LA-UR-97- - 3 5 1 1

Approved for public release;
distribution is unlimited

Title:

Fluxes of Water and Energy in Physically Heterogeneous Environments

Authors:

D. D. Breshears, EES-15
F. J. Barnes, EES-8
D. W. Davenport, EES-15
S. N. Martens, UC-Davis
C. W. Meyer, EES-8
H. J. Turin, CST-7
W. E. Soll, EES-5
B. P. Wilcox, EES-15
C. D. Allen, U.S. Geo. Survey
P. M. Rich, U. Kansas

Submitted to:

DOE Office of Scientific and Technical Information
(OSTI)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

MASTER

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Form 836 (10/95)
ST 2629

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Fluxes of Water and Energy in Physically Heterogeneous Environments

David D. Breshears,* Fairley J. Barnes, David W. Davenport, Clifton W. Meyer,
H. Jake Turin, Wendy E. Soll, and Bradford P. Wilcox
Los Alamos National Laboratory

Scott N. Martens
University of California-Davis

Craig D. Allen
U.S. Geological Survey

Paul M. Rich
University of Kansas

Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). Fluxes of water and energy at the near-surface environment are tightly interrelated with a heterogeneous vegetation pattern that is a mosaic of tree canopies and intercanopy area. Our objective was to improve the ability to predict these interrelationships, which are not well quantified. We (1) quantified how vegetation overstory determines the patterns of soil moisture and near-ground solar radiation, (2) developed spatial neighborhood analyses that demonstrated how woody plants exploit canopy/intercanopy heterogeneity, (3) developed a spatially explicit model for predicting near-ground solar radiation for sites along a grassland-forest continuum, (4) developed a water balance model that predicted temporal shifts in soil moisture between canopy and intercanopy patches, and (5) used the collective results to assess large-scale ecosystem responses to climate variations that lead to accelerated soil erosion.

Background and Research Objectives

A fundamental problem in earth and environmental sciences is predicting fluxes of water and energy at the near-surface environment, which are interrelated with vegetation pattern. The interrelationships between vegetation pattern and fluxes of water and energy are of fundamental importance to many current issues of global and regional concern, including evaluation of feedbacks between climate and terrestrial ecosystems in assessing global change; linking ground measurements of soil moisture to micrometeorology predictions; modification of moisture inputs for prediction of subsurface hydrology; and ecosystem management of soil erosion, forage, and fuel wood.

* Principal Investigator, E-mail: daveb@lanl.gov

There are many models for predicting fluxes of water and energy at two extremes of a vegetation continuum: physically homogenous grasslands—which have no surface area covered by trees (or other woody plants)—at one end, and physically homogeneous forests—which have surface area completely covered by woody plants—at the other end. A large proportion of the global terrestrial environment, however, is comprised of shrublands and woodlands that are physically heterogeneous—these areas are partially covered by trees or other woody plants. Large differences in the fluxes of water and energy are expected beneath woody plants in comparison with those areas around them. Yet, despite the magnitude and significance of these expected differences, current models for predicting fluxes of water and energy in physically heterogeneous environments ignore the physical heterogeneity corresponding to partial coverage by woody plants—this could result in greatly erroneous predictions. Further, the fluxes of water and energy should influence vegetation pattern, yet this interrelationship has not been demonstrated within complex vegetation patterns.

Our overall goal was to improve the ability to predict the interrelationships between vegetation pattern and fluxes of energy and water for environments with complex vegetation pattern. Our specific objectives were to:

- *Quantify the interrelationships between patterns of soil moisture, near-ground solar radiation, and vegetation overstory;*
- *Develop and test a new suite of spatial neighborhood analyses relating the spatial pattern of woody plants to the surrounding intercanopy areas;*
- *Develop a spatially explicit model for predicting near-ground solar radiation and apply it to sites along a grassland-forest continuum;*
- *Develop a water balance model that differentiates between canopy and intercanopy patches and compare temporal predictions of soil moisture with field data; and*
- *Assess large-scale responses of vegetation pattern to climate variations and associated responses that can lead to accelerated erosion.*

Importance to LANL's Science and Technology Base and National R&D Needs

This project directly supports LANL's core competencies. The research supports the core competency in *Earth and Environmental Science* by relating fundamental processes of water and energy fluxes to vegetation patterns. This project has advanced the theory of

how these water and energy fluxes are interrelated with vegetation pattern using a modeling approach; applying these results to larger spatial scales and longer time frames will require high performance computing. Hence, this project also supports the core competency in *Theory, Modeling and High Performance Computing*. The research in this project addresses the Environmental Stewardship component of Los Alamos National Laboratory core mission to Reduce the Nuclear Danger—our results are required to predict the movement of contaminants and the stability of engineered landfill covers for waste sites. Further, our results support the Civilian National Mission in Energy and the Environment. Lastly, this project directly supports the Integrated Environmental Science Tactical Goal, including the thrusts for actinides and the environment and for global issues (e.g., water resources, atmospheric sciences, and urban security).

Scientific Approach and Accomplishments

To improve predictions of the interrelationships between vegetation and fluxes of water and energy, we analyzed previously collected data, developed spatial analyses and models, and applied nonlinear conceptual models to unify differing perspectives.

Objective 1: Quantify the interrelationships between the patterns of soil moisture, near-ground solar radiation, and vegetation overstory.

Approach

We quantified the interrelationships between the patterns of soil moisture, near-ground solar radiation, and vegetation overstory using previous estimates obtained from a study site at Los Alamos National Laboratory in a piñon-juniper woodland. This woodland is covered in nearly equal proportions by tree canopies and intercanopy area. Estimates of soil moisture, solar radiation, and vegetation overstory were obtained at 1-m interval stations along a 102-m transect. Soil moisture was measured at each station in the top 30 cm by time domain reflectometry (TDR) over a three year period [1]. Near-ground solar radiation was estimated using the CANOPY program [1, 2], which estimates the fraction of solar radiation that reaches the near-ground environment as modified by neighboring obstructions (woody plants, in this case) using hemispherical photographs. Vegetation overstory was categorized at each station as “canopy” or “intercanopy” on the basis of whether woody overstory was present directly over the station. In addition, we noted

whether there was an edge between canopy and intercanopy patch types within 1 m to the north and 1 m to the south.

We tested for spatial autocorrelation in each of the three state variables (soil moisture, solar radiation, and vegetation overstory) by calculating Moran's I values as a function of lag distance between sampling stations [1]. After, removing the primary effects of spatial autocorrelation, we tested for differences between canopy and intercanopy locations.

Accomplishments

Our results quantified fundamental relationships among vegetation overstory, soil moisture, and solar radiation [1]. There was significant autocorrelation in all three variables at similar scales, indicating that the spatial pattern of the vegetation overstory is a series of alternating canopy and intercanopy patches that imposes corresponding spatial patterns in near-ground solar radiation and soil moisture through interception by tree canopies of both solar radiation and precipitation (Figure 1). Not only do canopy patches receive less solar radiation and soil moisture than intercanopy patches, but there are gradients within each patch type: within intercanopy patches, the south edges receive less solar radiation than the north edges, whereas for canopy patches the reverse is true; soil moisture is greatest at edges between canopy and intercanopy patches because of canopy drip. The differences vary temporally: the magnitude of differences in solar radiation is greatest in the time interval around the winter solstice, when solar zenith angles are greatest; the magnitude and the direction of soil moisture differences at any point in time are related to the recent precipitation history (although intercanopy patches are usually wetter than canopy patches, the magnitude of this difference decreases as soil dries and the direction of this difference can be reversed—with intercanopy patches becoming less wet than canopy patches—following intense storms, which generate proportionally more runoff from intercanopy patches).

The spatial and temporal variation that we quantified in both solar radiation and soil moisture in piñon-juniper woodlands are of direct relevance for solving environmental problems related to water resources, biotic resources, and contaminants because they provide the basis for linking an understanding of processes at a smaller scale, where measurements are usually made, to larger scales relevant to assessment and management. Further, they should be applicable to a wide variety of other sites characterized by heterogeneous vegetation overstory.

Objective 2: Develop and test a new suite of spatial neighborhood analyses relating the spatial pattern of woody plants to the surrounding intercanopy areas.

Approach

We tested for the effects of spatial heterogeneity in solar radiation and soil moisture on the pattern of trees at the same piñon-juniper woodland study site. Previously, all woody plants greater than 1 m in height were mapped and the size of the canopy of each was estimated. We investigated the spatial pattern of these woody plants using Ripley's K-function [3]. Further, we developed neighborhood analyses that related the size of a tree to the area surrounding it, as defined by locations, sizes, and species of neighboring trees [4]. We tested for three types of asymmetrical interactions among individuals: (1) spatial asymmetry—tree size is better correlated with the area surrounding it when that area is allowed to be asymmetrical about the shoot; (2) size asymmetry—a larger individual has a disproportionately larger competitive effect for its size relative to smaller individuals; and (3) species asymmetry—the effect of a first species on a second differs from the effect of the second on the first.

Accomplishments

We demonstrated that the spatial patterns of trees are interrelated with spatial heterogeneities in soil moisture and solar radiation [3]. Trees were aggregated at scales of 2 to 4 m and these canopy patches were composed of individuals of both species. Crown centers of both species were always less aggregated than stem centers at scales less than canopy patch size, indicating morphological plasticity of competing crowns in response to heterogeneity in near-ground solar radiation. At scales larger than canopy patches, younger trees showed repulsion from older trees of the same species, indicating below-ground competition in response to heterogeneity in soil moisture. Vegetation dynamics depend on the scale and composition of canopy patches. The woodland is intermediate in a grassland-forest continuum (a gradient of increasing woody canopy cover) and hence we expected, and were able to detect, the effects of both above-ground competition for solar radiation and below-ground competition for soil moisture.

The neighborhood analyses that we developed yielded highly predictive relationships in above-ground spatial pattern of individuals that enabled us to infer use of intercanopy soil moisture (i.e., below-ground competition) was structuring the plant community [4]. In contrast traditional methods (i.e., analyses of spatial point pattern and nearest neighbor) did not yield evidence for competition or lacked predictive ability in explaining variation. We also found significant asymmetrical interactions among

individuals. Considering spatial asymmetry improved predictive relationships and provided evidence for root displacement away from neighbors. Size asymmetry was so strong that, without consideration of it, prediction of competitive interactions among individuals would have been either lacking or very weak. Interactions among individuals of different species were asymmetrical—the effect of juniper on piñon was greater than the effect of piñon on juniper. These three types of asymmetrical interactions should be considered when applying neighborhood analyses to other plant communities. Neighborhood analyses, which can be more powerful in detecting competition than traditional methods, have not previously been applied to arid and semiarid plant communities, and hence below-ground competition may be much more important in structuring these plant communities than previously thought. Consideration of asymmetrical interactions among neighboring individuals should improve the ability to predict plant community dynamics and associated ecosystem processes in other arid and semiarid environments.

Objective 3: Develop a spatially explicit model for predicting near-ground solar radiation and apply it to sites along a grassland-forest continuum.

Approach

The spatial structure of many vegetation-dominated landscapes can be viewed as a continuum between grassland and forest with intermediate coverage of the ground by trees. Along this continuum, changes in structure of vegetation overstory include an increase in cover, an increase in tree height, and a change in spatial pattern from regular to aggregated. We developed a ray-tracing model to estimate below-canopy solar radiation for total stand areas, canopy patch locations, and intercanopy patch locations for the period encompassing the majority of the growing season (April through October). We used actual stand data from three locations and simulated stand data for differing cover, height, and spatial pattern to estimate changes in the spatial distribution of solar radiation along the grassland/forest continuum.

Accomplishments

Our estimates of solar radiation from actual and simulated stand patterns agreed well with one another. Mean total radiation was highly dependent on percentage of cover and was sensitive to tree height but was not sensitive to spatial pattern. Variance in total radiation was dependent on all three factors (percentage of cover, height, and spatial pattern). The estimates of solar radiation obtained with a one-dimensional (1-D) model for

solar radiation were less than our estimate using a 3-D model, indicating an overestimate of the effects of shading around trees, whereas estimates obtained from a two-phase model of canopy and intercanopy patches weighted by the relative proportions of each were greater than our estimate, indicating an underestimate of the effect of shading around trees (Figure 2). These results provide a conceptual framework for viewing the grassland/forest continuum as a set of canopy and intercanopy patches and for assessing the role of the spatial structure of those patch types on incoming solar radiation for a site and for locations within that site.

Objective 4: Develop a water balance model that differentiates between canopy and intercanopy patches and compare temporal predictions of soil moisture with field data.

Approach

Models of water balance generally assume vegetation overstory is homogeneous; lacking are water balance models for systems that are comprised of canopy and intercanopy patches. We developed a daily time-step model that distinguishes between canopy and intercanopy patches in estimating water balance: interception is much greater for canopy than intercanopy locations; runoff is greater in intercanopy locations, some of which runs on to canopy locations; solar radiation is greater for intercanopy locations and affects snow melt soil and evaporation; and uptake from canopy locations is primarily by woody plants whereas uptake from intercanopy locations is by both woody and herbaceous plants. We used a weighting function to estimate plant water potential and plant water uptake. We tested our model with field measurements of soil moisture, runoff, plant water potential, and transpiration.

Accomplishments

Our model predictions of temporal changes in soil moisture were similar to field measurements. More specifically, the temporal changes in the difference in soil moisture between canopy and intercanopy locations [1] were accurately simulated. Other existing models do not account for this horizontal heterogeneity.

Objective 5: Assess large-scale responses of vegetation pattern to climate variations and associated responses that can lead to accelerated erosion.

Approach

The pattern of vegetation overstory is expected to shift relatively rapidly in response to

changes in climate, particularly at ecotones—the boundaries between adjacent ecosystems, but most studies relating climate change to ecotone shifts have evaluated time-scales of centuries or much longer. We used field observations, historic records, and GIS analyses of aerial photographs at several points in time between 1935 and 1991 to evaluate changes in the ecotone between ponderosa pine forest and piñon-juniper woodland on the Pajarito Plateau in northern New Mexico [5]. A severe, regional drought occurred during this period in the 1950s. We mapped the vegetation overstory into classes of ponderosa pine coverage. We also used previous measurements of erosion at sites within and outside of this ecotone.

Accomplishments

In response to the drought, the ecotone between ponderosa pine forests and piñon-juniper woodlands shifted upslope by as much as 2 km. The 1950s drought probably reduced herbaceous ground cover in these ecotone areas. The results demonstrate that changes in ecotones can occur rapidly over large areas and provide an analogue for the types of changes expected in many semiarid regions in response to climate warming. Our results are significant because they document the largest response by woody vegetation to climate variations within a decade time-frame.

Our measurements indicate that high rates of erosion are now occurring within the former ecotone in response to the changes in the vegetation, whereas erosion rates are low at other locations. We generalized these results by developing a conceptual model of soil erosion thresholds [6]. Soil erosion rates in general are determined by (1) site erosion potential, which is largely inherent to a site and is a function of climate, geomorphology and soil erodibility; and (2) ground cover, which is most directly linked to vegetation patterns and may change rapidly in response to land management practices or climatic variations. Using a predominant erosion model (USLE), we demonstrated how site erodibility and cover act synergistically to determine soil erosion rates. The patterns of sensitivity of erosion to site erodibility and cover can be visualized as a cusp catastrophe surface, on which some changes occur rapidly and are not directly reversible.

The mechanisms associated with a shift from low to high erosion rates can be described using percolation theory, in which the hillslope is viewed as a network of nested grid cells, each of which has a limited capacity for water storage. Percolation theory predicts both a sharp threshold in runoff response that is dependent on the water storage capacity of individual cells and scale-dependent differences in runoff, as has been observed (Figure 3). Collectively, these conceptual models provide a unifying perspective of soil erosion

thresholds in piñon-juniper ecosystems and can be used to improve land management practices through better understanding and prediction of erosion rates.

Publications

1. Breshears, D. D., Rich, P. M., and Barnes, F. J., "Heterogeneity in solar radiation and soil moisture imposed by overstory with intermediate closure", *Ecological Applications*, Submitted / in revision [LA-UR-95-4310] (1996).
2. Breshears, D. D., Martens, S. N., and Meyer, C. W., "Inferring below-ground competition from above-ground pattern: asymmetric interactions in plant communities", *Ecology*, Submitted / in revision [LA-UR-96-1891] (1996).
3. Martens, S. N., Breshears, D. D., Meyer, C. W., and Barnes, F. J., "Scales of above- and below-ground competition as detected from spatial pattern", *Journal of Vegetation Science*, Submitted / in review [LA-UR-96-2521] (1996).
4. Davenport, D. W., Breshears, D. D., Wilcox, B. P., and Allen, C. D., "Viewpoint: Sustainability of piñon-juniper ecosystems: a unifying perspective of soil erosion thresholds", *Journal of Range Management*, Submitted [LA-UR-96-3782] (1996).

References

- [1] Breshears, D. D., Rich, P. M., and Barnes, F. J., "Heterogeneity in solar radiation and soil moisture imposed by overstory with intermediate closure", *Ecological Applications*, Submitted / in revision [LA-UR-95-4310] (1996).
- [2] Rich, P. M., "A manual for analysis of hemispherical canopy photography", Los Alamos National Laboratory Report LA-11733-M, (1989).
- [3] Martens, S. N., Breshears, D. D., Meyer, C. W., and Barnes, F. J., "Scales of above- and below-ground competition as detected from spatial pattern", *Journal of Vegetation Science*, Submitted / in review [LA-UR-96-2521] (1996).
- [4] Breshears, D. D., Martens, S. N., and Meyer, C. W., "Inferring below-ground competition from above-ground pattern: asymmetric interactions in plant communities", *Ecology*, Submitted / in revision [LA-UR-96-1891] (1996).
- [5] Allen, C. D., "Changes in the landscape of the Jemez Mountains, New Mexico", Ph.D. Dissertation, University of California at Berkeley, Berkeley, California, (1989).
- [6] Davenport, D. W., Breshears, D. D., Wilcox, B. P., and Allen, C. D., "Viewpoint: Sustainability of piñon-juniper ecosystems: a unifying perspective of soil erosion thresholds", submitted to *Journal of Range Management* [LA-UR-96-3782] (1996).

Figure 1. Near-ground solar radiation (Direct Site Factor—DSF) and soil moisture (% volumetric water content) for canopy and intercanopy patches within a piñon-juniper woodland; locations within each patch type are divided into north, center, and south.

Figure 2. (A) Photosynthetically Active Radiation (PAR) estimated as a function of % vegetation cover using one-dimensional, two-phase, and three-dimensional models; solid symbols are simulated tree stands, open symbols are actual stands. (B) Generalized changes in PAR.

A. Low connectivity

B. High connectivity

■ Canopy patch with storage
A = 47% B = 47%

▤ Intercanopy patch with storage
A = 11% B = 9%

□ Intercanopy patch with no storage: not connected
A = 31% B = 12%

▥ Intercanopy patch with no storage: connected
A = 11% B = 32%

Figure 3. Erosion for sites with (A) low and (B) high connectivity. A small change in the % intercanopy patches with storage (11% vs. 9%) produces a large change (11% vs. 32%) in the % intercanopy patches with no storage that are interconnected with the downslope edge.