Final Report to Wyoming Water Development Commission for the Project:

**Impact of bark beetle outbreaks on forest water yield in southern Wyoming**

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**Abstract**

A Rocky Mountain Region outbreak of bark beetles and their associated fungi from British Columbia to New Mexico is having profound impacts on forest function and ecosystem services. These forests are key components of major river watersheds which could magnify any impacts on downstream users of water including those in Wyoming. Current and ongoing research is documenting the potential extent, causes and impacts on carbon exchange and evapotranspiration but less is known about how water yields will be impacted on short to long time scales. This project will enhance preliminary measurements of evapotranspiration and soil moisture from a mid-elevation lodgepole pine forest undergoing infestation by 1) reasonably closing stand water budgets to better quantify and thus predict water yield and 2) extending replicate measurements and analyses to post-infection management to facilitate future scaling to landscape water yield. New stands will be established in mid elevation former lodgepole pine that has been clearcut after infestation. We will provide complete water budgets that are closed on a stand basis by measuring 1) spatially explicit snow accumulation and loss, 2) detailed liquid canopy interception and stem flow, 3) appropriately scaled transpiration from living, dying and dead trees’ water use (or lack thereof) through sap flow and leaf gas exchange, 4) soil hydraulic characteristics and modeling and runoff for water yield and 5) stable isotopes of soil, plant and atmospheric water as a further test of water budget component closure. Our proposed data collection and analysis will provide highly probable predictions of water yield during the first 5 to 10 years of the outbreak and provide the basis for first order predictions of the next 10 to 100 years of impact. The results of this project will be communicated with State and Federal agency personnel, providing data necessary for future water management decisions in all areas of Wyoming impacted by the bark beetle outbreak.

**Objectives**

1) Quantify how precipitation is partitioned into evapotranspiration, throughfall, stemflow, soil storage and water yield across forest types (including a clearcut) as trees die and the forests begin initial recovery from bark beetle-induced mortality

2) Determine errors and associated uncertainty in closing a water budget across forest types

**Methodology**

All major components of forest stand water budgets were measured at the lodgepole pine bark beetle sites with a select group of major components at the higher elevation spruce and fir bark beetle site. Some of the following measurements were also funded by a National Science Foundation Hydrologic Science and UW Agriculture Experiment Station grants. Precipitation was measured with multiple approaches to obtain incoming liquid and frozen precipitation as well as throughfall and snowpack depth and density
prior to infiltrating or running off of soil. **Drainage** was estimated by combining soil physical properties with soil water storage measurements. Piezometers measured **streamflow** out of the forests at multiple spatial locations. **Evapotranspiration** was quantified through eddy covariance methods at the lodgepole pine, clear cut lodgepole pine and spruce and fir forests. **Tree transpiration** was measured in nearly 50 trees representing a range of bark beetle infestation and responses of trees to forest management such as thinning or clear cutting. Stable isotope measurements of water vapor fluxes were used to partition evapotranspiration into transpiration and evaporation.

Measurements of leaf gas exchange and plant hydraulic conductance were made to test mechanisms of tree mortality in response to the bark beetle epidemic. A spatial grid of 144 plot level measurements of tree and understory characteristics was sampled to scale up plot level flux measurements to watersheds.

**Principal Findings (Cited Papers are Publications Section)**

We accomplished both objectives of the project; the outcomes of each objective are listed as the following specific findings. 1) Tree transpiration declines 50% within a month and is zero by the end of the first growing season in lodgepole pine while spruce takes two years (Edburg et al 2012). 2) Water fluxes to the atmosphere from the stands drop at the same rate as carbon fluxes resulting in a near constant water use efficiency until dead trees become a significant component of the stand (Reed et al In Review, Frank et al In Review). 3) Snowpack increases slightly in stands dominated by dead trees but sublimation is increased and snowmelt occurs earlier (Biederman et al 2012). 3) Liquid water interception is 25% lower in stands with high mortality. 5) Soil moisture increases with the decline in transpiration and evapotranspiration in all stands (Reed et al In Revision). 6) Energy balance closure is low (~50%) unless spatial heterogeneity and energy storage changes from mortality are included then closure is higher (~80%) (Reed et al In Revision). 7) Common sonic anemometers likely underestimate sensible and latent (i.e. evapotranspiration) heat fluxes (Frank et al 2013). 8) Increased soil moisture does not appear to increase streamflow likely due to a) earlier snow melt with declining canopy structure, b) increased evaporation and sublimation as indicated by stable isotopes of water and c) potential storage effects at the watershed scale (Somor et al In Review).

Some of the key figures for these findings are included below.
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Figure 1 Mortality progresses quickly in lodgepole pine forests because the trees die in one growing season from fungal occlusion of the xylem. The process takes two years in spruce trees but the results are largely the same, dramatic decreases in tree transpiration. (Reed et al. In Revision).
Evapotranspiration (ET) response to radiation that drives photosynthesis (PPFD). Letters indicate significant differences in the response; before the beetles (2005 – 2007) have higher ET values at the same radiation. Figure 2 Because of the drop in tree transpiration, all of the post-beetle epidemic years have evapotranspiration rates that are at least 20% lower. (Frank et al In Review).
Figure 3 Snow pack depths are greater in beetle red and gray stands (used as line colors above). However, the snow pack is reduced faster due to increased sublimation and melt occurring 1-2 weeks faster due to darker albedos and more radiation and turbulence in dying and dead stands. (Biederman et al 2012).
Figure 4 The ratio of soil water equivalent to precipitation (SWE:P) normalizes for precipitation differences. There was no difference in the mean value of the ratio across living (a), green but infested (b), red (c) or gray stage (d) stands. The difference between no tree and dense trees also became less as the epidemic progressed. (Biederman et al 2012).

Figure 5 Unimpacted stands show little isotopic enrichment in the snowpack compared to new snowfall (a) while MPB impacted stands show enrichment suggesting increased sublimation due to increased turbulence and radiation drivers. (Biederman et al 2012).
Eight watersheds from northern Colorado that were hit by bark beetles from 2003-2007. Neither streamflow nor runoff ratio (runoff/precipitation) responded to the beetle outbreak. Temperatures were consistently high during the beetle outbreaks.

Figure 6 Stand level data from evapotranspiration, transpiration and soil moisture suggests that more water should leave infested stands while snow data suggests less water is available. The resulting streamflow from eight infested stands in Colorado (infestation began in 2002) does not show an increase in streamflow (Somor et al In Review).
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**Catchment-scale hydrological response in central Colorado**

The response to MPB is variable; the only significant change in annual water yield is a decrease in the most heavily impacted catchment.

**Common observations:**
- Slight increase in baseflow – consistent with reduced T
- No change in timing – change in melt rate not important

Figure 7. Analysis of data from Figure 6 showing that there was no increase in streamflow once climate variability between years was incorporated with empirical models.

**Significance**

This work provided measurements and analysis of stand-level water balance that are critical to developing and testing forecasting tools for determining the impact of bark beetles on streamflows from primary streams to major river systems. We found very clear and compelling direct impacts of mortality on precipitation partitioning at the stand scale as expected. However, the mechanistic impact of bark beetles on streamflow is unresolved. Empirical data shows that soil moisture increases do not lead directly to streamflow increase. Thus, the scaling of bark beetle-induced water budget changes from stands to watersheds is the most uncertain result of this project.

Our work from this project has lead to the following significant impacts. First, Wyoming State and regional water managers cannot assume that the reduction in evapotranspiration from forests with high bark beetle mortality will lead directly to increased streamflow. The PI of this project has given many talks around the state and region with this message which has led to heated, ongoing policy debates. Second, our results suggest a clear research path. Models of bark beetle impacts on streamflow must be able to replicate the stand-scale changes in water budgets; our new funding from this agency will test a model at this scale and then use the resulting parameterization to explore the watershed consequences. The same model will also be used to examine how long the stand scale...
consequences of bark beetle mortality will last. This research effort will additionally require resources to investigate sublimation more thoroughly as well as alternative sources of error in watershed scaling including storage by geological substrates. The results of this project were used as a major, scientific justification for the largest NSF Award to U.W (see leveraged support below). Third, many undergraduate and graduate students as well as a post-doc were partially supported on this project. Several of these students will continue to work in the state and region resulting in ongoing benefits to the state.

**Students/Post-Docs Supported**
Julia Angstmann, PhD student, helped establish research sites, graduated before project began. Currently employed at Indiana University.

Tim Aston- ongoing PhD student, helped set up sap flux measurements, no direct support from project beyond logistics.

Bujidma Borkhuu-ongoing PhD student, main responsibilities are soil measurements and assistance with atmospheric measurements. Received partial support from project.

John Frank- ongoing PhD student, main responsibilities are all of the flux measurements from the spruce and fir bark beetle site (note: John Frank is a full time employee of the USFS RM Exp St in Ft. Collins, and does not receive any salary support from this project). Support from this project is used for field visits and site maintenance through a USFS subcontract.

David Reed-ongoing PhD Student, main responsibilities are the atmospheric and streamflow measurements. Received partial support from project.

Faith Whitehouse-MS Student, main responsibilities were the tree physiology measurements. Faith decided to leave graduate school and become a full time photographer; she is currently operating her own photography business in Laramie. Received partial support from project.

Claire Hudson-Undergraduate Student, main responsibilities were assisting with soil trace gas measurements and lab processing and vegetation measurements. Now a graduate student at UW working on an MS regarding Alaskan Forests and Climate Change. Received partial support from project.

Margo Hamann-Undergraduate Student, main responsibilities are assisting with tree physiology field measurements and lab processing. Received partial support from project.

Holly Barnand-Post-doc, main responsibilities were isotopic measurements for ET partitioning. Holly is now an Assistant Professor at CU-Boulder. Received partial support from project.
Publications *(Students and Post-Docs are italicized)*


-----Following manuscript was cited in Principle Findings none of the authors were funded by this project.

Somor et al. In Review. Mountain pine beetle mortality does not lead to increased streamflow. Water Resources Research.

Presentations *(Students and Post-Docs are bolded)*

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, U. of New Mexico, February, 2013

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, Los Alamos National Labs, February, 2013

(Invited) Ewers BE. Impact of Fire and Insect Disturbance on Water Cycling in Ecosystems. Land Managers of the Laramie District of the Medicine Bow National Forest. February 2013


