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YEAR 1 PROGRESS REPORT

Project Title "A Comprehensive Statistical Analysis System to Associate Local Land-Cover/Land-Use Change and Regional Aerosol Composition and Concentration"

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Abstract

Aerosols, particularly carbonaceous aerosols, will likely play an increasingly important role in the earth's energy balance and in global climate change. Much of these carbonaceous aerosols are generated by anthropogenic activities, including slash-and-burn agriculture, as well as fossil fuel combustion. The proposed research seeks to add to scientific understanding of the relationship between biomass burning and carbonaceous aerosols by estimating the spatial and temporal dependence structure of regional carbonaceous aerosol concentrations, given atmospheric circulation processes and observed fire occurrences. We examine these trends using a Bayesian hierarchical statistical framework coupled with a global chemical transport model in a manner that explicitly accounts for the uncertainty associated with these processes. While it is difficult to separate the contribution of biomass burning to regional carbonaceous aerosols due to the chemical and physical processes occurring within the atmosphere, our analytical technique allows us to estimate the contribution of biomass burning to regional carbonaceous aerosols via the local fire/regional aerosol space-time associations. Finally, we embed the statistical model into an integrated system that will allow the user to forecast aerosol distributions under various environmental policy scenarios. This integrated system will seamlessly retrieve and examine data on aerosols and fires from MODIS and MISR, and visualize the results. In developing our system, we will focus on fire/aerosol relation in mainland Southeast Asia from the end of 2000 to the present. Mainland Southeast Asia is currently experiencing much varied land-use/cover change (including urbanization), though forest clearing for agricultural and forestry activities remains a dominant pattern; our tool is designed to deal with these complex processes and multiple sources of carbonaceous aerosols, yet emphasizes the estimation of the fire-aerosol relationship. We expect to add to the scientific understanding on the processes and changes at work in the study region, but our tool will ultimately have broad applicability to other regions and applications. Thus, the project contributes to NASA strategic objectives to understand and protect the earth, to study the earth from space, and to use NASA's space-based technology to study to the interactions between land and atmosphere.

Keywords Bayesian hierarchical modeling**,** Biomass burning**,** Carbonaceous aerosols**,** Land-atmosphere interactions**,** Mainland Southeast Asia**,** MODIS**,** MISR**,** Spatio-temporal statistics

I. Research Objectives

1. To develop a hierarchical Bayesian framework to study the association between biomass burning and regional carbonaceous aerosol concentrations that incorporates a process-based description of aerosol transport over space and time;
2. To quantify explicitly the uncertainty involved in the relationship between biomass burning and regional aerosols, given available data and the nature of complex, circulatory atmospheric transport patterns;
3. To contribute to the understanding of the implications of current land-use changes in Southeast Asia given the measured effects of biomass burning in the last 5 years on regional aerosol concentrations; and
4. To conduct scenario and sensitivity analyses at a regional level that advance the understanding of the implications of biomass burning.

II. Year 1 -- Summary of Progress

GOAL Develop software tools to automate the process of extracting MODIS (fire and thermal anomalies, burned area, and land cover) and MISR (aerosol optical depth, particle shape and size) data.

Accomplishments:

- A data extracting software tool was developed based on a variety of existing libraries. The tool consists of two main modules: one that can be used to extract information from MODIS data sets and the other from MISR data files. Both MODIS and MISR files are stored using a file format called HDF (Hierarchical Data Format). Our tool modules can be used to output MODIS and/or MISR variables for specified geographical regions and time periods using text files that can be easily imported into statistical software packages (e.g., R and Matlab).
    i. The MODIS tool module contains a set of Java programs that were developed using a package called HDF Java Products. A key component in this package is the Java HDF Interface, a Java Native Interface that is used as a wrapper of the HDF4 Software (version 4.2r1) developed by the National Center for Supercomputing Applications (NCSA) using C and FORTRAN. Though the HDF4 Software is generally efficient, it is a "low-level" library and tedious programming would be expected to develop general-purpose programs to access different HDF4 files. In addition, the HDF4 Software may not be suitable for the purpose of data visualization. The current version of the HDF Java Products is 2.3 and is also maintained by NCSA. Based on the functions provided by the HDF Java Products, our MODIS tool module can be used to 1) subset regions that may include or span into multiple MODIS tiles, and 2) stitch MODIS data from multiple tiles into one file.
    ii. The MISR module was developed based on a set of C libraries called MISR ToolKit (Mtk) developed by a research team at the Jet Propulsion Laboratory. Though MISR files are stored in HDF, a specific file structure called "stacked blocks" is used to store the relatively large geographic extent of MISR swaths. Mtk was developed to expedite the process of reading MISR swath information with a capability that allows a user to subset for specific regions. Based on Mtk, we developed our MISR module that can be used to 1) subset and stitch multiple swaths in a specified region, and 2) choose specific version or automatically choose latest version of each MISR data file.
- Compiled ancillary spatial data for the study region including land cover (IGBP classes), topography, road infrastructure and population centers.

GOAL Explore the strength of the associations between fire occurrence and atmospheric concentration of carbonaceous aerosols using MODIS and MISR data products in the context of current land-use changes in the region.

Accomplishments:

- Our exploratory analyses were primarily based on the MODIS Fire and Thermal Anomalies Product (center point of a 1km resolution pixel where a fire has occurred; Justice et al., 2002) and MISR products for aerosol concentration and composition (17.6 km resolution optical depth, size and shape of aerosols, Angstrom component and single-scattering albedo; Diner et al., 1998). In order to conduct an initial exploration of the information available in these data sources, we chose to focus on a subregion bounded by 17° N, 98° E and 21° N, 105° E of our study area in northern Thailand, western Laos and Vietnam. We also limited our preliminary analysis to the dry season of 2004 (January-April, November-December).
- For this preliminary study region, we compared aerosol optical depth values for areas with fires to areas without fires both numerically and graphically. We also explored how this relationship varied by land cover class, by elevation, and by land cover class and elevation.
- Given the difference in resolution between the MISR (17.6 km resolution) and MODIS (1 km resolution) data products, our statistical summaries of the relationship between fires and aerosols were calculated in two ways: i) assigning the MISR aerosol optical depth value to all MODIS pixels that fall within the larger MISR pixel; and ii) summing the number of MODIS fire pixels within each MISR pixel. Comparison of these two approaches allowed us to examine the effect of data integration over space on the empirical associations.
- We explored the strength of the fire-aerosol relationship at different spatial resolutions by comparing the average aerosol optical depth in different sized windows around each MODIS pixel. Ultimately, we believe that our formal spatio-temporal model will reveal the most appropriate window shape and size to capture the regional effect of local fire occurrences.
- In order to understand the social context underlying biomass burning, we conducted a substantial literature review (summarized in Munroe et al. 2007) linking land-use practices to fire activity in the study region. In the countries that compose mainland Southeast Asia (Burma, Thailand, Laos, Cambodia, and Vietnam) there are a number of human-induced causes for fire occurrence, including subsistence farming, the production of cash crops, and logging. There are several interesting dimensions across which the variations in fire and land-use practice are evident:
    - <u>Lowland and upland cultivation patterns</u>. Lowland areas are the location of continuous cultivation areas, particularly along the region's rivers, and the coastal lowlands are where most plantation agriculture can be found. Upland areas traditionally tended to be used for shifting cultivation (i.e., slash-and-burn agriculture), where fields were subject to extended fallow periods to regenerate, and periodic burning was the norm. Shifting cultivation has decreased in the region, and been replaced by an increase in such cash crops as rubber, palm oil, plantation tree crops, and coffee (Fox and Vogler 2005). Estimates of aerosol emissions due to biomass burning indicate that the burning of crop residue also releases a significant amount of black carbon (Streets et al. 2003); therefore, it is difficult to say currently whether the replacement of shifting cultivation with more permanent cash crop production will lessen the overall amount of carbonaceous aerosols released from biomass burning into the atmosphere, but it may change the location, timing and magnitude of these patterns.
    - <u>Variations in political and economic policy</u>. Vietnam, a socialist country, has made sweeping political and economic changes with regard to land and natural resources. The effect of the transition from individual-based shifting cultivation to plantation-based cash cropping is evident in land-cover changes (Giri et al. 2003). Dramatic

increases in agricultural exports from the region (e.g., coffee, rubber and cashews) and the building of new road infrastructure linking Thailand and southern China have spurred forest clearing in Vietnam and Laos. There is a qualitative ranking in the degree of current political and economic transition in the study area, with Vietnam as the most dynamic, followed by Laos, and then Cambodia, and finally Burma, due to continued political instability. Given our knowledge of these variations in external factors that strongly influence land-use practice, it will be important to monitor any variations in the biomass-burning/aerosol associations that we see across these respective countries.

GOAL Use the output from a global chemical transport model, Model for OZone And Related chemical Tracers (MOZART), to characterize the spatio-temporal covariance structure of aerosols based on a concept termed "atmospheric distance".

Accomplishments:

- Established a cooperative agreement with researchers at NCAR, which will enable us to use MOZART runs as a component of our spatio-temporal model.
- Obtained output from MOZART runs under three types of initial conditions: i) fire emissions and plume height information; ii) fire emission information, but no plume height information; and iii) no fire emission information and only roughly estimated plume height information. Currently, we are studying the spatial and temporal structures of the model output generated under these conditions.

Significant results

The Global Land Project has identified the need to understand better the impact of land-use/cover change on the atmosphere. In particular, there is a need to quantify the impact of carbonaceous aerosols emitted locally on the atmospheric concentration of aerosols over a region. Previous research has only considered the land-use change/aerosol relationship at a single scale, either by quantifying the amount of emissions from a local source or by studying the aerosol distribution over a large region without considering individual aerosol sources. As our proposal for this project hypothesizes, reconciling regional concentrations of carbonaceous aerosols with local land-use/cover change requires a multiscale (in time and space) approach. Using the MISR Level 2 Aerosol Parameters and the MODIS "Fire and Thermal Anomalies" product we explored the associations between fires and aerosol optical depth, and aerosol particulate size and shape (carbonaceous aerosols are assumed to be spherical and medium-sized).

Our exploratory analyses of fire occurrence and aerosol data have confirmed the need for a sophisticated statistical framework to explore the association of interest. We briefly discuss some of these analyses here (over our preliminary study region); further details can be found in Munroe et al. (2007). Figures 1-4 illustrate the bivariate relationship between average aerosol optical depth for pixels with fires and without fires, where areas and time points with unavailable fire occurrence and/or aerosol information are omitted. The relationship between fires and aerosols is clearly mediated by the elevation and land cover type, through varying land-use practices, atmospheric circulation associated with elevation, and expected fuel load.

Figures 1 through 3 present differences in aerosol optical depth for pixels with and without a fire averaged over all dry season months and displayed by land cover (Figure 1), by elevation classes (Figure 2), and by land cover and elevation classes (Figure 3). The difference in average optical depth for fire pixels compared to non-fire pixels is qualitatively highest in forested areas, then savannas, grassland/shrubland, and lowest in cropland areas. Breaking up the range of elevation into three classes (0-500 m, 500-700 m and above 700 m), average optical depth through the dry season in 2004 is higher for fire pixels in each class than non-fire pixels, though slightly more pronounced at medium elevation ranges. Figure 3 displays this process, again aggregated over the dry months in 2004, by land cover and elevation. The differences in aerosol optical depth between fire and non-fire forested pixels are consistent across elevation classes, but more overlap in distributions is evident at medium elevation ranges for grassland/shrubland and cropland. Differences in average optical depth for fire and non-fire savanna pixels are the highest at this elevation class. The distribution of average optical depth for pixels without fires is much more left-skewed for non-fire pixels, which is to be expected due to other non-biomass burning sources of carbonaceous aerosols that likely affect the distribution of aerosols for these pixels.

For comparative purposes, Figures 4 summarizes the fire-aerosol relationship at a lower level of aggregation. Here, the difference between the average optical depth for pixels with fires and without fires is plotted over time; values greater than 1 indicate that optical depth is higher for fire pixels than non-fire pixels, and the sizes of the symbols are proportional to the number of fires each day. Compared with Figures 1-3, the data summaries in Figure 4 reveal that aggregated over space, but not over time, the fire-aerosol relationship appears to be much weaker. The greatest number of fires is to be found in March, peaking around the 26th of March. Over the six-month period, there are more days when aerosol optical depth is higher for pixels with fire than without fire, but not significantly so. Moreover, the same seasonal trend is evident for both fire and non-fire pixels. Given these conflicting summaries, it is clear that there is a need to develop tools for exploring the fire-aerosol relationship without aggregating over the spatial or temporal dimension of the problem.

Dissemination of Results

Publication

Munroe, D.K., Calder, C.A., Shi, T., Xiao, N., Lam, C.Q., Li, D., Wolfinbarger, S.R., 2007. Quantifying the relationship between biomass burning, land-cover/use change, and the distribution of carbonaceous aerosols in mainland Southeast Asia. Department of Statistics Preprint No. 793, The Ohio State University. To be submitted to *Journal of Land Use Science.*

Presentations at technical meetings and conferences

Munroe, D.K., Calder, C.A., Shi, T., Xiao, N., Lam, C.Q, Li, D., Wolfinbarger, S., 2006. A Comprehensive Statistical Analysis System to Associate Local Land-Cover/Land-Use Change and Regional Aerosol Composition and Concentration. NASA's Land Cover Land Use Change Program Science Team Meeting, University of Maryland, College Park, MD, October.

Xiao, N., Munroe, D.K., Calder, C.A., Shi, T., Lam, C.Q., Li, D., Wolfinbarger, S. 2006. Exploring the space-time associations between biomass burning, land-cover/use change, and the distribution of carbonaceous aerosols in mainland Southeast Asia. Earth System Science Partnership Open Science Conference, Beijing, China, November.

Calder, C.A. and Shi, T., 2006. Spatio-temporal statistical modeling of biomass burning and regional black carbon aerosols in Southeast Asia MISR Data Users Science Symposium, Caltech, Pasadena, CA, December.

Sessions organized at professional meetings

Munroe and Xiao organized the session "Modeling Coupled Human-Environment Systems: Regional Approaches" at the upcoming Association of American Geographers Annual Meeting, San Francisco, CA. April 17-21.

Calder and Shi organized the session “Remote Sensing in Environmental Statistics” at the upcoming Joint Statistical Meetings, Salt Lake City, UT. July 29-August 2.

III. Year 2 – Summary of Goals

GOAL Using MOZART output, we will characterize the spatial and temporal structure of aerosol transportation in and around our study region. This structure will be summarized in terms of space and time dependency, which will be an important component of the statistical models we plan to build. This task will require the development of statistical methodology to accommodate the nonstationarity and anisotropic features of the dependence structure, as well as the computational challenges in model-fitting associated with high dimensional data.

GOAL We will explore the potential for using surrogate information for fire occurrence and emissions. Due to incomplete spatial and temporal coverage of the satellite imagery and derived data products, we plan to explore the extent to which additional data sources can be used within our analysis. While the Bayesian hierarchical framework can readily accommodate missing data in terms of accounting for this source of uncertainty, supplementing direct measurements of key variables using surrogate information may provide greater precision in forecasts. A goal for this coming year is to compile and explore additional data sources including information on area burned (i.e., burn scar), estimates of fuel load per land cover type (as detailed in Streets et al. 2003), and plume height measurements.

GOAL Based on the software tools created so far, we will be ready to go to the next step of developing a web-server with a Java-based graphical user interface (GUI) to allow users to explore impacts of user-defined emission scenarios. Our web server will allow users to access (query and display) our data and test the results of our statistical models. This server will be created using a technique called JavaServer Pages that can be used to handle both client-side query and server-side data generation. We will develop programs to display the data and model results. A significant portion of such display will be based on maps and graphs, which will be encoded using scalable vector graphs (SVG), an open source file format for visualization and web design. Finally, a technique called Asynchronous JavaScript and XML (AJAX) will be used to support rich, usable web applications that would allow users to update a portion of the web page (a map, for example) without having to wait until the entire web page to be loaded.

References

Diner, D., Beckert, J., Reilly, T., Bruegge, C., Conel, J., Kahn, R., Martonchik, J., Ackerman, T., Davies, R., Gerstl, S., Gordon, H., Müller, J.-P., Mynei, R., Seller, R., Pinty, B. and Verstraete, M., 1998. Multi-angle Imaging SpectroRadiometer (MISR) description and experiment overview. *IEEE Transactions on Geoscience and Remote Sensing* 34(4):1072-1087.

Fox, J., and J. Vogler. 2005. Land-Use and Land-Cover Change in Montane Mainland Southeast Asia. *Environmental Management* 36 (3):394-403.

Giri, C., P. Defourny, and S. Shrestha. 2003. Land cover characterization and mapping of continental Southeast Asia using multi-resolution satellite sensor data. *International Journal of Remote Sensing* 24 (21):4181.

Justice, C.O., Kendall, J.D., Dowyt, P.R., and Scholes, R.J., 2002. The MODIS fire products. *Remote Sensing of Environment* 83:244-262.

Munroe, D.K., Calder, C.A., Shi, T., Xiao, N., Lam, C.Q., Li, D., Wolfinbarger, S.R., 2007. Quantifying the relationship between biomass burning, land-cover/use change, and the distribution of carbonaceous aerosols in mainland Southeast Asia. Department of Statistics Preprint No. 793, The Ohio State University.

Streets, D.G., T.C. Bond, G.R. Carmichale, S.D. Fernandes, Q. Fu, D. He, Z. Klimont, S.M. Nelson, N.Y. Tsai, M.Q. Wang, J.-H. Woo, and K.F. Yarber, 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research 108 (D21): 30-1:30-23.

Figure 1. Comparisons of average optical depth dry season (January-April; November-December 2004) for pixels with and without fire. Averages are by land cover type (aggregated IGBP categories).

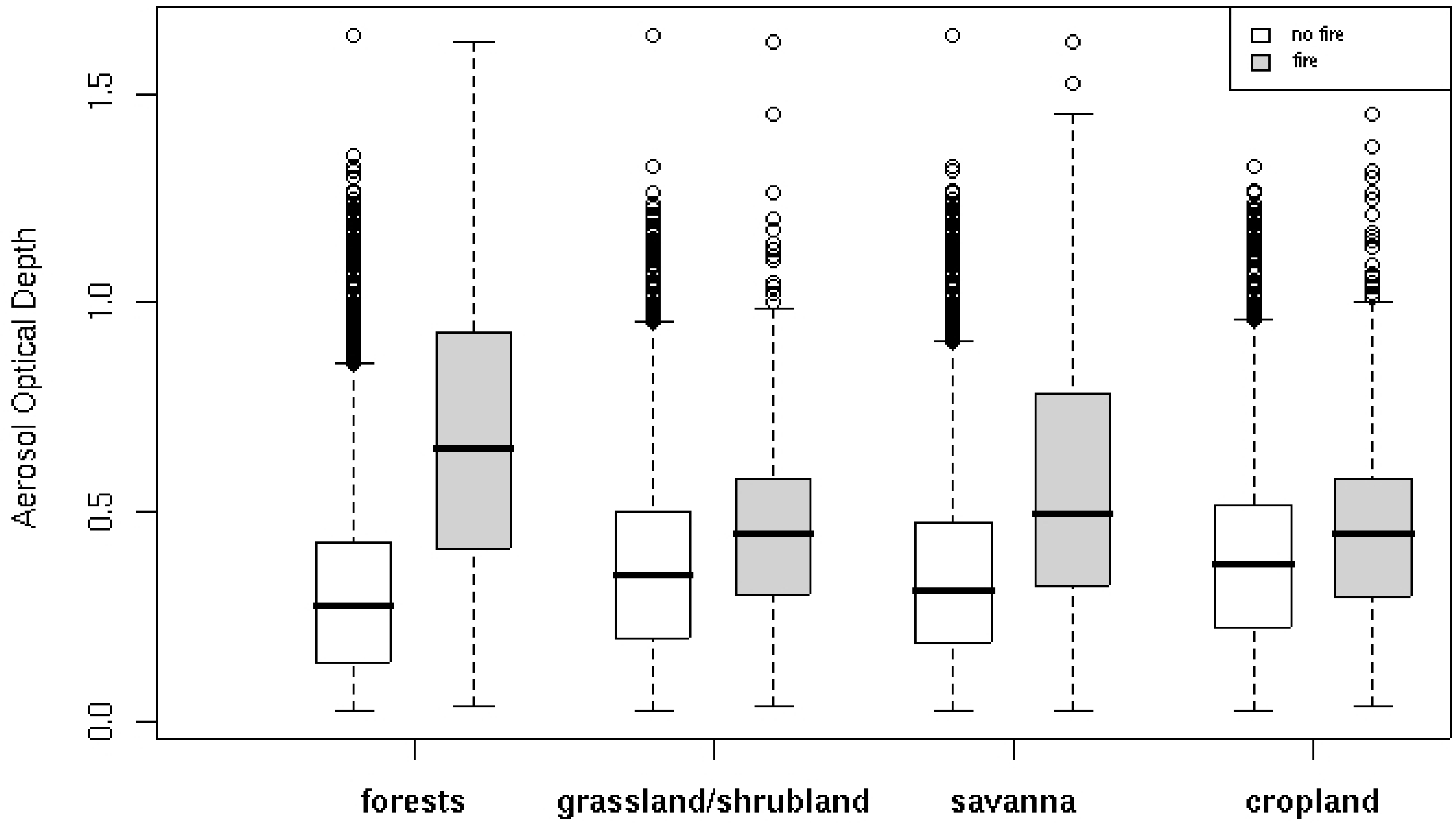

Figure 2. Comparisons of average optical depth dry season (January-April; November-December 2004) for pixels with and without fire. Averages are elevation classes.

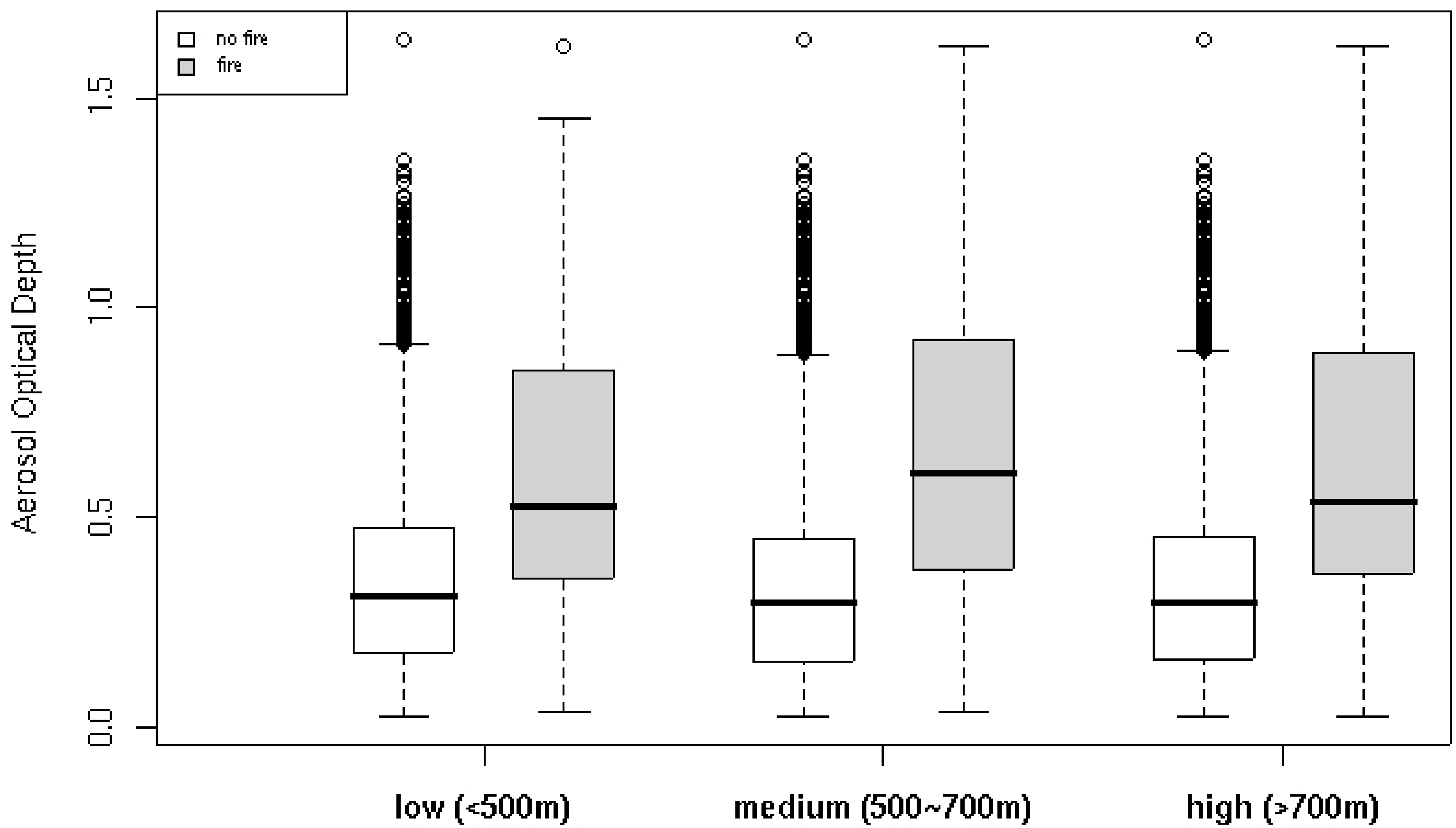

Figure 3. Comparisons of average optical depth dry season (January-April; November-December 2004) for pixels with (white boxes) and without fire (gray boxes). Averages are by land cover type (aggregated IGBP categories) and by elevation classes.

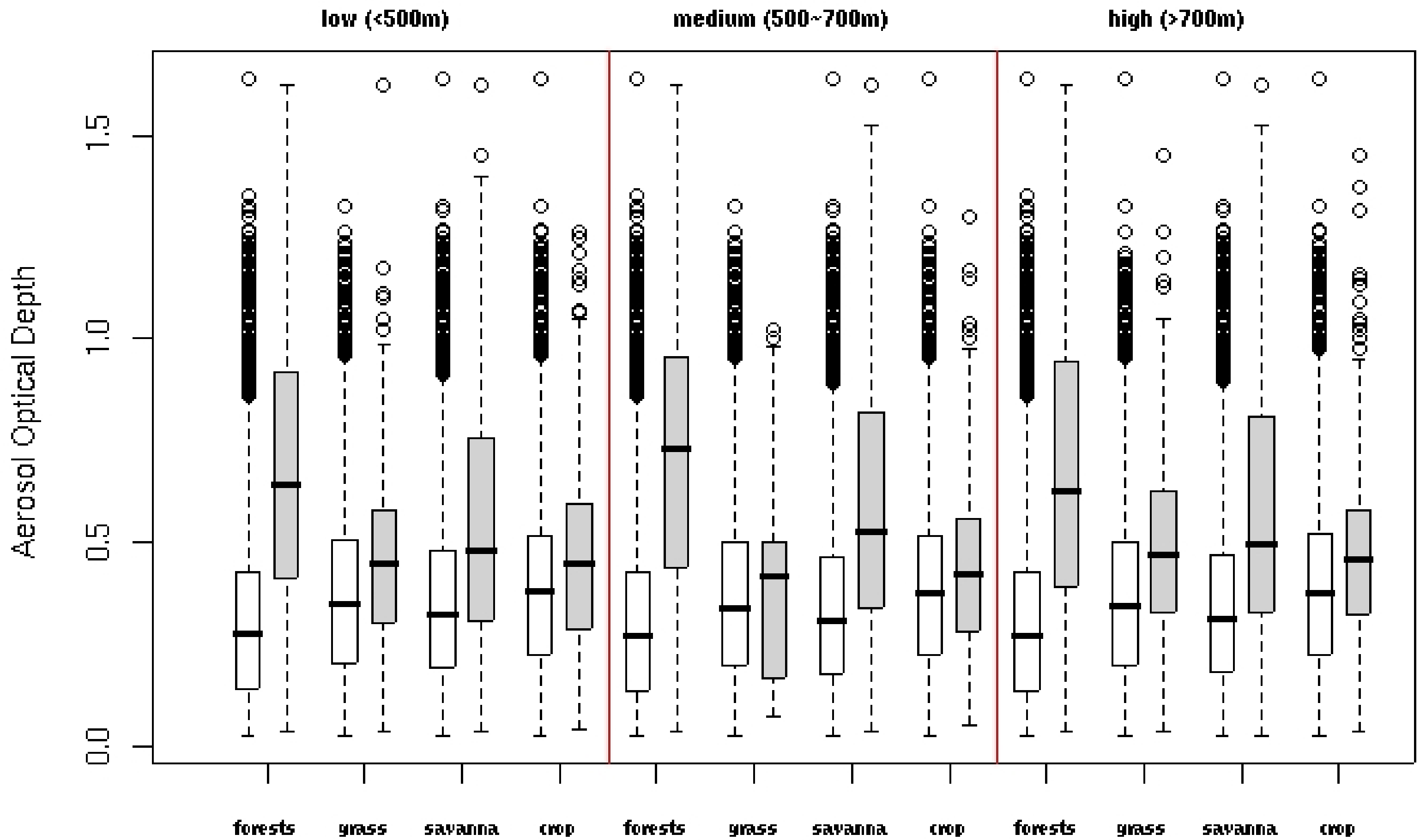

Figure 4. Differences in daily averages in aerosol optical depth (AOD) between pixels with fire occurrence and pixels without for the dry season (January-April; November-December 2004). Positive numbers imply that AOD is higher for fire pixels than non-fire pixels on that day. Circle size is proportional to the number of fires on that day.