6.12 MONITORING THE EFFECTS OF EXTREME CLIMATE DISTURBANCES ON FOREST HEALTH IN THE NORTHEAST U.S.

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1. INTRODUCTION

No methodology has been developed to date to predict when a forest population is at risk to specific climate and air pollution stressors. Yet, this information is important to natural resource managers who need frequent, updated assessments of forest health upon which to base management decisions and respond to public concerns on forest health.

The USDA Forest Service's Forest Health Monitoring (FHM) Program is a comprehensive network of about 5000 permanent plots nationwide on which systematic observations are made on a critical array of tree and ecosystem parameters. Begun in 1991, some regions now have several complete four-year cycles of data on which to assess health trends. The observations, made every year on about one-quarter of the plots, undergo necessary quality-assurance / quality-control (QA/QC) procedures and then are made available to the public, usually within 12 to 24 months. In its present form, the FHM network serves as a passive system that allows interpretation and response only after well-defined patterns emerge. An ideal approach would be to complement the existing network of actual observations with a means of predicting where and when different kinds of injuries are likely to occur. This would enable not only early treatment and possible prevention of forest health problems, but also a valuable means of identifying areas where intensive monitoring is justified.

Our objective is to predict forest health out-comes using physical data on weather, climate, and air quality. The end goal is a series of indicators that use existing streams of information to evaluate the changing risk to forest health. Once tested and refined, these indicators would then be used to develop a formal decision support system. This would be designed to assist the manager in making timely and accurate choices for improving health and achieving long-term sustainability. Related goals include developing approaches to strengthen the display and analysis of the FHM data, and improving the monitoring process by feeding back new information on any apparent gaps or redundancies in the FHM field observations.

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2. DATA AND METHODS

2.1 *General Approach*

Four salient features of our approach tie closely to the aims of the FHM Program. *First*, the climate parameters as well as the forest health observations were mapped in a Geographic Information System (GIS) format. This permitted visual display as well as integration and correlation among different data strata. *Second*, the analysis of the FHM data, still at an initial stage, requires that we adopt a flexible, experimental approach. It was essential that we try various, optional methods and document findings as a part of the discovery and refining process of achieving effective and universal methods of climate, weather, and air-quality indicator design. The working premise was that there is value in an array of indices that measure different facets of health risk, some general and some more specific in their definition and purpose. *Third*, there is a debate on which forest health parameter(s) will provide the best initial focus of study. We chose two -- crown dieback and ozone bioindicator parameters. These are known to have links to freezing events and high ozone levels, respectively. Discussion with FHM staff indicated, however, that other FHM parameters are of considerable interest and could just as well be a focus initially, including crown density, crown transparency, and integrated crown health. *Fourth*, to successfully tie proactive management with monitoring objectives, there is a need to develop a capability to anticipate where, when, and what kinds of forest health injuries are likely to occur. We will address this need by developing a decision support system that will alert forest managers to potential forest health problems arising from climate, weather, and air quality disturbances. This design is consistent with the FHM Intensive Site Evaluation Monitoring initiatives that focus attention on areas and processes in the landscape that are undergoing rapid degradation. It also provides an important advantage in the early silvicultural treatment of forest types and areas shown to be at risk.

This first phase of the study focused on an analysis of the relationship between winter temperature anomalies and crown dieback in the northeastern and north central forest regions of the U.S. (USDA Forest Service Region 9). The analysis of precipitation, ozone levels, ozone bioindicators, and ecosystem parameters are not reported in this paper. Equally, the subsequent development of an early warning system was omitted but remains the objective of the on-going analyses.

2.2 ***Basic Datasets***

The datasets accessed in this study were all from pre-existing sources either in electronic format on CD-ROM, the Most Excellent Software System (USDA Forest Service, in progress), and/or on the Web. They consisted of the following:

Meteorological Parameters. Daily minimum and maximum temperature and daily total precipitation data over the 1950 to 1998 period were obtained from a subset of the National Climatic Data Center's (NCDC) Summary of the Day dataset. This subset dataset consists of temperature and precipitation observations from the Cooperative Observers Network at approximately 1200 stations across the northeastern and north central regions of the U.S. These data are part of the NCDC TD-3200 file as corrected by NCDC's Validated Historical Daily Data Project. Systematic obser-vations on snowdepth (for the determination of potential root-freeze injuries) are being accessed for the same period and region through the NCDC website http://www4.ncdc.noaa.gov/ol/documentlibrary/datasets.html#TD6900.

Ozone Concentration Parameters. Annual summary data on ozone concentration were accessed on the US Environmental Protection Agency's AIRS (Aerometric Retrieval Information System) Website:http://www.na.fs.fed.us/spfo/fhm/ozonetrng/biozone.htm

Forest Crown Dieback Parameters. This parameter was accessed from the USDA Forest Service FHM Program site: http://www.na.fs.fed.us/spfo/fhm. The FHM network in Region 9 consists of 2275 permanent plots. Crown dieback levels measured at these plots range from 0 to 100 % of the total crown area and are defined as "recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk". Values are formatted as 21 FHM class codes of 5% increments to allow estimator flexibility and consistency with other datasets.

Ozone Bioindicator Parameters. The ozone biomonitoring data from the FHM network for years 1996 through 2000 were accessed at http://www.na.fs.fed.us/spfo/fhm/ozonetrng/biozone.htm. The ozone bioindicator data were collected at some sites and states in 1994 and 1995, but not routinely in all cases. Data for these years were accessed separately on a state-by-state basis (Gretchen Smith, per comm). Sampling started in the New England States in 1994, and in the Great Lakes States in 1996. Ozone bioindicator levels range from 0 to 100 % and are defined as "the amount and severity of injury present on leaves or plants sensitive to ozone injury. Bioindicators are plants (trees, shrubs, or herb species) that respond to ambient levels of ozone pollution with distinct visible foliar symptoms that are easy to diagnose".

Ecosystem Parameters. Ecosystem data form part of the stand-level and plot description of the FHM network and were accessed from the website http://www.na.fs.fed.us /spfo/fhm. These data included forest type classification, stand composition (tree species), density, diameter at breast height (dbh), slope, aspect, elevation, drainage, and soil classification. The soil structure and soil chemistry data for selected northeastern and north central U.S. states (MI, WI, MN, IA, WV, MA, MD, PA, ME, NH, NJ) were available for 1998 and 1999 on the Most Excellent Software System (USDA Forest Service, in progress). Data for year 2000 will be available in early 2002. Although some soils data were collected as early as 1991, these were part of a pilot study; routine soil sampling began only in 1998. Soil sampling was done once every two cycles (i.e., 8 year intervals). On each plot, organic (1-10 cm) and mineral (10-20 cm) horizons were characterized; erosion, compaction, chemical, nutrient, and pH properties were analyzed; and results were made available in a GIS referenced format.

2.3 ***Methods***

Our analysis consisted of three steps. First, we used the NCDC Summary of the Day daily maximum and minimum air temperature data for the 1950 to 1998 period, inclusive, to create two measures of extreme stress -- the winter (December-March) incidence of thaw-freeze events, and the incidence of minimum air temperatures less than or equal to –30°C. Thaw-freeze events were defined, in increasing order of severity, as follows:

- *Level 1:* Maximum daily air temperatures ≥ 1°C for at least one day followed by daily minimum air temperatures ≤ -10°C for at least one day within the succeeding ten days since the last day of thaw.

- *Level 2:* Maximum daily air temperatures ≥ 5°C for at least two consecutive days followed by daily minimum air temperatures ≤ -15°C for at least one day within the succeeding six days since the last day of thaw.

- *Level 3:* Maximum daily air temperatures ≥ 10°C for at least three consecutive days followed by daily minimum air temperatures ≤ -10°C for at least one day within the succeeding seven days since the last day of thaw.

- *Level 4:* Maximum daily air temperatures ≥ 10°C for at least three consecutive days followed by daily minimum air temperatures ≤ -20°C for at least one day within the succeeding three days since the last day of thaw.

Thaw-freeze and extreme cold events were mapped across Region 9 for each year, and as an average of the 1950-1998 period. Second, at ten selected observation sites, trends in the occurrence of each thaw-freeze scenario and extreme cold event over the 48-year period were examined using both the yearly and five-year running mean values. The crown dieback data were treated in a similar way for the 1991 to 1998 period. Third, the annual and averaged spatial patterns as well as the temporal trends of the thaw-freeze and extreme cold events were correlated with crown dieback occurrences.

3. INITIAL RESULTS AND DISCUSSION

3.1 *Thaw-Freeze Events*

Ten or more Level 1 thaw-freeze events tend to occur each winter season (December-March) over much of the north central and northeastern U.S. based on the 1950-1998 average. The exception is over the coastal areas of the Mid-Atlantic and over southern Illinois and much of Kentucky (Fig. 1). Notably high incidence (20 events/yr or more) is apparent along the Appalachian Mountains in parts of West Virginia, Pennsylvania, New York, Vermont, New Hampshire, and Maine. Level 2 events also occurred region-wide (2 or more events/yr), with 4 or more events/yr typically occurring over areas of West Virginia, New York, Vermont, and New Hampshire (Fig. 2). More than two events per year are also common over southwestern Iowa and northwestern Missouri.

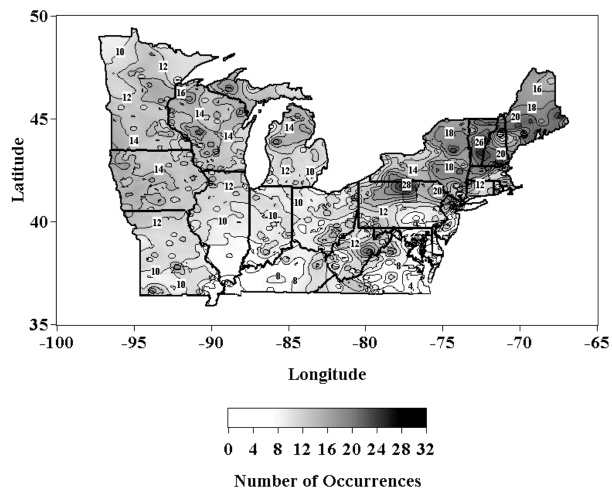

Figure 1. Average number of Level 1 thaw-freeze events occurring each winter season (December-March) over the north central and northeastern U.S. for the period 1950-1998.

As the level of severity increased, thaw-freeze occurrence became sharply defined and limited geographically. Level 3 thaw-freeze occurrences were typically most common in the southern half of the region (Fig. 4). In the northern tier of states, these events, although rare, have been especially damaging. Marked thaws characterized by a meltdown of the snowpack, and sap ascent in specific cases, have resulted in extensive damage to fine roots and sapwood when conditions suddenly turned cold (Auclair et al. 1996). Interestingly, the major episodes of dieback have occurred mainly in the northern half of the region. Further south, where +10°C to -10°C thaw-freeze events are fairly common, the risk of damage is less since trees seldom initiate sap ascent under a brief +10°C warming and there is rarely an accumulated snowpack (which paradoxically, serves as insulation but also limits frost hardening of fine roots in more northern areas). Level 4 thaw-freezes were almost non-existent with only a few isolated occurrences.

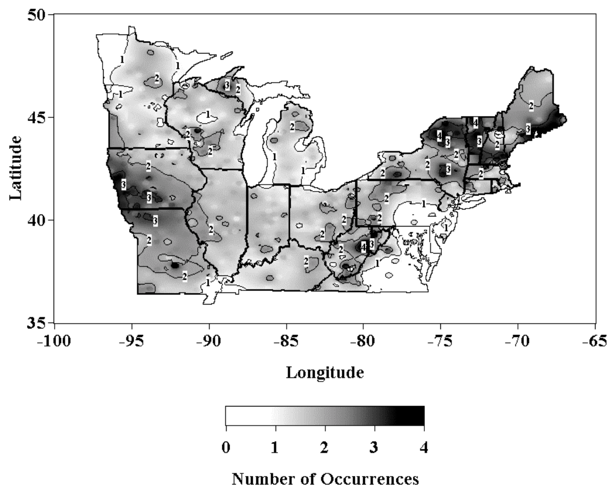

Figure 2. Same as Figure 1 except for Level 2 thaw-freeze events.

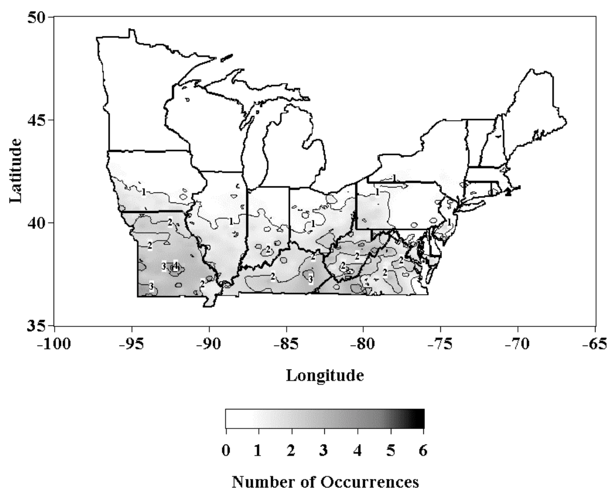

Figure 3. Same as Figure 1 except for Level 3 thaw-freeze events.

3.2 *Extreme Cold Events*

The frequency of extreme cold events during the 1950-1998 period was high in northern Minnesota (i.e., 14 days/year or more), but also was evident at a frequency of 6 days/year or more in northern Wisconsin, Michigan, Vermont, New Hampshire, and Maine. Minimum air temperatures below –30°C are unlikely to cause severe damage in these northern locations unless prolonged. Extreme cold events that occur in more southern locations and in areas along the eastern coast of the New England States can be expected to cause more damage. In these locations, forest hardening is typically less, whereas native trees in northern continental locations typically “frost harden” to –45°C. Maps indicated that the southern limit of –30°C events from 1990 to 1998 varied annually by as much as 400 km. This suggests that southern and coastal areas could experience damage from these types of events periodically.

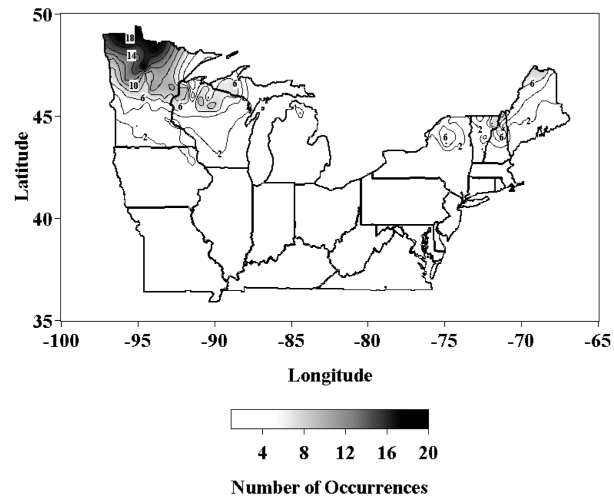

Figure 4. Average number of occurrences of daily minimum temperatures ≤ -30°C over the north central and northeastern U.S. for the period 1950-1998.

3.3 *Crown Dieback*

Maps of the spatial patterns of dieback were not available at the time of publication. There was no apparent trend in the level of dieback over the 1990-1998 period, inclusive. Values for the north central and northeastern region of the U.S. remained in the 4.5-6.0% range, which is mild to moderate overall. In individual states and years, values reached as high as 15%. The average for Wisconsin in 1996, for example, reached 10.2%. This coincided with distinctly above-average geographic incidence of Level 3 thaw-freezes (and extent of –30°C extremes) in 1996. The numbers of thaw-freeze events were also relatively high in previous years (1990, 1991, 1992, 1994, 1995), suggesting a prolonged interval of high freezing stress for parts of Wisconsin compared to the historic norm.

3.3 *General Discussion*

We observed strong patterns in the incidence of winter cold and freezing stresses over the north central and the northeastern U.S. Preliminary evidence suggests that the increased incidence of dieback in Wisconsin in 1996 was related to above-average incidence of these stresses in that year and in the recent years leading up to 1996. In general, the links between physical stresses and the impacts on forest health remain largely undocumented and poorly understood. Never-theless, the techniques used here show promise as powerful tools in unraveling basic indicator relationships and in the prediction of forest health.

Other methods of analyses have yet to be applied such as the use of additional health, tree, and ecosystem parameters to stratify the data. Indicators based on multiple stresses are envisioned. We anticipate this will significantly improve the results. For example, crown dieback occurs mainly in older forest populations (Auclair et al. 1992) and ozone damage appears to be strongly affected by drought (Gretchen Smith, per comm).

True early warning of potential health problems can be achieved by using real-time meteorological and air quality data. This would provide on-line assessments well ahead of the availability of the field data. The value of anticipatory planning is immeasurable as a proactive management tool to enhance forest protection. It can also serve as a test of our capacity to accurately predict health outcomes, and hence to better understand key mechanisms of forest health. An important variant on prediction is the use of monthly and seasonal climate forecasts in developing forest health warnings. Lead times can be as much as 3 to 18 months in advance of actual stressing events and first appearance of visible symptoms.

In choosing winter temperature extremes as a starting point, the question remains: Why focus the analysis initially on temperature data, especially when dieback research in the past identified drought as the significant stress?

The traditional perception has been that, among climate factors, drought is by far the most important triggering factor in dieback (Houston 1987). Freezing injury to the tree-water transport system as a cause of dieback is a new perception. Recent work suggests that forest dieback is a response to drought stress in trees *previously injured* by freezing (Auclair et al 1992, 1996). Dieback of the crown progresses to the extent that leaves and branches desiccate in the absence of active water transport (due to dead or injured root, stem, and branch conductive tissues) (Pomerleau and Lortie 1962). The process is accelerated by soil moisture deficits and strong evapo-transpirational demands on the canopy.

Contrary to earlier studies, it appears that winter freezing events initially injure the tree (Auclair et al. 1992, 1996). These injuries include irreversible tracheid and vessel cavitation (Greenidge 1951, 1955; Sperry et al. 1988; Tyree and Sperry 1988, 1989), freeze-kill of ray parenchyma cells (Wodzicki and Brown 1970), and root-kill (Greenidge 1951; Pomerleau and Lortie 1962). Subsequent to freezing injuries, the tree is hypersensitive to drought, heat stress, and to a plethora of pathogens and insect pests, and typically experience rapid declines in health and productivity (Wargo and Auclair 2000). Freezing associated with dieback typically follows a prolonged thaw in the winter or early spring (Auclair et al 1996) that suddenly reverses to sub-zero (^{o}C) conditions. The thaw exacerbates the loss of frost resistance (Sakai and Larcher 1987), and in some cases results in sap ascent (Robitaille et al. 1995) at a time the tree is normally dormant and fully frost hardy. In U.S. Northern Hardwood areas, snowpack is typical in winter and roots are insulated from deep frost and only minimally frost resistant. Other injury mechanisms include (1) the lack of accumulated snow (i.e. “open winters”) or a meltdown of the snowpack in winter, which puts the tree at risk for deep-soil frost and root kill in the event of particularly cold air temperatures (Pomerleau 1991, Pomerleau and Lortie 1962), and (2) extreme cold that can injure or kill fine roots and ray parenchyma cells essential for active water transport (Wodzicki and Brown 1970).

Experience has proven it can be particularly difficult to unravel the precise role and sequence of climate parameters that can influence forest health. Major dieback episodes appear to occur during intervals (e.g., 8-12 years) of acute climatic variability and may erupt only after several years of exceptionally high stress. (Auclair 2001). The fact that drought, heat, and other climate stresses are typically co-mingled and concurrent with freezing events has frustrated statistical efforts to reach definitive conclusions on the role of specific parameters. Factors other than climate, such as disease and insect defoliation, are often present, and they complicate the analysis even further.

4. REFERENCES

Auclair, A.N.D., 2001: The role of extreme climatic variability in dieback of U.S. Northern Hardwoods: Analysis of climatic impacts and development of indicators of risk of major dieback episodes. (in progress)

Auclair, A.N.D., R.C. Worrest, D. Lachance, and H.C. Martin, 1992: Climatic perturbation as a general mechanism of forest dieback. Chapter 4, p. 38-58 In P.D. Manion and D. Lachance (eds) Forest Decline Concepts. American Phytopathological Society Press, St. Paul, Minnesota. USA.

Auclair, A.N.D, J.T. Lill, and C. Revenga, 1996: The role of climate variability and global warming in the dieback of Northern Hardwoods. *Water, Air and Soil Pollution*, **91,** 163-186.

Greenidge, K.N.H., 1951: Dieback: A disease of yellow birch (*Betula lufea* Michx.) in eastern Canada. Ph.D. Dissertation, Dept. Biology, Harvard University, Boston, Massachusetts.

Greenidge, K.N.H., 1955: Studies in the physiology of forest trees. II. Experimental studies of fracture of stretched water columns in transpiring trees. *American Journal of Botany* **42**, 28-37.
.
Houston, D.R., 1987: Forest declines of past and present: Current understanding. *Canadian J. Plant Pathology,* **20,** 349-367.

Pomerleau, R., 1991: Experiments on the causal mechanisms of dieback on deciduous forests in Quebec. Information Report LAU-X-96, Forestry Canada, Quebec Region, Sainte Foy, Quebec. Canada. 48 p.

Pomerleau, R., and M. Lortie, 1962: Relationships of dieback to the rooting depth of white birch. *Forest Science,* **8,** 219-224.

Robitaille, G., R. Boutin, and D. Lachance, 1995: Effects of soil freezing stress on sap low and sugar content of mature sugar maples (*Acer saccharum*). *Canadian J. Forest Res.* **25,** 577-587.

Sakai, A., and W. Larcher, 1987: Frost survival of plants. Ecological Studies. Volume 62. Springer-Verlag, Berlin, Germany.

Smith, G., 2001: Personal communication. Dr. Gretchen Smith, Dept. Natural Resources Conservation, University of Massachusetts, Amherst, Massachusetts.

Sperry, J.S., J.R. Donnelly and M.T. Tyree. 1988. Seasonal occurrence of xylem embolism in sugar maple (*Acer saccharum*). *American J. Botany,* **75,**1212-1218.

Tyree, M.T., and J.S. Sperry, 1988: Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? *Plant Physiology* **88**, 574-580.

Tyree, M.T., and J.S. Sperry, 1989: Vulnerability of xylem to cavitation and embolism. *Annals of Plant Physiology and Molecular Biology,* **40**, 19-38.

Wargo, P.M., and A.N.D. Auclair, 2000: Forest declines in response to environmental change. *Responses of Northern U.S. Forests to Environmental Change*, Chapter 4, p. 117-145 In R.A. Mickler, R.A. Birdsey, and J. Hom, (eds), Ecological Studies 139. Springer-Verlag Inc., New York, NY.

Wodzicki, J.T., and C.L. Brown 1970. Role of xylem parenchyma in maintaining the water balance of trees. *Acta Societa Botanica Polska,* **39,** 617.