Fire, drought, insect and pathogen outbreaks, introduced species, hurricanes, ice storms, and landslides are all influenced by climate change.
2. Disturbance agents interact; effects may be compounded or produce feedbacks.
3. Forest management strategies need to focus on reducing vulnerability, prevention of disturbances, recovery efforts, and adaptive management.

The authors state that this study provides a perspective on the complexity of climate variables related to forest disturbances, that may ultimately lead to integrated research, and mitigative and management strategies.

9. Ayres, M.P., & Lombardero, M.J. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Science of the Total Environment. 262: 263-286.

Context

This review paper assesses the potential changes in forest disturbances, economics, biodiversity, recreation, and water quality in light of 32 different biotic agents of disturbance, including many insect species. In addition, this paper outlines research priorities that facilitate risk assessment and management strategies.

Synopsis

The overall objective of this paper was to review the current impacts of forest herbivores and pathogens in North America.

The methods critical to this review paper include an extensive set of tables listing herbivores and pathogens that are significant agents of biological disturbance and the respective host species and citation. In addition, this paper address multiple facets of forest disturbance including economic impacts, ecological importance, human activity, feedbacks to climate change, direct effects of climate change on herbivores, pathogens, and their host species. Finally, a list of specific research priorities directed at understanding future losses to these disturbances.

Major results from this research include:

1. Climate change induced forest disturbance alterations will affect community structure and function, biodiversity, biogeochemistry, and disturbance regimes.
2. Economic costs are difficult to assess, but overall losses to the timber industry will be significant. In addition, prevention, and restoration costs are considerable.
3. Human activity such as fire manipulation, atmospheric nitrogen deposition, and forest fragmentation can influence forest disturbances.
4. Alteration of forest species, size structure, overall distribution, and abundance affect ecosystem functions such as CO_2 flux, evapotranspiration, and heat transfer. Changes in these functions create feedbacks to climate change.
5. Developmental rates of poikilothermic insects are directly influenced by climate. In general, reproductive potential is increased. In addition, climate change alters host tree physiology and defense mechanisms.
6. Research priorities include: physiological models to predict host tree and herbivore and pathogen responses to climate change, strategies for maintaining genetic diversity of tree species, and predictions of future patterns mineralization rates and nutrient availability.

The authors state that this study provides a perspective on both the gravity of the consequences of alterations of herbivore and pathogen forest disturbance and a set of research objectives to meet the potential challenges.

Ecology

1. Bergant, K. & Trdan, S. 2006. How reliable are thermal constants for insect development when estimated from laboratory experiments? Enomologia Experimentalis et Applicata. 120:251-256.

Context

A linear relationship between developmental rate and environmental temperature for poikilothermic animals is commonly utilized, due to the wide acceptance of this approach, in studies of insect population dynamics. This

paper investigates the uncertainty of the thermal constants that can be extrapolated from the linear relationship. A thermal constant is comprised of a lower developmental threshold and a sum of effective temperatures.

Synopsis

The objectives of this paper were to determine if the thermal constant values reported in the literature and used in models of insect dynamics were reliable. In addition, the authors wished to determine the sources of uncertainty that result in varying linear regression coefficients for each relationship between insect developmental rate and temperature.

The method critical to this study was a metaananalysis, or the combination of multiple data sets from previous research, in which egg-to-adult development time for western flower thrips was regressed against temperature. The authors used only data that were based on total development time from egg-to-adult.

Major results from this research include:

1. Similar estimates of thermal constants to those found in literature, but with significant variation in the regression coefficients.
2. Thermal constants for insects living in different climatic conditions overlap, making it difficult to distinguish variation in lower developmental temperature thresholds.
3. Factors other than temperature play a role in thermal constants, such as photoperiod, food resources, or predator abundance.
4. It is nearly impossible to separate the possible sources of variation in thermal constants among experiments.

The authors state that this study provides evidence that thermal constants contain much uncertainty and should be used with caution. This uncertainty could be addressed during experiments by including a range of temperatures wide enough to capture the borders of the linear response, a sufficient number of insects to obtain a more accurate population mean, a report on the caveates to the final thermal constant, and potentially attempting to incorporate other factors affecting life history, such as photoperiod.

2. Logan, J.A., & Powell, J.A. 2005. Ecological consequences of climate change altered forest insect disturbance regimes. *In* F.H. Wagner (ed.) Climate change in western North America: evidence and environment effects. Allen Press.

Context

This paper utilizes three case histories to illustrate the unique attributes of the unprecedented outbreaks of native bark beetles. Currently mountain pine beetle outbreaks are occurring with greater intensity, in locations where they have not previously been recorded, and for greater durations than those previously experienced. The authors feel that outbreaks occurring in novel habitats have potentially devastating ecological consequences.

The objective of this paper is to describe the application of a mathematical model used to predict mountain pine beetle response to temperature and climate to three spatially variable analyses of ongoing beetle outbreaks.

Synopsis

Critical to this study was the development of a mathematical framework for evaluation of adaptive seasonality. This conceptual framework is able to capture the temperature dependence of the mountain pine beetle, in particular their lack of a physiological timing mechanism for development. This insect phenology model includes a sequence of developmental stages, in which the duration of each is controlled by temperature.

Major results from this research include:

b. Mountain pine beetle outbreaks have intensified within their historic distribution, shifted their populations northward, and invaded easterly into jackpine forests.
c. Mountain pine beetle population dynamics change immediately in response to changes in climate, making them valuable indicator species for climate change.
d. Warming climate has shifted some thermally marginal habitats into those that are thermally suitable to the mountain pine beetle, specifically high elevation whitebark pine habitats.

The authors state that this study indicates that whitebark pine ecosystems are highly susceptible to mountain pine beetle outbreaks. Widespread whitebark mortality would have implications on the social and ecological services they provide.

3. Louis, Halloin. 2003. Major Bark Beetles of the Intermountain West. Washington Department of Natural Resources. 1-18.

Context

This paper was written to provide a basic overview of bark beetles as well as some methods for improving forest resistance to bark beetle invasion and information specific to various species of bark beetles.

Synopsis

This paper explains the historical benefit of bark beetles, however as a result of human influence, many forests lack the necessary stand diversity that is so vital to their ability to resist bark beetle attacks. Consequently, we are faced with the current explosion of bark beetles in the Intermountain West. Along with providing management suggestions for reducing future outbreaks, this paper also includes information specific to the beetles that affect the Intermountain West and management suggestions for each one.

4. Logan, J.A., & Powell, J.A. 2003. Modelling mountain pine beetle phenological response to temperature. *In* Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia.T.L. Shore, J.E. Brooks, & J.E. Stone (eds.) Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Context

This paper addresses the ecological and management issues associated with the relationship between mountain pine beetle outbreak potential and temperature. The life cycle of poikilothermic insects is directly controlled by annual temperature cycles. The mountain pine beetle is unique due to their lack of diapause, or a physiological mechanism that enables the beetle to maintain synchrony. This leads to an important ecological question addressed by this paper.

Synopsis

The overall objective of this paper was to address the question of how temporally variable egg-laying events can later be focused into an essentially simultaneous emergence period, without a physiological mechanism. In addition, the authors examine the current unprecedented outbreaks in light of their framework.

Methods critical to this study were the use of quantitative analysis of direct temperature control and mountain pine beetle synchrony, also known as adaptive seasonality. The model uses developmental rates for the bark beetles, based on temporal progressions of instar to emergence. This is a common method utilized in insect ecology. This developmental rate incorporates temperature, time, and physiological age. The authors refined this rate to determine a sequence of developmental milestones to capture the circularity of mountain pine beetle generation to generation, or a "G-function".

Major results from this research include:

1. Reproductive success and synchrony is related to fixed stable points on the circle of development.
2. The fixed stable points are within a specific temperature band, which means it can be either too cold or too warm for beetle adaptive seasonality.

The authors state that this study provides evidence that temperature is driving beetle life history and outbreaks characteristics. In addition, this study supports the idea that climatic marginality results in immediate and measurable beetle population responses to slight variations in annual weather patterns.

5. Bentz, B.J., Logan, J.A., & Vandygriff, J.C. 2001. Latitudinal variation in Dendroctonus ponderosae (Coleoptera: Scolytidae) development time and adult size. Canadian Entomologist. 133: 375-387.

Context

This paper investigates the difference between adult mountain pine beetle size and development time from a northern (central Idaho) and southern population (southern Utah). Because insects often respond phenotypically to the local environment, the authors wanted to determine if these life history parameters were controlled by genetics or environmental factors. Prior to this paper, the genetic diversity of the species was unclear and this differentiation is key to understanding bark beetle population dynamics at specific geographic regions.

Synopsis

There were two overall objectives of this paper. First, was to test the hypothesis that latitudinal distribution, and not host tree nutritional variation, will affect mountain pine beetle developmental rates and, therefore adaptive seasonality. Second, was to investigate whether differences in developmental time and adult size were heritable traits.

The method critical to this study was the use of a "common garden experiment" to separate heritable from environmental effects by rearing offspring from the two geographically dissimilar populations in a standardized laboratory experiment under a constant temperature.

Major results from this research include:

1. Median emergence time was shorter from northern populations.
2. Brood from southern populations was larger than from northern.

3. Brood food source, or host tree species, was not a statistically significant explanation of differences in developmental rates or adult beetle size between populations from different latitudes. Host tree species, however, was influential on a local spatial scale.

The authors state that by removing the influence of temperature on mountain pine beetle development, they have shown that there are genetically based traits which are dissimilar for beetles from varying latitudes. From their dataset, the authors concluded that, in colder environments, selection for faster development time would be stronger. In warmer environments, where time available for development would be greater so would selection for larger adult size.

6. Logan, J.A., & Bentz, B.J. 1999. Model analysis of mountain pine beetle (Coleoptera: Scolytidae) seasonality. Environmental Entomology. 28(6): 924-934.

Context

This paper was primarily written to further the understanding of the beetle phenology and subsequently address the effects of climate on an insect with a temperature driven life history. Specifically, the topic of direct temperature control of bark beetle seasonality and synchrony that enables the beetles to immerge simultaneously during a single week in the early fall was explored. This synchrony is critical to the success of the bark beetle, as the only way they can overcome a tree's defensive resin production is through a mass attack behavior, in which 100s of beetle attack a single tree within a short period of time. Seasonality simply refers to this synchrony of emergence of large numbers of beetles. Direct temperature control is unusual in insects, which typically exhibit some timing mechanism.

Synopsis

The overall objectives of this paper were to answer three questions. First, is typical weather independent of phenology in regard to seasonality? Second, how well does the authors model predict weather variation? And finally, what properties stabilize mountain pine beetle seasonality?

The development of a model that explores the effects of weather and climate on mountain pine beetle seasonality was critical to this paper. This model was based on a developmental rate curve in which the inverse of the time required to produce a single brood is expressed as a function of temperature. This curve is both nonlinear and asymmetric. This model used two such curves, one for cold specific, and another for warm specific regimes. This model was parameterized for immature development rates and egg gallery production. Temperature data was based on intricate readings taken hourly by thermocouple in tree phloem in order to capture microhabitat temperatures.

Major results from this research include:

1. Model results indicate that the mountain pine beetle have the ability to maintain seasonality in response to varying thermal regimes.
2. Model results indicate that direct control by temperature alone is sufficient to explain mountain pine beetle seasonality.
3. Because climatic warming can transform cold, thermally inhospitable habitats into benign, favorable habitats, geographic shifts of bark beetles northward and upward in elevation should be expected.

The authors state that this study provides evidence that the mountain pine beetle is under direct temperature control, making this insect an ideal bio-indicator of climate change. In addition, these results indicate that the bark beetle is capable of thermal plasticity that results in their rapid adaptation to varying environmental conditions.

7. Romme, W.H., & Turner, M.G. 1991. Implications for global climate change for biogeographic patterns in the Greater Yellowstone Ecosystem. Conservation Biology. 5(3): 373-386.

Context

In context of this bibliography, this paper serves as an overview of the implications of climate change on the ecology, specifically the distribution and disturbance dynamics, of a tree which is one of the main hosts of the mountain pine beetle, the whitebark pine. In a broader sense, this paper was written to explore the ramifications of changes in global climate on biogeographic patterns and biodiversity in the Greater Yellowstone Ecosystem.

Synopsis

The objective of this paper was to project the probable effects of three climate scenarios on several specific plant species and community types representing a range of biota in the Greater Yellowstone.

Methods critical to this study were the creation of the three climate scenarios and the subsequent protections of their effects on local biota. The climate scenarios were based on a pool of potential effects indicated by GCM simulations. The authors then distilled three scenarios from this pool by using factors that would

encompass a range of climate conditions. These factors included: atmospheric CO_2 and other greenhouse gas levels, evapotranspiration rates, surface temperatures, precipitation patterns, and water use efficiency by vegetation.

Major results from this research include:

1. A warm, dry climate scenario with no plant compensation by increased water use efficiency results in:
    a. Longer growing season which would shift timberline species to higher elevations, contracting the total area of the alpine zone (i.e.: a 90% decrease in whitebark pine habitat).
    b. Summer drought stress would increase in forests.
    c. Low elevation, non-forested community types would expand.
2. A warm, dry climate scenario with increased water use efficiency results in:
    a. Longer growing season and upward shift and reduction in area of timberline/alpine zone.
    b. In low elevation communities, higher potential evapotranspiration would be compensated for by increased water use efficiency.
    c. Drought stress would not change.
3. A warm, wet climate scenario
    a. Warm temperatures result in longer growing season and an upward shift and reduction in area of alpine zone (including whitebark).
    b. Increased precipitation would result in whitebark pine being out competed by species previously limited by moisture. This could result in reduction or localized extinction of this species.
    c. Low elevation community types may be reduced by the encroachment of forested types.

The authors state that this study provides a way to delimit the range and magnitude of possible changes in the ecosystem. This information may promote successful research and monitoring efforts. In addition, the overall conclusions from all three climate scenarios indicate a reduction in the overall area of the alpine zone, impacting those species restricted to those sites. Because other community types may expand, overall species diversity may remain unchanged.

Other Factors: Climate Change

1. Hays J. L., and Lundquist, J. E., comps. 2009. The Western Bark Beetle Research Group: a collaboration with Forest Health Protection – proceedings of a symposium at the 2007 Society of American Foresters Conference. U.S. Dept of Agriculture, Forest Service. PNW-GTR-784: 111-136. http://www.fs.fed.us/pnw/pubs/pnw_gtr784.pdf.

Context

This report was compiled following a symposium held at the 2007 Society of American Foresters Convention in Portland, Oregon. The symposium covered a variety of topics that paralleled the goals of the Western Bark Beetle Research Group, including current knowledge about beetle responses to management and climate change, the interactions between fire and bark beetles as well as the ecological and socioeconomic impacts of bark beetle infestations. Also covered was the use of behavioral chemicals and a case-study concerning the potential risks posed by nonnative invasive bark beetles.

Synopsis

This report contains a variety of papers covering a range of bark beetle issues including management, interactions, and fire concerns.

Particularly relevant for our purposes are the McMillan and Fettig paper “Bark Beetle Responses to Vegetation Management Treatments,” and the Gillette and Munson paper “Semiochemical Sabotage: Behavioral Chemicals for Protection of Western Conifers From Bark Beetles.” The content of both papers focuses specifically on the management of bark beetles.

2. Stahl, K., Moore, R.D., & McKendry, I.G. 2006. Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. Climate Research. 32: 13-23.

Context

This paper was written to relate the role of synoptic and large-scale climate trends to recent epidemics of mountain pine beetle, specifically in relation to the frequency and distribution of extreme wintertime cold events that result in beetle mortality. Because the abundance of susceptible host trees and beetles drive bark beetle outbreaks, understanding the mechanisms controlling these dynamics is crucial.

Synopsis

There were two overall objectives of this paper. First, was to examine connections between winter beetle mortality cold events and large-scale climate modes. Second was to understand the influence of synoptic-scale circulation patterns on these same cold events.

Methods critical to this study were the combination of several parameters of different scales. This analysis was strengthened by combining teleconnection, synoptic-scale, and temperature data. This was an innovative approach, illustrating the recent advances in the understanding of both large-scale climate modes and synoptic-scale patterns. In addition, the use of chi-square tests of independence was a simple, yet powerful way to determine if relationships existed within the data set. The authors addressed the potential for violations of the chi square tests due to the correlation of their cold-mortality days and the clustering of some of their categorical data.

Major results from this research include:

1. The spatial distribution of cold-mortality days. The highest frequency of potential cold mortality days were found in northeastern British Columbia (BC), where arctic air masses dominant during winter. Overall, cold mortality days have decreased since 1957.
2. Cold mortality events were associated with a synoptic circulation pattern when cold Arctic air flows coastward from the interior mountains of BC.
3. The frequency of synoptic circulation patterns depends on large-scale climatic modes, including the El Nino Southern Oscillation, Pacific Decadal Oscillation, and Pacific North American pattern.
4. The frequency of cold-mortality events coincides with strong negative Pacific Decadal Oscillations and all teleconnection patterns. Recently the PDO has been in a positive or neutral phase resulting in less frequent or severe cold events.

The authors state that this study provides linkages between synoptic circulation, climate variability, and surface temperatures in BC, and how this relates to the reduced frequency of cold events and mountain pine beetle mortality. This information can be applied to climatic conditions predicted for the future, in relation to both synoptic-scale weather patterns and bark beetle dynamics.

3. Logan, J.A., Regniere, J. & Powell, J.A. 2003. Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ. 1(3): 130-137.

Context

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5. Overall, the majority of assessments of pest species response to climate change indicate increased outbreak severity.
6. Insects will shift their distributions and increase outbreak intensity.
1. Models provide a way to evaluate future events.
2. Current high-resolution databases used to build models are improving and becoming more accessible.

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Synopsis

This review was not a breakthrough, but serves as an excellent resource for ecologically based empirical models of insect phenology and population dynamics, and reliable weather records for the western United States. In addition, this paper provides an excellent perspective of the inputs used to build many of the forest pest models.

Overall, this article was a substantive contribution to both climate change and bark beetle research.

4. Carroll, A.L., Taylor, S.W., Regniere, J. & Safranyik, L. 2003. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. *In* Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia.T.L. Shore, J.E. Brooks, &

J.E. Stone (eds.) Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Context

This paper addresses the current increase in the number of mountain pine beetle infestations since 1970 into formerly thermally unsuitable habitats. The authors wished to quantify the effect of global warming on mountain pine beetle populations in North America, as genetic and ecological adaptations have already been quantified in Europe.

Synopsis

There were two questions addressed in the paper. First, has there been a shift in climatically suitable habitats during the recent past? Second, have mountain pine beetle populations expanded into these novel habitats?

In order to perform this study, a model developed in the late 1970s was adapted to evaluate the impact of climatic conditions on the establishment and persistence of mountain pine beetles. Climatic variables included in the model are: number of degree days above 5.5°C, minimum winter temperatures, average maximum August temperatures, total precipitation April to June, variability of growing season precipitation and an aridity index. This information was used to create a map of the spatial distribution of climatically suitable habitats as a function of climate norms derived from historic daily weather from 1921. Mountain pine beetle infestation grids, in the form of GIS shape files, were overlaid on climatic layers. In addition, the infestations were regressed against the historic distribution of climatically suitable habitats.

Major results from this research include:

1. Areas suitable for mountain pine beetle have expanded dramatically.
2. Present mountain pine beetle epidemics correlate very closely to the areas predicted to be suitable by the model.
3. Areas previously considered optimal have experienced declines in outbreaks due to reduced host trees and adverse effects on beetle synchrony due to warmer temperatures.
4. Eastern expansion into areas where mountain pine beetle have not previously been recorded threaten jack pine forests.

The authors state that this study provides evidence that changes in climate explain the current increase in occurrence of mountain pine beetle into previously unsuitable habitats, regardless of forest stand age. In addition, in the absence of an extreme cold winter event that, in the past has resulted in the collapse of an outbreak, current outbreak duration and extent may increase.

5. Logan, J.A., & Powell, J.A. 2003. Modelling mountain pine beetle phenological response to temperature. *In* Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia.T.L. Shore, J.E. Brooks, & J.E. Stone (eds.) Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Context

This paper addresses the ecological and management issues associated with the relationship between mountain pine beetle outbreak potential and temperature. The life cycle of poikilothermic insects is directly controlled by annual temperature cycles. The mountain pine beetle is unique due to their lack of diapause, or a physiological mechanism that enables the beetle to maintain synchrony. This leads to an important ecological question addressed by this paper.

Synopsis

The overall objective of this paper was to address the question of how temporally variable egg-laying events can later be focused into an essentially simultaneous emergence period, without a physiological mechanism. In addition, the authors examine the current unprecedented outbreaks in light of their framework.

Methods critical to this study were the use of quantitative analysis of direct temperature control and mountain pine beetle synchrony, also known as adaptive seasonality. The model uses developmental rates for the bark beetles, based on temporal progressions of instar to emergence. This is a common method utilized in insect ecology. This developmental rate incorporates temperature, time, and physiological age. The authors refined this rate to determine a sequence of developmental milestones to capture the circularity of mountain pine beetle generation to generation, or a “G-function”.

Major results from this research include:

1. Reproductive success and synchrony is related to fixed stable points on the circle of development.
2. The fixed stable points are within a specific temperature band, which means it can be either too cold or too warm for beetle adaptive seasonality.

The authors state that this study provides evidence that temperature is driving beetle life history and outbreaks characteristics. In addition, this study supports the idea that climatic marginality results in immediate and measurable beetle population responses to slight variations in annual weather patterns.

6. Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrniodis, I., Watt, A.D., & Whittaker, J.B. 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biology. 8: 1-16.

Context

Climate acts directly on insects by regulating growth and development rates or through direct mortality. This review paper explores the direct impacts of increased temperature on insect phenology, life cycles, and distribution in natural, rather than agricultural, systems in relation to the spatial variation of insect response. Temperature is the focus of this review because many other studies have shown that this component of climate change has the greatest effect on insects.

Synopsis

The main objective of this paper was to develop hypotheses on how insect life-history characteristics and distributions may respond to climate change scenarios.

The method critical to this study was the formation of a matrix of all possible insect and plant type combinations from predictions of insects response to particular climate change scenarios. These combinations are based upon prior research on the life history parameters of the insects in question, the growth strategy and phenology of the host plants, and the phenotypic flexibility exhibited by the insects. These matrixes are working hypothesis, used to make predictions. These predictions of insect response are placed in simple categories of increase, decrease or no change in population or distribution.

The review of the relevant literature provided by this paper indicates the following:

1. Life cycles events, such as voltinism, population density, rate of development, and extent of host plant exploitation, are impacted by temperature change.
2. Temperature also regulates plant growth and seasonal availability. Insect herbivore synchrony with host phenology becomes increasingly important when climatic envelopes become smaller. This interaction regulates insect distribution.
3. Warming will allow the majority of insects to increase their elevational and latitudinal distributions.
4. Fossil evidence indicates that insects have responded to climate change in the past.
5. Insect species that have a significant diapause event in their life cycle may experience range contraction as winter temperatures increase.
6. Insect predation interactions will be altered.

The authors state that this study provides a useful basis for predictions of insect responses to climate change. Relative growth rates and diapause data for a specific insect can be applied to their framework to predict range expansion or contraction. Their information is based upon empirical analyses of changes in insect life history traits, phenology, and distributions.

7. Williams, D.W., & Leibhold, A.M. 2002. Climate change and the outbreak ranges of two North American bark beetles. Agricultural and Forest Entomology. 4: 87-99.

Context

This paper investigates the potential range shifts of two bark beetle species (*Dendroctonus ponderosae* and *D. frontalis*) and their associated host trees in relation to climate change. The context of these investigations is that of predicted temperature changes influencing forests distributions and insect herbivore population dynamics.

Synopsis

The overall objectives of this paper were to develop canonical discriminant function models of the occurrence of host forests and bark beetles under current climatic conditions and then to predict range shifts under several climatic scenarios.

Methods critical to this study were threefold. First, maps of bark beetle outbreaks, climatic variables, and susceptible forest types were developed using Idrisi raster-based GIS. These maps were based on compiled USDA records, Forest Health Protection Aerial Detection Survey data, USDA forest type satellite imagery, and Global Ecosystems Database historical climatic variables. Next, two canonical discriminate function models were developed to determine which variables contributed to the infestation by bark beetles and which variables indicated the presence of susceptible pine forest types for each grid cell on the maps produced prior. Finally, the fitted

canonical discriminate functions were modified to create several climate change scenarios. The authors used this method, rather than GCMs because they wanted to capture climatic variability on a local-scale.

Major results from this research include:

1. Mean June temperatures were most strongly correlated with forest distribution.
2. *D. ponderosae* outbreaks were most strongly correlated with susceptible forest type and less so with climatic variables.
3. Both susceptible forest and beetle outbreaks area were predicted to decrease with an increase in temperature due to the loss of area available at higher elevations.
4. *D. frontalis* range increases with increased precipitation.

The authors state that this study demonstrates two patterns of climate induced geographical range shifts for two similar bark beetle species. These shifts may occur with relatively small changes in climatic conditions yet the effects of these shifts on forested landscapes may be profound. An understanding of the nonlinearity of these shifts will assist in the anticipation of directional movement by the bark beetles as climate change continues.

8. Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., & Wotton, B.M. 2001. Climate change and forest disturbance. Bioscience. 51(9): 723-734.

Context

This review paper addresses the effect of climate change on forest disturbance, and the interactions of human-caused and naturally induced disturbances. The authors feel that the effects of climate change on forests will be expressed in alterations in disturbance regimes, due to the long-lived nature of trees.

Synopsis

The specific objectives of this paper were to first examine eight different disturbances and their influence on forest structure, composition, and function, and second, to examine the influence of climate change on the severity, frequency, and magnitude of these disturbances.

The methodological approach taken for this review paper includes a literature review of examples of disturbances in the United States in relation to two modeled climate scenarios from two GCMs, and a section about research needs. Considering the broad scope of this review paper, the 15 authors utilize a rather small number of peer-reviewed documents. This paper is one in a series by the forest portion of the National Assessment of Climate Variability and Change.

Major results from this research include:

1. Fire, drought, insect and pathogen outbreaks, introduced species, hurricanes, ice storms, and landslides are all influenced by climate change.
2. Disturbance agents interact; effects may be compounded or produce feedbacks.
3. Forest management strategies need to focus on reducing vulnerability, prevention of disturbances, recovery efforts, and adaptive management.

The authors state that this study provides a perspective on the complexity of climate variables related to forest disturbances, that may ultimately lead to integrated research, and mitigative and management strategies.

9. Powell, J.A., Jenkins, J.L., Logan, J.A., & Bentz, B.A. 2000. Seasonal temperature alone can synchronize life cycles. Bulletin Mathematical Biology. 62: 977-998.

Context

This paper utilizes existing general development models to illustrate the effects of yearly temperature variation on the development and seasonal occurrence of poikilotherms.

Synopsis

The overall objective of this paper was to prove that seasonal temperature variation alone can synchronize life cycles.

Methods critical to this study were the use of mathematical developmental rate equations based on insect life history traits and environmental temperature, the integration of multiple equations for each life stage to predict cycles and synchrony, and then the application of these equations to the mountain pine beetle. The interactions of the curves associated with each life stage result in stable points or thresholds within a range of temperatures. These curves can also be used to determine the number of brood that will be produced under a given temperature regime. Actual developmental curves for mountain pine beetle were compared to those linear approximations from developmental rates. The authors also performed a very high-temperature simulation to facilitate comparisions.

Major results from this research include:

1. Insect seasonality is under direct temperature control when:

a. There is sufficient thermal energy for development of each life stage in a single season
b. And, when at least one of the developmental thresholds is significantly greater than the mean threshold.

10. Logan, J.A., & Bentz, B.J. 1999. Model analysis of mountain pine beetle (Coleoptera: Scolytidae) seasonality. Environmental Entomology. 28(6): 924-934.

Context

This paper was primarily written to further the understanding of the beetle phenology and subsequently address the effects of climate on an insect with a temperature driven life history. Specifically, the topic of direct temperature control of bark beetle seasonality and synchrony that enables the beetles to immerge simultaneously during a single week in the early fall was explored. This synchrony is critical to the success of the bark beetle, as the only way they can overcome a tree's defensive resin production is through a mass attack behavior, in which 100s of beetle attack a single tree within a short period of time. Seasonality simply refers to this synchrony of emergence of large numbers of beetles. Direct temperature control is unusual in insects, which typically exhibit some timing mechanism.

Synopsis

The overall objectives of this paper were to answer three questions. First, is typical weather independent of phenology in regard to seasonality? Second, how well does the authors model predict weather variation? And finally, what properties stabilize mountain pine beetle seasonality?

The development of a model that explores the effects of weather and climate on mountain pine beetle seasonality was critical to this paper. This model was based on a developmental rate curve in which the inverse of the time required to produce a single brood is expressed as a function of temperature. This curve is both nonlinear and asymmetric. This model used two such curves, one for cold specific, and another for warm specific regimes. This model was parameterized for immature development rates and egg gallery production. Temperature data was based on intricate readings taken hourly by thermocouple in tree phloem in order to capture microhabitat temperatures.

Major results from this research include:

1. Model results indicate that the mountain pine beetle have the ability to maintain seasonality in response to varying thermal regimes.
2. Model results indicate that direct control by temperature alone is sufficient to explain mountain pine beetle seasonality.
3. Because climatic warming can transform cold, thermally inhospitable habitats into benign, favorable habitats, geographic shifts of bark beetles northward and upward in elevation should be expected.

The authors state that this study provides evidence that the mountain pine beetle is under direct temperature control, making this insect an ideal bio-indicator of climate change. In addition, these results indicate that the bark beetle is capable of thermal plasticity that results in their rapid adaptation to varying environmental conditions.

11. Romme, W.H., & Turner, M.G. 1991. Implications for global climate change for biogeographic patterns in the Greater Yellowstone Ecosystem. Conservation Biology. 5(3): 373-386.

Context

In context of this bibliography, this paper serves as an overview of the implications of climate change on the ecology, specifically the distribution and disturbance dynamics, of a tree which is one of the main hosts of the mountain pine beetle, the whitebark pine. In a broader sense, this paper was written to explore the ramifications of changes in global climate on biogeographic patterns and biodiversity in the Greater Yellowstone Ecosystem.

Synopsis

The objective of this paper was to project the probable effects of three climate scenarios on several specific plant species and community types representing a range of biota in the Greater Yellowstone.

Methods critical to this study were the creation of the three climate scenarios and the subsequent protections of their effects on local biota. The climate scenarios were based on a pool of potential effects indicated by GCM simulations. The authors then distilled three scenarios from this pool by using factors that would encompass a range of climate conditions. These factors included: atmospheric CO_2 and other greenhouse gas levels, evapotranspiration rates, surface temperatures, precipitation patterns, and water use efficiency by vegetation.

Major results from this research include:

1. A warm, dry climate scenario with no plant compensation by increased water use efficiency results in:

a. Longer growing season which would shift timberline species to higher elevations, contracting the total area of the alpine zone (i.e.: a 90% decrease in whitebark pine habitat).
b. Summer drought stress would increase in forests.
c. Low elevation, non-forested community types would expand.

2. A warm, dry climate scenario with increased water use efficiency results in:
   a. Longer growing season and upward shift and reduction in area of timberline/alpine zone.
   b. In low elevation communities, higher potential evapotranspiration would be compensated for by increased water use efficiency.
   c. Drought stress would not change.
3. A warm, wet climate scenario
   a. Warm temperatures result in longer growing season and an upward shift and reduction in area of alpine zone (including whitebark).
   b. Increased precipitation would result in whitebark pine being out competed by species previously limited by moisture. This could result in reduction or localized extinction of this species.
   c. Low elevation community types may be reduced by the encroachment of forested types.

The authors state that this study provides a way to delimit the range and magnitude of possible changes in the ecosystem. This information may promote successful research and monitoring efforts. In addition, the overall conclusions from all three climate scenarios indicate a reduction in the overall area of the alpine zone, impacting those species restricted to those sites. Because other community types may expand, overall species diversity may remain unchanged.

12. Shrimpton, D.M. & Thomson, A.J. 1984. Weather associated with the start of mountain pine beetle outbreaks. Can. J. For. Res. 14: 255-258.

Context

Once again, because the abundance of susceptible host trees and beetles drive bark beetle outbreaks, understanding the mechanisms controlling these dynamics is crucial. This paper compares long-term climographs to mountain pine beetle outbreaks and lodgepole pine (host tree) growth, which is correlated to the defensive capabilities of the host tree.

Synopsis

There were three objectives of this paper. First, to determine the weather patterns associated with the start of a mountain pine beetle outbreak. Second, to investigate the timing, duration, and frequency of a weather pattern associated with an outbreak. Last, to compare lodgepole radial growth to weather patterns associated with the outbreak.

Methods critical to this study was the creation of climographs which served as long-term averages. This was done using records of temperature and precipitation for a 50-year period. Next, climographs of years preceding outbreaks, during outbreaks and years of low lodgepole radial growth were superimposed on the long-term averages and deviations reflect extreme weather patterns. Because the authors wanted to establish the nature of relationships, rather than quantify them statistically, they used a graphical representation of correlations.

Major results from this research include:

1. Years preceding, and during beetle outbreaks, were warm and dry compared to other years.
2. Low precipitation levels were associated with reduced tree growth.
3. The effect of months with extremely low precipitation was not mediated by wetter adjacent months.

The authors state that the information from their study provides additional factors that need to be included in hazard rating systems for mountain pine beetle. These factors are lodgepole pine growth rates and deviations from long-term weather patterns.

<u>Other Factors: Fire</u>

1. Hays J. L., and Lundquist, J. E., comps. 2009. The Western Bark Beetle Research Group: a collaboration with Forest Health Protection – proceedings of a symposium at the 2007 Society of American Foresters Conference. U.S. Dept of Agriculture, Forest Service. PNW-GTR-784: 111-136. http://www.fs.fed.us/pnw/pubs/pnw_gtr784.pdf.

Context

This report was compiled following a symposium held at the 2007 Society of American Foresters Convention in Portland, Oregon. The symposium covered a variety of topics that paralleled the goals of the Western Bark Beetle Research Group, including current knowledge about beetle responses to management and

climate change, the interactions between fire and bark beetles as well as the ecological and socioeconomic impacts of bark beetle infestations. Also covered was the use of behavioral chemicals and a case-study concerning the potential risks posed by nonnative invasive bark beetles.

Synopsis

This report contains a variety of papers covering a range of bark beetle issues including management, interactions, and fire concerns.

Particularly relevant for our purposes are the McMillan and Fettig paper "Bark Beetle Responses to Vegetation Management Treatments," and the Gillette and Munson paper "Semiochemical Sabotage: Behavioral Chemicals for Protection of Western Conifers From Bark Beetles." The content of both papers focuses specifically on the management of bark beetles.

2. Jenkins, Michael J. et al. 2008. Bark Beetles, Fuel, Fires and Implications for Forest Management in the Intermountain West. Forest Ecology & Management. 254. 1: 16-34.

Context

This paper was written as a resource for management options to aid in the reduction of bark beetle impact in the intermountain west. Another goal of this paper is to help readers understand the relationship between bark beetle management, populations, fuels and fire hazard and behavior.

Synopsis

This paper discusses various fire regimes (fire risk, hazard and severity) among a variety of tree species, the ecology of various types of bark beetles, the impacts bark beetles have upon forest fuels, the relationship between fire behavior and stage of beetle infestation, strategies for managing bark beetle and the implications they carry for fuels and fire behavior, the implications management strategies have for bark beetles, and ideas for future research.

3. Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., & Wotton, B.M. 2001. Climate change and forest disturbance. Bioscience. 51(9): 723-734.

Context

This review paper addresses the effect of climate change on forest disturbance, and the interactions of human-caused and naturally induced disturbances. The authors feel that the effects of climate change on forests will be expressed in alterations in disturbance regimes, due to the long-lived nature of trees.

Synopsis

The specific objectives of this paper were to first examine eight different disturbances and their influence on forest structure, composition, and function, and second, to examine the influence of climate change on the severity, frequency, and magnitude of these disturbances.

The methodological approach taken for this review paper includes a literature review of examples of disturbances in the United States in relation to two modeled climate scenarios from two GCMs, and a section about research needs. Considering the broad scope of this review paper, the 15 authors utilize a rather small number of peer-reviewed documents. This paper is one in a series by the forest portion of the National Assessment of Climate Variability and Change.

Major results from this research include:

1. Fire, drought, insect and pathogen outbreaks, introduced species, hurricanes, ice storms, and landslides are all influenced by climate change.
2. Disturbance agents interact; effects may be compounded or produce feedbacks.
3. Forest management strategies need to focus on reducing vulnerability, prevention of disturbances, recovery efforts, and adaptive management.

The authors state that this study provides a perspective on the complexity of climate variables related to forest disturbances, that may ultimately lead to integrated research, and mitigative and management strategies.

4. Romme, W.H., J. Clement, J. Hicke, D. Kulakowski, L.H. MacDonald, T.L. Schoennagel, and T.T. Vleben. Undated. Recent Forest Insect Outbreaks and Fire Risk in Colorado Forests: A Brief Synthesis of Relevant Research. http://warnercnr.colostate.edu/images/docs/cfri/cfri_insect.pdf.

Context

The intent of the paper is to inform forest management in the face of fire and insect outbreak. The focus is primarily on ecological factors associated with fire and insect outbreak, rather than factors associated with economics, wildlife, recreation, aesthetics and other elements of forest management. The paper is organized around key questions about the ecology of insect outbreaks.

Synopsis

The authors argue that responses to insect outbreaks and fires must be consistent with the ecology of the affect forests. The paper addresses which insect species are prevalent in the outbreaks in Colorado forests, reasons for the intensity and geographic scope of the current outbreak, fire behavior and intensity over the last 100 years, how insect outbreaks and fire are related, and how water quality and flow are affected by insect outbreaks. The authors also synthesize several management options.

Other Factors: Drought

1. **Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., & Wotton, B.M. 2001. Climate change and forest disturbance. Bioscience. 51(9): 723-734.**

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The authors state that this study provides a perspective on the complexity of climate variables related to forest disturbances, that may ultimately lead to integrated research, and mitigative and management strategies.

Future Implications

1. **Hays J. L., and Lundquist, J. E., comps. 2009. The Western Bark Beetle Research Group: a collaboration with Forest Health Protection – proceedings of a symposium at the 2007 Society of American Foresters Conference. U.S. Dept of Agriculture, Forest Service. PNW-GTR-784: 111-136. http://www.fs.fed.us/pnw/pubs/pnw_gtr784.pdf.**

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2. Stahl, K., Moore, R.D., & McKendry, I.G. 2006. Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. Climate Research. 32: 13-23.

Context

This paper was written to relate the role of synoptic and large-scale climate trends to recent epidemics of mountain pine beetle, specifically in relation to the frequency and distribution of extreme wintertime cold events that result in beetle mortality. Because the abundance of susceptible host trees and beetles drive bark beetle outbreaks, understanding the mechanisms controlling these dynamics is crucial.

Synopsis

There were two overall objectives of this paper. First, was to examine connections between winter beetle mortality cold events and large-scale climate modes. Second was to understand the influence of synoptic-scale circulation patterns on these same cold events.

Methods critical to this study were the combination of several parameters of different scales. This analysis was strengthened by combining teleconnection, synoptic-scale, and temperature data. This was an innovative approach, illustrating the recent advances in the understanding of both large-scale climate modes and synoptic-scale patterns. In addition, the use of chi-square tests of independence was a simple, yet powerful way to determine if relationships existed within the data set. The authors addressed the potential for violations of the chi square tests due to the correlation of their cold-mortality days and the clustering of some of their categorical data.

Major results from this research include:

1. The spatial distribution of cold-mortality days. The highest frequency of potential cold mortality days were found in northeastern British Columbia (BC), where arctic air masses dominant during winter. Overall, cold mortality days have decreased since 1957.
2. Cold mortality events were associated with a synoptic circulation pattern when cold Arctic air flows coastward from the interior mountains of BC.
3. The frequency of synoptic circulation patterns depends on large-scale climatic modes, including the El Nino Southern Oscillation, Pacific Decadal Oscillation, and Pacific North American pattern.
4. The frequency of cold-mortality events coincides with strong negative Pacific Decadal Oscillations and all teleconnection patterns. Recently the PDO has been in a positive or neutral phase resulting in less frequent or severe cold events.

The authors state that this study provides linkages between synoptic circulation, climate variability, and surface temperatures in BC, and how this relates to the reduced frequency of cold events and mountain pine beetle mortality. This information can be applied to climatic conditions predicted for the future, in relation to both synoptic-scale weather patterns and bark beetle dynamics.

3. Logan, J.A., Regniere, J. & Powell, J.A. 2003. Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ. 1(3): 130-137.

Context

This review paper summarizes the state of knowledge, data, and modeled predictions of forest pest dynamics in relation to climate change for two reasons. The first reason was to illustrate the current and future impacts of climate change on forest resources. The second reason was to promote cooperation among researchers and managers to pool their current software tools, databases and models to monitor, evaluate and manage events.

The objectives of this paper were to evaluate specific forest pests and their associated hosts because of the substantial ecological, economic, and social impacts related to their changing population dynamics.

Methods critical to this study were a review of the: 1) methods used to assess the impact of climate change on insects; 2) databases required to build and test models; 3) available insect life cycle models based on temperature; and 4) quantitative models used to predict and evaluate outbreaks.

Major results from this research include:

1. Overall, the majority of assessments of pest species response to climate change indicate increased outbreak severity.

2. Insects will shift their distributions and increase outbreak intensity.
3. Models provide a way to evaluate future events.
4. Current high-resolution databases used to build models are improving and becoming more accessible.

The authors state that this study provides evidence that forest pests are valuable indicators for assessing climate change and the models currently available provide the building blocks for systematic assessments.

Synopsis

This review was not a breakthrough, but serves as an excellent resource for ecologically based empirical models of insect phenology and population dynamics, and reliable weather records for the western United States. In addition, this paper provides an excellent perspective of the inputs used to build many of the forest pest models.

Overall, this article was a substantive contribution to both climate change and bark beetle research.

4. Ayres, M.P., & Lombardero, M.J. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Science of the Total Environment. 262: 263-286.

Context

This review paper assesses the potential changes in forest disturbances, economics, biodiversity, recreation, and water quality in light of 32 different biotic agents of disturbance, including many insect species. In addition, this paper outlines research priorities that facilitate risk assessment and management strategies.

Synopsis

The overall objective of this paper was to review the current impacts of forest herbivores and pathogens in North America.

The methods critical to this review paper include an extensive set of tables listing herbivores and pathogens that are significant agents of biological disturbance and the respective host species and citation. In addition, this paper address multiple facets of forest disturbance including economic impacts, ecological importance, human activity, feedbacks to climate change, direct effects of climate change on herbivores, pathogens, and their host species. Finally, a list of specific research priorities directed at understanding future losses to these disturbances.

Major results from this research include:

1. Climate change induced forest disturbance alterations will affect community structure and function, biodiversity, biogeochemistry, and disturbance regimes.
2. Economic costs are difficult to assess, but overall losses to the timber industry will be significant. In addition, prevention, and restoration costs are considerable.
3. Human activity such as fire manipulation, atmospheric nitrogen deposition, and forest fragmentation can influence forest disturbances.
4. Alteration of forest species, size structure, overall distribution, and abundance affect ecosystem functions such as CO_2 flux, evapotranspiration, and heat transfer. Changes in these functions create feedbacks to climate change.
5. Developmental rates of poikilothermic insects are directly influenced by climate. In general, reproductive potential is increased. In addition, climate change alters host tree physiology and defense mechanisms.
6. Research priorities include: physiological models to predict host tree and herbivore and pathogen responses to climate change, strategies for maintaining genetic diversity of tree species, and predictions of future patterns mineralization rates and nutrient availability.

The authors state that this study provides a perspective on both the gravity of the consequences of alterations of herbivore and pathogen forest disturbance and a set of research objectives to meet the potential challenges.

5. Romme, W.H., & Turner, M.G. 1991. Implications for global climate change for biogeographic patterns in the Greater Yellowstone Ecosystem. Conservation Biology. 5(3): 373-386.

Context

In context of this bibliography, this paper serves as an overview of the implications of climate change on the ecology, specifically the distribution and disturbance dynamics, of a tree which is one of the main hosts of the mountain pine beetle, the whitebark pine. In a broader sense, this paper was written to explore the ramifications of changes in global climate on biogeographic patterns and biodiversity in the Greater Yellowstone Ecosystem.

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Major results from this research include:

1. A warm, dry climate scenario with no plant compensation by increased water use efficiency results in:
    a. Longer growing season which would shift timberline species to higher elevations, contracting the total area of the alpine zone (i.e.: a 90% decrease in whitebark pine habitat).
    b. Summer drought stress would increase in forests.
    c. Low elevation, non-forested community types would expand.
2. A warm, dry climate scenario with increased water use efficiency results in:
    a. Longer growing season and upward shift and reduction in area of timberline/alpine zone.
    b. In low elevation communities, higher potential evapotranspiration would be compensated for by increased water use efficiency.
    c. Drought stress would not change.
3. A warm, wet climate scenario
    a. Warm temperatures result in longer growing season and an upward shift and reduction in area of alpine zone (including whitebark).
    b. Increased precipitation would result in whitebark pine being out competed by species previously limited by moisture. This could result in reduction or localized extinction of this species.
    c. Low elevation community types may be reduced by the encroachment of forested types.

The authors state that this study provides a way to delimit the range and magnitude of possible changes in the ecosystem. This information may promote successful research and monitoring efforts. In addition, the overall conclusions from all three climate scenarios indicate a reduction in the overall area of the alpine zone, impacting those species restricted to those sites. Because other community types may expand, overall species diversity may remain unchanged.