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## FOREWORD

The Northern Global Change Program meeting was held March 14-16, 1995, in Pittsburgh, Pennsylvania. Its purpose was to chronicle the research activities of the Northern Global Change Program over the past five years, and outline the implications of these research results for natural resource management. We thank the authors for their participation and for promptly submitting their papers in both paper and electronic form.

THIRTY-THREE YEAR CHANGES IN ABOVE- AND BELOW-GROUND BIOMASS IN NORTHERN  
HARDWOOD STANDS IN VERMONT

A. H. Johnson<sup>1</sup> and G. R. Strimbeck<sup>2</sup>

SUMMARY

In 1957-1960, R. O. Curtis and B. W. Post surveyed 81 even aged (45-90 y old) northern hardwood stands on acid till soils over the length of Vermont's Green Mountains. The purpose of the original study was to determine predictive relationships between site index and site characteristics, including latitude, elevation, soil drainage class, soil organic matter content and soil nutrients. The sites were not randomly selected in the 1950s. Rather, they were chosen to represent a range of stand ages and the range of environmental conditions associated with northern hardwood forests growing on acid till. In 1990-92 we were able to reliably relocate 40 of the original plots using sketch maps and witness trees. In 1990-91 we sampled 23 of the plots which were relocated exactly by blazed witness trees. These plots showed no signs of human disturbance other than possible minor removal of red maple for stand improvement. In 1992, we relocated 17 sites that had been selectively logged. The original witness trees had been removed in most cases, and these plots were located from roadside monuments, measured distances and compass bearings. Remeasurements of tree and soil characteristics allowed comparison of tree heights, basal areas, volumes, above-ground biomass, and soil organic matter pools.

These comparisons allowed us to explore some issues of environmental quality that surfaced in the 1980s. Areas of sugar maple decline were identified in Vermont and neighboring Canada, and several studies were conducted to determine what factors were related to maple decline, and if there was evidence of air pollution involvement. We reasoned that if there were adverse environmental changes in air or soil quality that had chronic effects on maple growth, patterns of individual and stand growth, and/or statistical relationships between growth and site characteristics established in the early part of this century might have been different in the latter half of the century.

In addition to the maple decline issue, long-term trends in soil organic matter are of interest in refining carbon budgets on local, regional and global scales. Careful determination of bulk density and soil organic matter in the Post and Curtis project has allowed a comparison of soil organic matter content. As we sampled both disturbed and undisturbed stands, the effect of forest harvesting on soil organic matter pools could be evaluated.

We have been able to test four hypotheses as outlined below.

Hypothesis 1

In undisturbed plots, changes in DBH, volume and biomass show that shade tolerant species, especially sugar maple, increased to a greater degree than less tolerant species as predicted by normal trends in aggrading northern hardwood stands.

Basal area increased in 19 of the 23 undisturbed plots, and volume decreased in only 1 plot, apparently due to the removal of large red maples for stand improvement. Red maple showed large decreases in basal area and volume in two other plots, and we suspect that this too is related to stand improvement. White and yellow birch decreased in several other plots as might be expected on the basis of shade tolerance of these species and competition in

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aggrading northern hardwood stands. Of the six species for which changes were determined, sugar maple showed the most consistent increases and the greatest relative and absolute increases. Figure 1 and table 1 show the results for biomass change. Changes in basal area and volume are, of course, similar to the biomass trends.

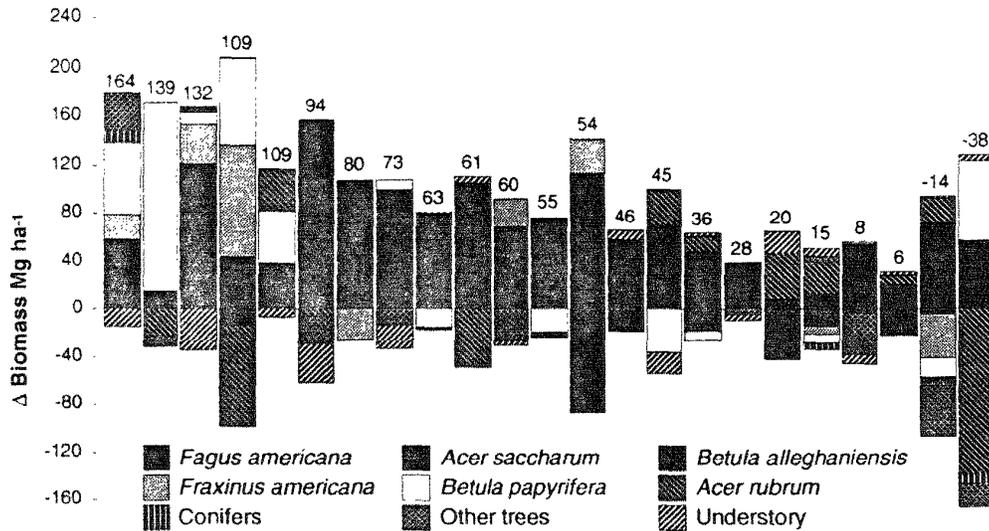


Figure 1. Change in biomass by species for the 23 remeasured plots. Numbers are net change in biomass.

Table 1. Biomass Summary.

Plot	Acer rubrum	Acer saccharum	Betula alleghaniensis	Betula papyrifera	Fagus americana	Fraxinus americana	Conifers	Other trees	Understory	Total biomass Mg ha <sup>-1</sup>	Stand Age	CSI
Δ Biomass												
5703	0.000	107.987	0.000	0.000	0.000	-26.775	0.000	0.000	-1.107	80.105	73	73.6
5704	30.526	36.482	-0.048	-36.238	32.557	0.000	0.000	0.000	-18.466	44.815	63	59.9
5706	0.000	61.742	6.100	0.000	0.000	23.813	0.000	-27.226	-4.612	59.817	69	75.7
5708	21.344	70.894	-5.512	-15.941	0.000	-36.621	0.000	-49.277	1.055	-14.058	63	78.0
5802	0.000	49.564	-3.468	2.189	3.581	0.000	0.000	-35.471	-8.018	8.377	47	59.5
5803	0.000	30.605	2.971	0.000	4.649	0.000	0.000	-5.340	-4.880	28.005	N.D.	N.D.
5804	0.000	21.074	73.261	7.766	5.166	0.000	0.000	-14.649	-20.028	72.590	50	65.8
5806	-24.199	11.084	3.655	155.486	0.000	0.000	0.000	-8.851	1.521	138.695	48	55.2
5807	0.000	23.431	6.846	59.297	26.865	21.746	9.913	31.817	-16.008	163.907	53	74.6
5819	0.000	112.748	-46.484	0.000	-41.821	27.616	0.000	0.000	1.583	53.643	95	75.9
5820	8.395	19.433	-23.779	0.000	0.000	0.000	0.000	0.000	2.116	6.165	50	91.2
5821	-85.437	-14.241	43.039	70.578	0.000	93.238	0.000	0.000	2.277	109.453	67	78.9
5826	0.000	39.311	17.207	-19.614	19.173	0.000	0.000	-5.901	4.573	54.749	56	50.7
5836	33.877	34.669	-0.032	43.139	3.398	0.000	2.115	0.000	-8.431	108.735	60	73.6
5901	-49.400	7.832	78.967	0.000	17.816	0.000	0.000	0.000	5.748	60.964	85	67.7
5902	38.344	-30.981	-12.667	0.000	7.724	0.000	0.000	0.000	17.846	20.266	82	66.4
5903	26.174	-8.609	11.941	-6.023	-6.898	-7.064	-6.277	5.402	6.803	15.449	69	67.2
5909	-7.092	157.133	0.000	0.000	0.000	0.000	0.000	-23.136	-32.627	94.279	64	72.7
5911	0.000	83.632	9.272	9.223	28.088	31.801	0.000	5.734	-35.333	132.416	54	85.4
5913	13.292	-19.926	23.116	-6.028	24.355	0.000	0.000	-1.052	2.011	35.768	74	63.1
5914	-2.398	64.447	0.000	-15.486	14.944	0.000	0.000	0.000	1.824	63.330	60	72.0
5915	-139.380	55.576	1.352	65.642	0.000	0.000	-7.488	-19.042	4.890	-38.450	75	75.3
5917	0.000	41.219	15.887	0.000	-19.956	0.000	0.000	0.000	8.634	45.785	97	56.0
Mean	-5.911	41.526	8.766	13.652	5.202	5.554	-0.076	-6.391	-3.853	58.5	66.1	69.9

Hypothesis 1 is supported by the comparisons, suggesting that normal stand dynamics have prevailed in the development of these stands.

#### Hypothesis 2

In undisturbed plots, the relationships between height (or BA/volume/biomass) and candidate predictors (site index, stand age and dbh) was unchanged between 1957-59 and 1990-91.

To test this hypothesis, we determined how height and biomass in the undisturbed plots were related to log dbh, stand age and site index. In both the 1957-59 and 1990-92 data sets, these variables explained ca. 70 percent of the variation in height. Figure 2 shows that the coefficients for these variables were not significantly different in the two studies. Both site index and stand age are significantly correlated with stand biomass as shown in figure 3 (shown for pooled data). The equations for the individual data sets are not different, with  $R^2 = .65$  for the 1990-92 data set, and  $R^2 = .59$  for the 1957-59 data set. We interpret these results to mean that stand growth from the late 1950s through the early 1990s has proceeded as expected based on the 1957-59 data, which integrates growth during the first half of the 20th century.

With respect to sugar maple, figure 4 shows that for a given DBH, sugar maple in 1990-92 were slightly (though not significantly) taller than in 1957-59. This is an expected result for aging stands, and adds more weight of evidence to the contention that sugar maple growth has not been adversely affected by changed growing conditions.

#### Hypothesis 3

In undisturbed stands, growing vegetation is an important sink for carbon, whereas there would be either a small change or no change in soil organic matter/soil carbon.

While there exists much uncertainty in the role of forest soils in global carbon budgets, hypothesis 4 follows conventional thinking with respect to accumulation of carbon in most forested ecosystems. Careful consideration of problems in delineating horizon boundaries, and of bulk density/depth/organic matter content relationships suggests some problems in comparing the organic matter content of soils sampled decades apart by different investigators. We have computed organic matter content on the basis of a fixed weight of soil mineral particles as being the least biased way of making the comparisons. Figure 5 shows that there was no change in soil organic matter in the profile (Oa through Bw horizons) at the undisturbed sites.

#### Hypothesis 4

In logged stands disturbed only by commercial harvesting operations, soil organic matter would be unchanged.

In accordance with recent reviews of the effect of forest harvesting on soil organic matter, figure 5 shows that there was no significant change in the soil organic matter content between 1958 and 1992 at the 17 logged sites.

### CONCLUSION

With respect to questions about recent trends in forest productivity, we found no evidence from these stands that the growth of sugar maple (or other northern hardwoods) was adversely affected by changes in growing conditions. Height and biomass of stands in the early 1990s can be predicted within reasonable error, from relationships derived from measurements of 45-90 y old stands done in the 1950s. With respect to the accumulation of carbon in these northern hardwood stands, the growing live biomass is a significant sink for atmospheric carbon, where as the soil appears to neither gain nor lose appreciable carbon regardless of whether the stands were logged or not.

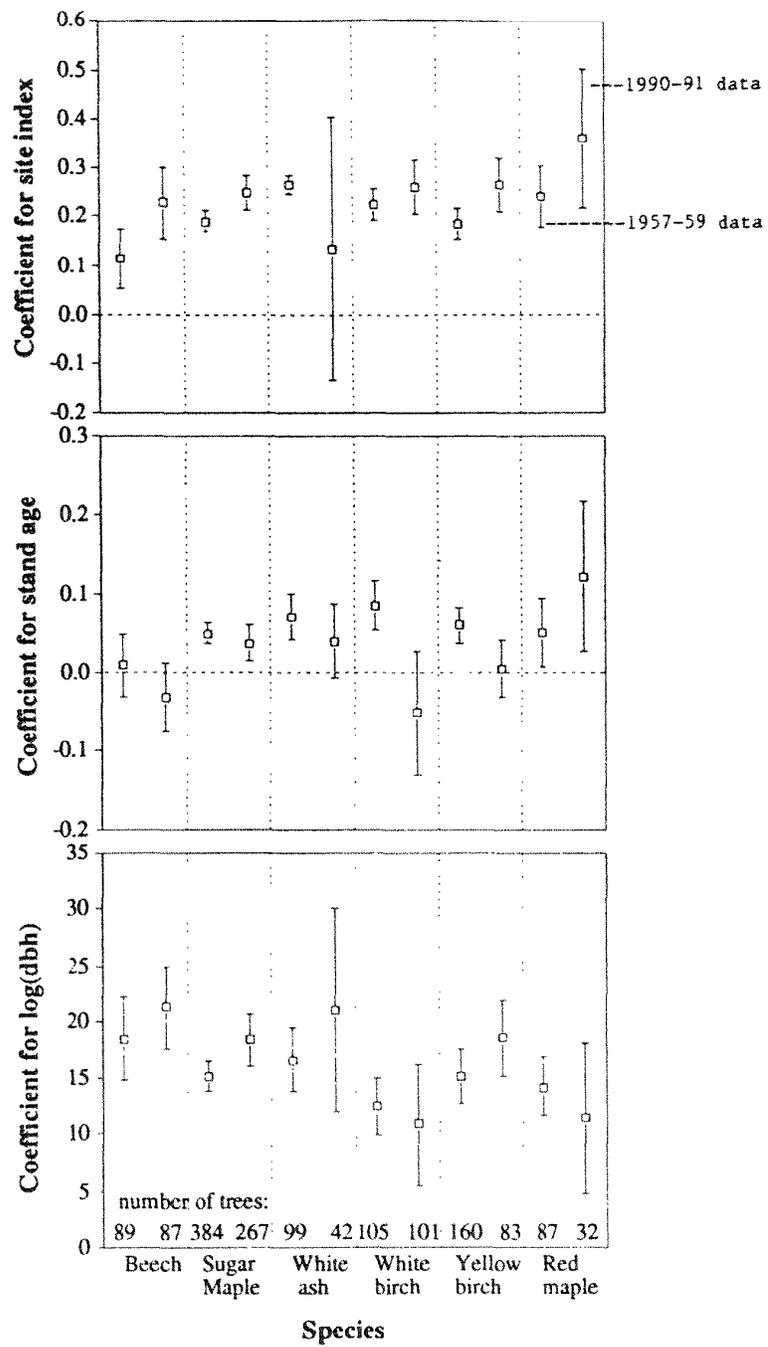


Figure 2. Coefficients for the equation  $\text{Tree Ht} = a + b(\log \text{ dbh}) + c(\text{stand age}) + d(\text{site index})$ .

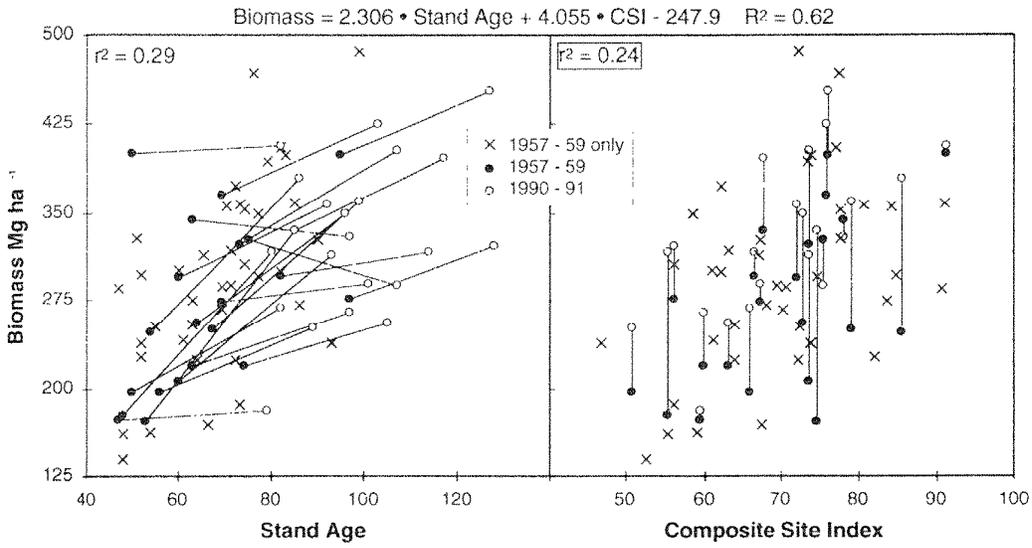


Figure 3. Biomass as a function of stand age and composite site index (height in ft at age 75).

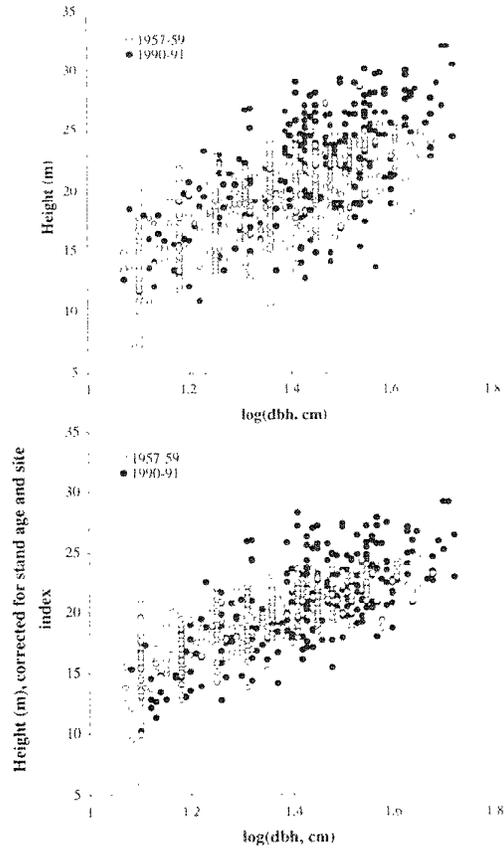


Figure 4. Height-diameter relationship for sugar maple.

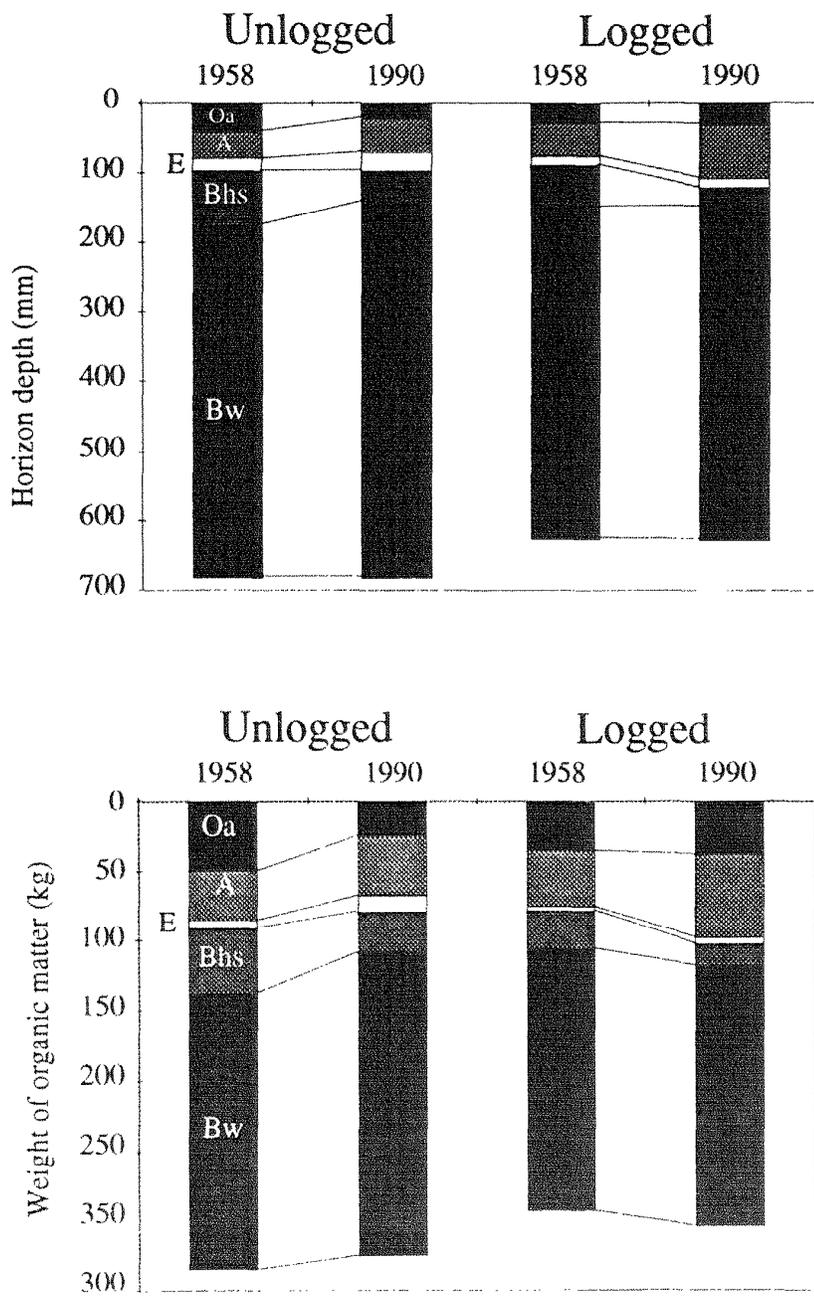


Figure 5. Changes in average horizon depth (top) and SOM mass (bottom) across all plots.

# EVALUATION OF METHODOLOGY FOR DETECTING/PREDICTING MIGRATION OF FOREST SPECIES

Dale S. Solomon and William B. Leak<sup>1</sup>

**Abstract:** Available methods for analyzing migration of forest species are evaluated, including simulation models, remeasured plots, resurveys, pollen/vegetation analysis, and age/distance trends. Simulation models have provided some of the most drastic estimates of species changes due to predicted changes in global climate. However, these models require additional testing against field data to ensure their reliability. Remeasured plots would provide a basis for model testing, but the number of plots required to detect short term trends might be excessive. Remeasurement data from forested areas where there have been no land-use changes provide a clearer picture of migrational trends. A 60-year record from the Bartlett Forest provided estimates of species changes in relation to management versus no management, land type, and elevation. Migration rates based on historical pollen analyses are of limited value because these analyses are derived from small, scattered samples formed under physical/biological conditions much different from those of today. Age/distance trends from carefully chosen and specified study locations will provide estimates of recent migrational trends and rates of elevational change. Independent surveys of vegetation in areas where previous plots cannot be relocated are subject to the same limitations as remeasured plots.

## INTRODUCTION

During the past decade, there has been renewed interest in plant migration due to the potential impacts of global climate change. Predictions have suggested major shifts in species ranges - even extinction - over the next 50 to 200 years in response to temperature shifts of up to 4.5 °C (e.g., Davis 1987; Peters 1990; Overpeck et al. 1991). Although some field studies have suggested actual changes in the elevational distribution of species due to climate change (Hamburg and Cogbill 1988; Grabherr et al. 1994), others show little or no detectable response (Solomon and Leak 1994; Leak and Smith<sup>1</sup>) that could be attributed to changes in climatic factors. We address this inconsistency by examining various approaches that are used to measure, detect, or predict species migration: simulation, remeasured plots, resurveys, interpretation of pollen records, and age/distance trends.

We use the term migration to mean the invasion of a species into a geographic region where it has not recently been able to grow due to climatic or edaphic conditions. Succession means the invasion or increased proportions of a species in an area where the species is readily able to grow but has been excluded due to stand dynamics or serial stage.

## SIMULATION

Some of the most drastic predictions of climatically induced vegetation change have been derived from computerized simulation models or graphical approaches. For example, Overpeck et al. (1991) predicted shifts in plant ranges of 500 to 1000 km within periods as short as 200 years. Others (e.g., Davis et al. 1994) suggest the possibility of near extinction of species such as sugar maple and beech due to an inability to migrate rapidly enough to keep pace with the changing climate. Most modeling attempts follow a similar format (Pastor and Post 1988; Solomon and West 1987). First, future changes in temperature and precipitation variables are predicted through one of several general circulation models (GCM). Relationships between species occurrence and climatic variables are developed or inferred using modern or historical geologic data. Future ranges are then predicted that can be compared to estimated migration rates by species as evidenced in the pollen record. The strength of this approach is that there is a strong relationship between species and climate as well as a wealth of empirical regional data (Denton

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and Barnes 1987; Gajewski 1987; Prentice et al. 1991; Spear et al. 1994). Questions about this approach relate to the extreme variability in GCM output (Cooter et al. 1993) (Fig. 1), and the validity of these models (e.g., Charlson and Wigley 1994). In addition, little is known about the responses of vegetation to climatic change with respect to growth, reproduction, genetic potential, and migration. This remains an extremely complex subject that cannot be understood simply by developing empirical vegetation/climatic relationships.

### Appendix

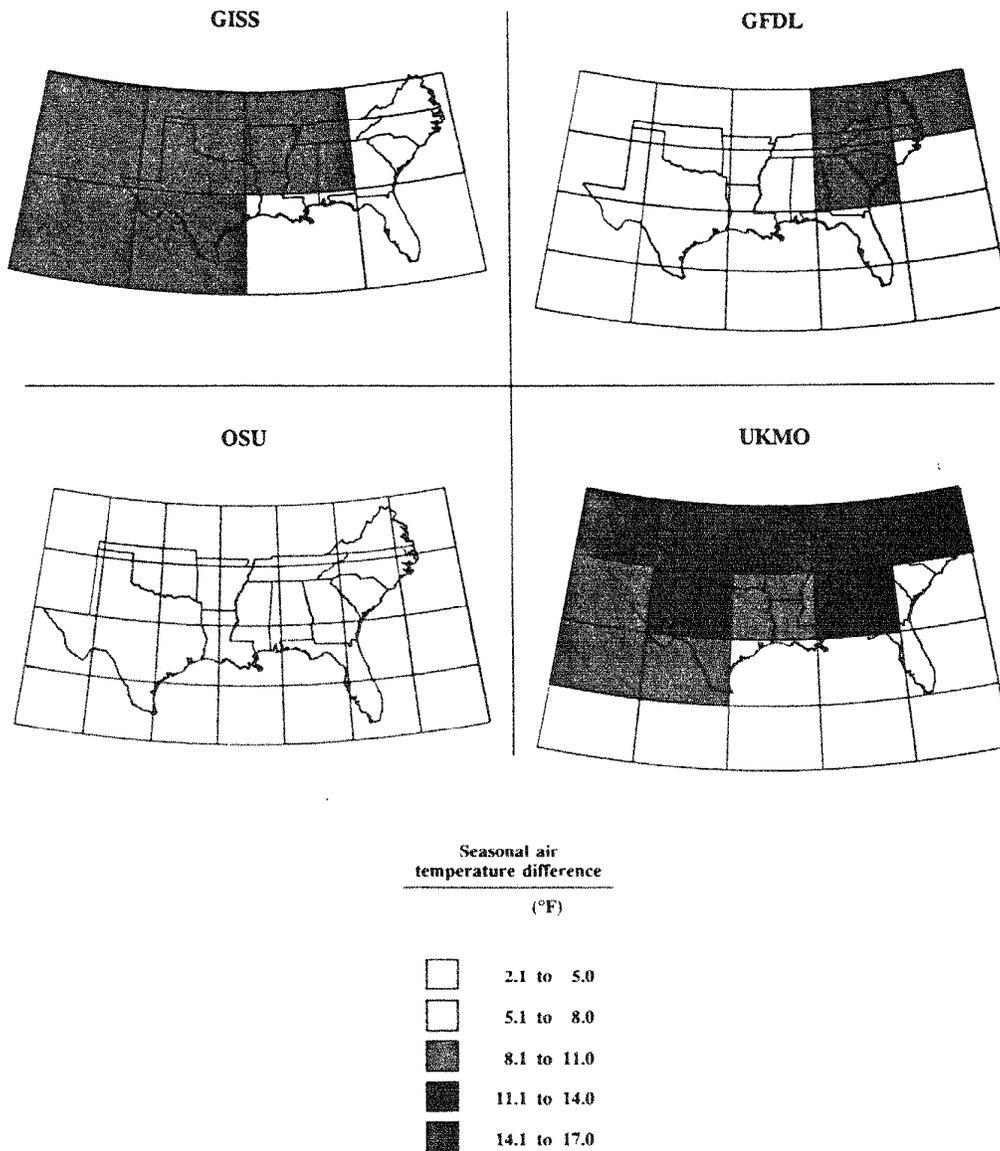


Figure 1. Winter season temperature increases after doubling the CO<sub>2</sub> concentration as predicted by four GCM models: GIS (Goddard Institute for Space Studies), GFDL (Geophysics Fluid Dynamics Laboratory), OSU (Oregon State University), and UKMO (United Kingdom Meteorological Office) (adapted from Cooter et al. 1993).

REMEASURED PLOTS

USDA Forest Service Forest Inventory and Analysis (FIA) plots are ideal for monitoring species migration. Also, they provide the data needed to test migrational models. One complication is that, on a regional scale, existing vegetation is responding to factors other than climate change. In New England, one dominant factor is natural successional change following prior disturbances from agricultural clearing and logging (Solomon and Leak 1994). This factor could easily mask any tendencies toward climatically driven changes in vegetation (Fig. 2, Table 1). A 24-year record on FIA plots in Maine indicated that white pine and balsam fir were declining in both average latitude and elevation. However, the area's land-use patterns suggested that these changes were not a reflection of climate change but the result of the invasion of abandoned agricultural land by these species.

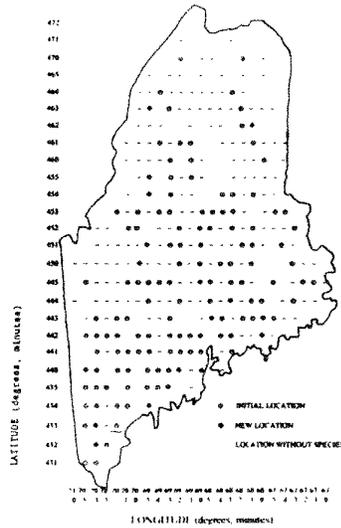


Figure 2. Initial locations in Maine with living white pine, new locations after an average 24-year period, and locations without white pine at either point in time (adapted from Solomon and Leak 1994).

Table 1. Average elevation (m) and latitude and longitude (degrees) of Maine plots occupied by major species at three measurement periods spanning 24-year average period from the 1950s and 60s to 1980s (adapted from Solomon and Leak 1994)

Measurement period	Red spruce	Hemlock	Balsam fir	White pine	Sugar maple	Beech	Red oak
Elevation							
1	242(7) <sup>*</sup>	136(8)	238(7)	150(9)	265(10)	243(11)	121(16)
2	240(8)	135(8)	241(7)	142(9)	273(10)	250(11)	117(16)
3	237(7)	136(7)	231(7) <sup>**</sup>	134(8) <sup>**</sup>	272(10)	245(11)	119(14)
Latitude							
1	45.66(.04)	44.98(.06)	45.69(.04)	44.82(.07)	45.64(.07)	45.41(.06)	44.15(.10)
2	45.68(.04)	44.96(.06)	45.71(.04)	44.73(.07)	45.62(.07)	45.42(.07)	44.12(.09)
3	45.64(.04)	44.95(.06)	45.65(.04) <sup>**</sup>	44.72(.06) <sup>*</sup>	45.58(.06)	45.40(.06)	44.10(.07)
Longitude							
1	69.05(.04)	69.18(.08)	69.08(.04)	69.50(.08)	69.30(.07)	69.25(.07)	70.00(.14)
2	69.01(.04)	69.20(.08)	69.09(.04)	69.53(.08)	69.36(.07)	69.27(.07)	70.01(.14)
3	69.02(.04)	69.23(.07)	69.07(.04)	69.44(.07)	69.39(.06) <sup>**</sup>	69.26(.07)	70.05(.12)

Standard error in parenthesis; <sup>\*\*</sup>Significant at 0.01 level; <sup>\*</sup>Significant at 0.05 level.

Table 2. Percent of basal area by species, elevation class (E), year (Y), and deciduous or coniferous landtype (T) for unmanaged stands on Bartlett Experimental Forest, with significance tests (\* = 0.05 level) among factors and interactions with year<sup>1</sup>

Species	Deciduous						Coniferous						T	E	Y	TY	EY
	200 to 350 m		200 to 350 m		500 to 650 m		500 to 650 m		650 to 820 m		650 to 820 m						
	1931	1940	1931	1940	1931	1940	1931	1940	1931	1940	1931	1940					
YB	14.5	11.5	6.9	12.9	12.1	6.6	12.9	14.	14.3	8.4	9.5	12.5	-	-	*	-	*
SM	6.2	5.9	6.6	2.9	2.8	2.6	11.7	11.	12.7	9.2	8.6	7.9	-	*	-	-	-
RM	19.3	22.4	25.7	21.9	24.6	29.2	9.3	8.3	8.2	8.2	7.4	6.4	-	*	-	-	*
PB	14.3	16.4	8.7	11.7	12.1	5.9	15.8	13.	5.5	21.6	21.8	6.6	-	-	*	-	-
WA	4.7	6.1	6.3	3.3	3.3	4.0	0.7	0.9	0.4	0.2	0.2	0.3	-	*	-	-	*
ASP	10.8	5.6	2.9	8.2	5.0	1.3	0.2	0.0	0.0	0.0	0.0	0.0	-	-	-	-	*
EH	6.9	7.9	14.9	13.3	13.5	24.8	3.0	3.4	7.8	1.1	1.2	3.0	-	*	*	-	*
RS	2.5	2.6	2.9	5.3	5.5	6.6	22.1	23.	25.9	34.5	34.9	43.4	*	*	-	-	-
BF	0.3	0.6	0.3	2.7	2.6	1.8	0.8	0.8	0.5	5.8	5.4	6.2	-	-	-	-	-

Note: YB=yellow birch, SM=sugar maple, RM=red maple, PB=paper birch, WA=white ash, ASP=aspens, EH=eastern hemlock, RS=red spruce, BF=balsam fir.  
<sup>1</sup>Leak, W.B., Smith, M.L. Sixty years of management and natural disturbance in New England forested landscape. (In preparation).

Local sets of long-term plot data in unmanaged or lightly managed conditions allow some assessment of both successional and migrational tendencies<sup>1</sup> (Table 2). A 60-year record on the Bartlett Forest in New Hampshire provided information on species changes related to management, disturbance, land type, and elevation. On coniferous, unmanaged land types, eastern hemlock increased from 13 to 25 percent of the basal area in the 200- to 350-m elevational class, from three to eight percent in the 500- to 650-m class, and from one to three percent in the 650- to 820-m class. The results indicate that hemlock shows only a slight tendency to increase its elevational range, a result developed from an independent study of age/distance/elevational trends at Bartlett (Solomon and Leak 1994).

Effects of global climate change on expansion or contraction of elevational range appear minimal or nonexistent at present. However, red spruce increased from 34 to 43 percent of the basal area in the 650-820 class (Table 2), and from 22 to 26 percent in the 500-650 class. Apparently, red spruce populations are maintaining themselves well at these elevations despite warnings about growth decline or winter injury due to acid deposition. In summary, the use of permanent plots is a long-term solution that requires careful selection and analysis to confirm migrational tendencies or serve as a data base for model testing.

### RESURVEYS

Under this topic we refer to remeasurements where the initial plots cannot be relocated. This type of information might include resurveys of general areas where earlier survey data are available (e.g., Grabherr et al. 1994) or surveys representing a sequence over time in comparable (but spatially different) locations (e.g., Hamburg and Cogbill 1988). Resurveys pose at least two special problems. First, species/area considerations make it necessary to use the same sampling protocol at each inventory so that the appearance or loss of species does not simply reflect a change in methodology. Second, in areas such as New England where there is high variability in environmental conditions over small spatial scales, it is difficult to resurvey without encountering different habitat conditions and different species.

### POLLEN/VEGETATION ANALYSIS

Pollen records developed from bog and lake sediments provide long-term estimates of changes in vegetation on a regional level over a time scale established by carbon dating or historical markers (e.g., Spear et al. 1994). This approach provides general estimates of species migrational rates and indicates how communities might change with drastic fluctuations in climatic, edaphic, and competitive conditions during the analysis period.

Pollen diagrams can be constructed from shallow-humus profiles that provide local point estimates of changes in vegetation over shorter periods (several hundred years) (Foster et al. 1992). A time scale seems difficult to establish, though certain historical markers provide some basis for calibration. Apparently, this approach has not been used sufficiently to establish its value in determining recent migrational trends. A careful series of samples along an elevational gradient in an unmanaged landscape might prove useful.

### AGE/DISTANCE TRENDS

Migrating species exhibit a sequential relationship between age and distance or elevation, that is, young plants will be out in front of old plants (Solomon and Leak 1994). The migration rate can be represented as the change in distance/change in time (Solomon et al. 1990).

$$\text{Migration rate} = \frac{d_{j+1} - d_j}{a_j - a_{j+1}}$$

where  $d_j$  = distance from parent stand and  $a_j$  = maximum tree age at  $d_j$ .

The age/distance approach is based on the premise that tree species under forested conditions gradually move away from a concentration of seed-producing trees (as opposed to discontinuous jumps), a concept that aligns with what we know about seedfall distribution and sprouting/suckering behavior (Davis 1987; Leak and Graber 1974). This approach requires intensive sampling of actual or predicted tree ages over a distance/elevational transect. It works best in carefully selected areas where there is a steep climatic gradient (on a mountain slope), no significant barriers to plant movement, and unmanaged stands. An example would be the forest species hemlock on Haystack Mountain, Bartlett, NH. While indicating an advancing front, new seedlings have not been established at higher elevations on new or different sites (Fig. 3).

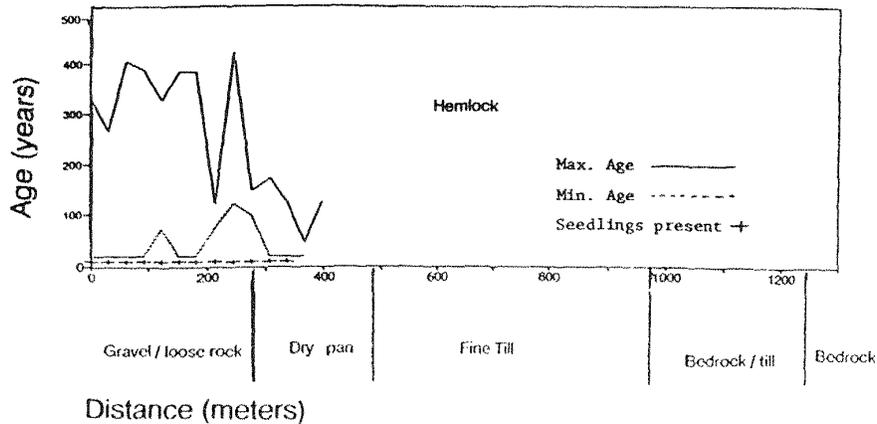


Figure 3. Example of an advancing front from the Bartlett Experimental Forest (adapted from Solomon and Leak 1994). Maximum and minimum ages over horizontal distance for hemlock on Haystack Mountain, Bartlett, NH.

## DISCUSSION

Each of the methods discussed has certain advantages and disadvantages. The modeling approach is the only way to predict future scenarios. However, this approach currently is unreliable due to a lack of available data on climatic change and vegetation response. A series of permanent plots, such as FIA plots, should be made available to test modeling theories if or when actual climatic change begins. Such plots need to be selected carefully or screened to ensure that we do not confuse migrational change with successional rebound from prior disturbance. Resurveys of areas with previous vegetation histories is fraught with problems *except* that some of our long-term information on vegetation change can be obtained only in this fashion. Typical bog/lake pollen analyses seem unsuited for detecting current migrational trends, though they are useful in providing a historical and long-term perspective on vegetation response to drastic climatic scenarios. Short-term pollen-profile data from well-designed surveys (e.g., along elevational gradients) could provide interesting insights into recent elevational shifts, especially if accompanied by historical, local weather data. Likewise, studies of age/distance trends provide one-visit estimates of recent migrational change when carried out in carefully selected study sites. This method can provide fairly precise estimates of recent migrational rates as well as details on patterns of movement, obstacles (such as site conditions), and species interactions. A better understanding of successional response of both overstory and understory plant species to climatic changes would aid in the interpretation of apparent migrational trends.

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GROWTH RESPONSES OF WHITE OAK AND BLACK OAK TO DROUGHT STRESS ACROSS GRADIENTS  
OF ACID DEPOSITION AND MICROCLIMATE

David LeBlanc<sup>1</sup> and Robert Haack<sup>2</sup>

Based on data from Illinois, Indiana, and Ohio following the 1988 drought, acid deposition does not increase the susceptibility of oak trees to drought stress. Measurements at six sites along a gradient from comparatively high to low levels of acid deposition refuted the hypothesis that high acid deposition rates would predispose oaks to growth decline and mortality after a severe drought. Neither patterns of growth rate nor outbreak of two-lined chestnut borer correlate with acid deposition patterns. Differences in growth and mortality between sites appear to relate to differences in the timing and duration of drought conditions.

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# ASSESSING THE ABILITY OF PLANTS TO RESPOND TO CLIMATIC CHANGE THROUGH DISTRIBUTION SHIFTS

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**Abstract:** Predictions of future global warming suggest northward shifts of up to 800 km in the equilibrium distributions of plant species. Historical data estimating the maximum rate of tree distribution shifts (migration) suggest that most species will not keep pace with future rates of human-induced climatic change. Previous plant migrations have occurred at rates typically ranging from 15-50 km per century. A simulation model, which incorporates the effects of forest fragmentation and habitat loss, predicts maximum potential migration responses of trees may be only 1-10 km per century, or two orders of magnitude below that required to keep pace with predicted climatic warming. These predicted migration rates suggest that plants will fail to respond adequately to even modest climatic changes. Gauging the actual response of forest species to climatic change, and then appropriately managing forest resources poses several problems. First, we do not know the distribution limits of most forest species with the degree of precision to detect migration events on a 1-10 km scale. Second, many species may become vulnerable to extinction by their inability to migrate, leaving them geographically isolated from regions within their climatic tolerance. Third, while the distributions of species can be artificially expanded if climate does warm, this is not currently part of acceptable conservation management practice. Deciding whether or not to artificially enhance species ranges forces a choice between species preservation and historical community composition models for conservation. A pressing concern for forest management is to discover how climate change, anthropogenic habitat change, and doubled CO<sub>2</sub> interact to alter forest species performance and regeneration within habitats they currently occupy. Range edges are the first place to look for key changes in these ecological responses.

## INTRODUCTION

General circulation models, estimating climatic change during the next century in response to a doubling of the atmospheric CO<sub>2</sub> and other trace gases, suggest warming sufficient to trigger major changes in the earth's living systems. These environmental changes will affect virtually all plants and animals. Predicted terrestrial responses include altered: 1) plant-insect interactions (e.g., Lincoln et al. 1986); 2) plant-soil relationships (e.g., Luxmoore et al. 1986); 3) biome boundaries (e.g., Solomon 1986); 4) distributions of crop production areas (e.g., Rosenzweig 1993); and 5) distributions of individual species (e.g., Davis and Zabinski 1992), to name but a few. In order to manage natural resources, for extractable resources (e.g., timber trees) as well as for broadscale biological diversity, it is imperative that we understand the full suite of possible responses of species to the spectrum of climatic change scenarios. Toward this end, I review here what is known regarding the abilities of forest plants to respond under the combined forces of climatic change and anthropogenically altered habitats. Finally, I make research recommendations based on perceived gaps in this knowledge.

### The Climate Scenarios

Various Global Circulation Models (GCM's) predict 2 to 6 °C temperature increases during the next century, as atmospheric CO<sub>2</sub> doubles (Mitchell et al. 1990). Predicted global increases in temperature vary strongly with season and latitude with higher latitudes experiencing greater temperature increases, particularly during the winter months. Thus, for North America, winter temperatures in the boreal forest under a doubled CO<sub>2</sub> environment may be increased by as much as 12 °C over current conditions. Further, growing season precipitation is, in general, predicted to decrease over much of North America, resulting in lower soil moisture. Model predictions, however, are recognized as a first approximation at a very complex problem in atmospheric chemistry and physics.

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The variables predicted by the GCM's (mean seasonal temperature and precipitation), however, are not likely to be the variables that are most important to plant growth (e.g., Woodward 1995). Solomon (1984), for example, modeled vegetation change based on climate projections using growing degree days, a variable one could estimate from, but not modeled by, GCM's. Frequently, it is the extremes of climate (e.g., drought frequency and severity, frost free days, lowest minimum temperatures) that may be the most important variables used to estimate responses of plants to their environment (Graumlich and Brubaker 1995). Unfortunately, climatologists cannot easily model these parameters. Rind et al. (1989) suggest that, whatever the exact magnitude of climate change, variability in weather is likely to increase. The biotic consequences of increased climatic variability are likely to be complex and unpredictable.

#### The Plant-Climate Relationship

Correlations between climate and plant distributions are widespread and well known (e.g., Good 1931, Cain 1944, Pigott 1970, Woodward 1987, Denton and Barnes 1987, and Grime 1990). Further, vegetation has been responsive to large-scale changes in climate with most tree species altering their distribution limits hundreds to thousands of kilometers during the past 10,000 years (Davis 1981, COHMAP 1988). Likewise, recent climatic shifts have resulted in measurable changes in the distribution and performance of plant species. For example, about a dozen coniferous species in North America alone have shifted their growth forms or distribution limits northwards during the past 100 years (see references in Graumlich and Brubaker 1995). The manifestations of these changes vary from changes in growth forms and increased seedling recruitment at tree line to expansion of tree line and increased elevation of successful growth (e.g., Kullman 1983). The observed increases, however, are not uniformly observed even where climate has warmed. In addition, some range shifts are a result of changes in precipitation, different disturbance regimes, or simply a brief series of relatively warm temperatures (Graumlich and Brubaker 1995). In yet other cases, tree line has recessed owing to changes in disturbance rates (Payette and Gagnon 1979). Evidence of recent tree line shifts are abundant in both directions (Graumlich and Brubaker 1995). These observed changes in treeline are often dependent on proximate ecological factors as well as climatic factors. Nonetheless, the physical evidence of the response of trees to their environment suggests that climatic warming will result in differential recruitment, growth, and survivorship of plants in and around their distribution limits. Our primary limitation in predicting species level responses to future climatic change is that we lack a mechanistic understanding of the climatic limitations of virtually all plants (except see Pigott and Huntley 1978, Cannell and Smith 1986, Richardson and Bond 1991). Even for important timber species much work remains on the physiological relationship between plants and climate to develop mechanistic models of climatic control on plant germination, growth, survivorship, and seed production.

Despite not fully understanding the mechanistic relationship between plants and climate, we can make assertions about the magnitude of vegetation change that ought to result of predicted future warming. Plant distributions correlate with mean annual temperature isobars (e.g., Denton and Barnes 1987). At present mean annual temperature isobars are distributed at approximately 100-125 km latitudinal intervals in eastern North America (Melillo et al. 1990). If plant-climate relationships remain intact, an increase in 5 °C may result in distribution shifts of 500 km for the equilibria ranges of most plants. Predictions of equilibrium plant distribution shifts become even more dramatic if one also considers both seasonal temperatures and precipitation. Davis and Zabinski (1991) predict that northward shifts of the equilibria distribution for plants could exceed 800 km. A pressing question then becomes: can plants keep pace with the predicted magnitude of climatic forcing?

#### FUTURE PLANT MIGRATION RESPONSE

Historical data suggest that plants will not keep pace with climatic warming. Most trees migrated to their current distributions at rates of 10-50 km per century (Davis 1981). Presuming our climate models are correct, historical migration rates are an order of magnitude too slow to keep pace with future warming. One must question, however, whether these past migrations were limited by rates of climatic change, or by the dispersal abilities of the plants. Detailed palynological studies have detected considerable lags in response to climatic change (e.g., Davis et al. 1986, Pennington 1986), suggesting that historical migration rates were at, or near, the limit set by the dispersal

abilities of trees. Further, the relative constancy of maximum migration rates through time, among regions, and among species, suggests that these migrations were limited by rates of seed dispersal and not climatic change, which varied through time and among regions, and to which species responses vary (Huntley 1989). Thus, Holocene migration rates may be good predictors of maximum migration rates for most species.

A few species, however, migrated much faster than 50 km per century. *Picea glauca* expanded from southern Alberta, through Northwest Canada to Alaska (nearly 2000 km) from 10,000 to 9,500 ybp (Anderson and Brubaker 1993, Ritchie et al 1983, Graumlich, and Brubaker 1995). This may be interpreted as a rapid expansion of the population with little to no dispersal limitation. Alternatively, treeline expansions may often be a result of krummholz vegetation beginning to grow upright as a result of amelioration and thus indicative of rapid population expansion without range expansion (Graumlich and Brubaker 1995). Thus, it is not clear what the actual migration rate of *P. glauca* was 10,000 ybp. Another issue complicating specific response predictions is that the climate of the past represents a unique combination of events that are unlike any potential climatic change of the near future. For example, summer insolation was higher, and winter insolation lower, 10,000 ybp owing to the perihelion (the point in orbit at which the earth is closest to the sun) occurring in summer rather than winter, as at present. Thus, there were probably higher seasonal extremes, creating different temperature and moisture regimes (Graumlich and Brubaker 1995). Indeed, there is evidence of past vegetations that have no modern analog (e.g., Jacobson and Grimm 1986). Nonetheless, there is a broad consensus that the predicted magnitude of climate change would require migration rates to far exceed any historical rates of vegetation change (Overpeck et al. 1991) and that rates are likely to be limited more by the biology of species than the rates of change in the environment (Huntley 1991).

Regardless of how well past climate reflects future climate scenarios, an additional factor that must be considered is that past migration rates are based on a different landscape. Past migration rates are estimated from regions where trees moved from largely forested regions into largely forested regions. Future migrations for many forest species will be within the context of a largely fragmented forest landscape (Peters 1991). The effect of habitat loss on potential migration has been stochastically modeled using a simulated landscape in which dispersal and colonization is a function of the distance between occupied and unoccupied patches (Schwartz 1993). This model varied dispersal and colonization probabilities to fit either one of two functions (inverse power function or negative exponential function) based on empirically derived seed density data (e.g., Harper 1977, Portnoy and Wilson 1993). These models were calibrated to result in a migration rate of 50 km per century when 80 percent of the habitat cells were available for occupation. In sequential runs: 1) dispersal function (inverse power or negative exponential), 2) habitat availability (10-90 percent), and 3) within stand frequency (10-90 percent) were varied to characterize the effect of habitat loss on migration potential. Assuming 50 km per century to be an average maximum migration rate under a saturated environment (80 percent habitat availability), Schwartz (1993) predicted migration rates under low (10-30 percent) habitat availability to be from 1-10 km per century, yet another order of magnitude below that predicted to keep pace with climatic change (Figure 1).

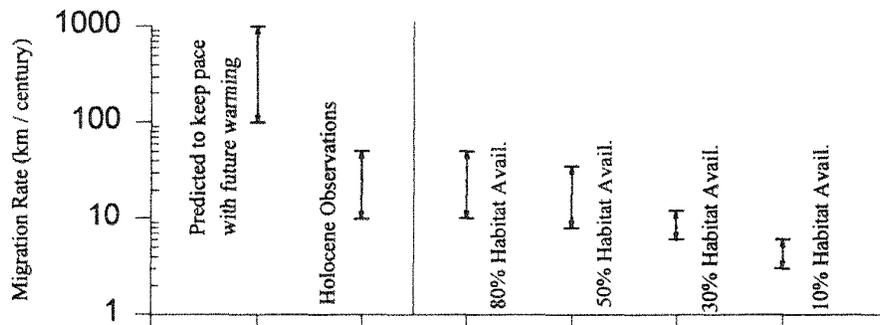


Figure 1. A schematic diagram of variation in tree migration rates comparing: 1) rates that would be required to keep pace with climate change; 2) observations of Holocene migration rates (based on palynological data); and 3) varying levels of habitat availability in a simulated landscape (redrawn from Schwartz 1993).

## The Potential for Species Loss

If plants can not migrate to keep pace with future climatic warming, then species may be vulnerable to extirpation as a result of climatic change because the current distribution of a species may become disjunct from a region of suitable climate (Peters 1991). Schwartz (1991) estimated the magnitude of this extinction potential using a compendium of 316 rare forest taxa of the Southeastern United States (Kral 1983). Using the north-south distribution breadth of species as a measure of sensitivity to extinction, Schwartz (1991) found that a substantial portion of the rare southeastern U.S. forest taxa are potentially vulnerable to extirpation under even modest warming, and that most rare taxa (> 85 percent) have north-south distributions of less than 500 km, the predicted baseline northward shift to keep pace with future warming (Figure 2). Naturally, not all, or even most, of these potentially vulnerable species are truly at risk. Many species are restricted by edaphic conditions, biogeographical boundaries or ecological factors, and not climate. Other species are in mountainous regions where relatively short geographical shifts upslope may be within the realm of migration potential. The point is that the risk of species loss is potentially large, and owing to our lack of a mechanistic understanding of the plant-climate relationship for most species, we have little ability to predict which species are truly at risk. We do not know which species are, or are not, limited by climate, and this lack of knowledge poses a conservation problem.

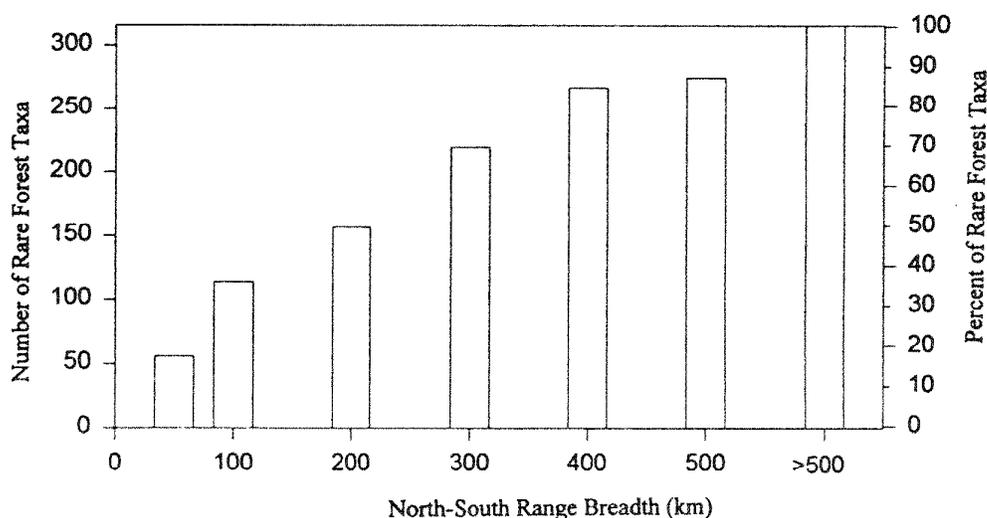


Figure 2. A histogram of the number of 316 rare forest species characterized by north-south distribution breadths of differing widths. The number of species in each range breadth category represent an upper estimate of the number, or percent, of species that are potentially vulnerable to extinction under different degrees of climatic change, assuming climatic control of distributions and an inability to migrate sufficiently to keep pace with future warming.

The lack of ability to migrate in response to climatic change for many species does not pose an insurmountable conservation problem. Certainly distributions can be altered through human intervention. This management activity, however, creates a conservation dilemma: we do not sanction range expansion as an acceptable conservation practice. Conserving historically accurate representatives of natural communities is, perhaps, the most common management directive and a common conservation goal. Intentional introduction of species perceived to be vulnerable to extinction into new habitats compromises traditional conservation efforts. Thus, if migration lag is severe, and causes species loss problems, then we must balance our efforts between two opposing conservation objectives: species conservation and maintaining community integrity (Schwartz 1994).

## CONCLUSIONS

How do we address the critical issues of climatic change and forest management given our sparse ecological knowledge? I suggest three areas of research that may focus our attention on the critical knowledge gaps in this area. First, we need spatially explicit models of predicted species range expansions in order to test whether species are, in fact, responding to climatic change. Work in this area has begun with an expansion of the simulation model of Schwartz (1993) to relax restrictions on the spatial scale and life histories of species modeled and to apply the model to real species in real landscapes (Schwartz and Iverson, personal communication). These spatially explicit models provide a testable hypothesis regarding the role of climate change in shifting species range boundaries. Knowledge of specific distribution limits, however, limits the extent to which we can test these hypotheses. Precisely indentifying the distribution limits of a few critical species would allow the model to be empirically tested.

The second area of emphasis is to increase our mechanistic understanding of the plant-climate relationship. By targeting species of particular interest we can begin to assess which species are likely to become vulnerable to climatic change. A good place to start would be to contrast species that have historically shifted their range boundaries, versus those that merely expanded their distributions during the Holocene. *Fagus grandifolia* and *Picea glauca* provide a good contrast in this regard. During the last full glacial both species were found in region that is now the Southeastern U.S. During the Holocene, *F. grandifolia* expanded its distribution northward, such that it is now distributed from Florida to Ontario, while *P. glauca* shifted its distribution northward, such that it is found from the Great Lakes and New England to northern Canada (Figure 3). Species that shift their distributions in response to future climatic changes are at greater risk than those that expand their distributions.

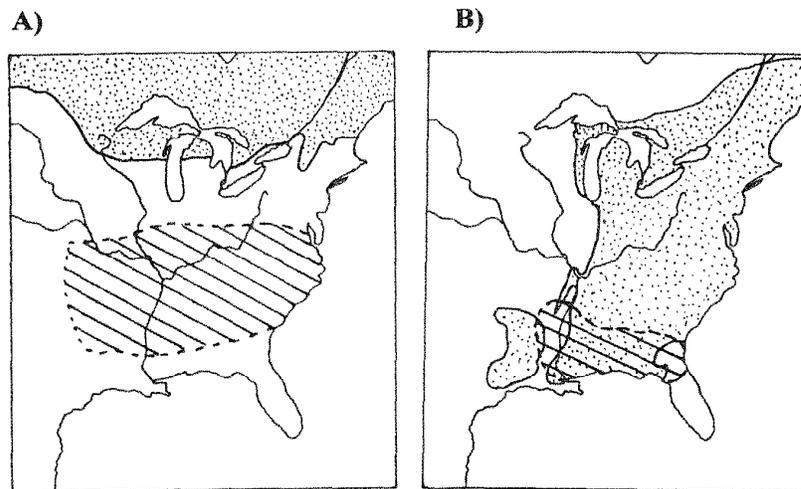


Figure 3. An estimate of the distribution of A) *Picea glauca* and B) *Fagus grandifolia* at 14,000 ybp (hashed) compared to the current (stippled) distributions showing a Holocene expansion of *F. grandifolia* compared to a wholesale shift in the distribution of *P. glauca*.

The third area of emphasis is relating species interactions and other dynamic ecological processes to estimates of species' responses to warming. Within stand changes in abundance may be the most immediate and strong effect of a changing climate. Thus, studying the interaction of climate to other ecological factors may best help us to understand changing abundances within forested communities. For example, rates of disturbance have been observed to be a strong correlative factor that can drive treeline response in conjunction with climate change (e.g., Payette and Gagnon 1979). On a global scale most grasslands are disturbance maintained. Changes in the disturbance regime may swamp climate change in the rates of movements of both species and community boundaries. Alternatively, differences in modern species abundances, such as high deer densities resulting in high herbivory rates on *Tsuga*

*canadensis* seedlings (e.g., Alvorson et al. 1988), seem likely to overwhelm the species' ability to respond to climate change through migration. The lack of passenger pigeons, an important presettlement seed disperser (Webb 1986), may also strongly affect the ability of trees to respond to climatic change.

Finally, we expect northward range limit expansions to be slow and fear that southern range limit contractions may be swift. Thus, we must focus our attention on ecological processes at both southern and northern distribution limits of species. Curtis (1959) defined a "tension zone" for the vegetation of Wisconsin as a region that is unusually rich in species distribution limits. Focusing research on "tension zones" allows us the ability to best capture the dynamic processes associated with climate change in a human-altered landscape. Further, sites that are characterized by anomalous microclimates, such as warm south-facing slopes, within these tension zones may be the most sensitive to early signs of climatic change. Lags are often observed in short term responses to climatic change owing to the fact that adult trees are less sensitive to the vagaries of climate than are juveniles; field studies targeting regeneration success and failure will most likely to detect critical changes in the response of species to their environment.

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## OVERVIEW OF CURRENT RESEARCH ON ATMOSPHERIC INTERACTIONS WITH WILDLAND FIRES

Warren E. Heilman<sup>1</sup>

**Abstract:** Changes in the large-scale mean thermal structure of the atmosphere have the potential for affecting the dynamics of the atmosphere across the entire spectrum of scales that govern atmospheric processes. Inherent in these changes are interactions among the scales that could change, resulting in an alteration in the frequency of regional weather systems conducive to fire occurrence. In support of the Northern Stations Global Change Research Program, we have designed a research program to examine the interactions of large-scale atmospheric processes with regional fire-weather systems. This paper provides a summary of four studies that have been performed or are in progress that address some of the fundamental characteristics of regional fire-weather systems and their behavior in response to larger-scale atmospheric conditions.

### INTRODUCTION

Atmospheric processes span a wide range of temporal and spatial scales. Ambient micrometeorological conditions as well as micrometeorological conditions generated by wildland fires play a significant role in affecting small-scale physical processes like wildland fire behavior. On the other hand, the frequency of occurrence of severe wildland fires is influenced by larger-scale atmospheric processes like synoptic and mesoscale circulations, precipitation patterns, climatic variability, and extreme weather events. In recent years, there has been considerable attention paid to the prospect of a globally warmer climate due to increases in atmospheric greenhouse gases. Altering the large-scale thermal structure of the atmosphere has the potential for affecting the dynamics of the atmosphere across a multitude of temporal and spatial scales, including those scales that characterize synoptic and regional circulations and regional climate/weather variability. In fact, climate variability and the effects of synoptic and mesoscale weather events with their associated circulation, temperature, and moisture patterns have a much greater influence on the frequency of severe fire occurrence than any global-scale temperature trends. In assessing the potential impact of a changed climate on wildland fire occurrence, it is critical that we examine the secondary effects of climate variability and the tertiary effect of individual weather events (Fosberg et al. 1993).

We have designed a research program to specifically address the mechanisms by which synoptic-scale atmospheric processes, particularly middle-tropospheric circulations, control regional weather systems that are conducive to severe fire occurrence. By examining some of the fundamental characteristics of these atmospheric fire-weather systems, their development, and their interactions with larger-scale atmospheric processes, we will be in a better position to assess the importance of secondary and tertiary effects of climate change in affecting severe fire occurrence. Our research approach for examining regional fire-weather systems and their interactions with larger-scale atmospheric processes includes the following four studies: 1) synoptic circulation, temperature, and moisture patterns during severe wildland fires, 2) surface pressure pattern relationships with fire occurrence in the northeastern U.S., 3) atmospheric synoptic effects on the mesoscale dynamics of fire-weather systems, and 4) simulations of soil-moisture and vegetation effects on fire-weather development.

### STUDY 1: SYNOPTIC CIRCULATION, TEMPERATURE, AND MOISTURE PATTERNS DURING SEVERE WILDLAND FIRES

As a first step in examining the relationship of large-scale atmospheric processes to regional fire occurrence, Heilman (1995) performed a series of empirical-orthogonal-function (EOF) analyses on the observed 500 mb geopotential height anomaly fields and 850 mb temperature anomaly fields at the onset of severe wildland fires (i.e.

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those fires that resulted in the burning of more than 1000 acres) between 1971-1991 in six different regions (NW, NC, NE, SW, SC, and SE) of the continental U.S. The EOF analyses were used as tools to identify the prevalent middle tropospheric synoptic circulation and temperature patterns that characterize severe fire occurrence on a regional basis.

For severe wildland fires occurring in the northeastern U.S. (typically in the spring and autumn months), defined as the region extending eastward from Wisconsin and Illinois to the Atlantic coast, two middle tropospheric circulation patterns were found to be predominant at the onset of the fires. The first circulation pattern is characterized by a 500 mb ridge centered over the western half of the U.S. accompanied by a prominent trough over the eastern U.S. and southeastern Canada, resulting in the transport of cool dry air into the northeastern U.S. This circulation pattern in the middle troposphere produces cooler than normal temperatures at the surface over much of the northeastern U.S., but relative humidity values can be anomalously low. This dryness contributes to the atmospheric conduciveness for severe wildland fires in this region. The second pattern is characterized by a strong 500 mb ridge over the eastern half of the U.S. or off the eastern U.S. coast, with the western and/or central states dominated by a 500 mb trough. Average temperatures and relative humidities in the lower atmosphere over the northeastern U.S. under this type of middle tropospheric circulation pattern are anomalously high and low, respectively. The presence of a middle tropospheric ridge over the eastern U.S. is conducive to the surface Bermuda high pressure system that can block the northward transport of Gulf moisture into the northeastern U.S. if it is displaced westward of its normal position.

Specific synoptic circulation, temperature, and moisture patterns prevalent in the middle and lower troposphere at the onset of severe wildland fires in the other regions of the U.S. were also identified. For all regions, the middle tropospheric circulations identified in this study as being associated with severe fire occurrence led to drier than normal lower atmospheric conditions over much if not all of the specific region of interest. Circulation patterns obtained from the EOF analyses were compared with similar but subjective analyses performed by Schroeder et al. (1964), and the results were found to be quite similar. Results from this study are being used to examine how specific synoptic circulation patterns influence the development and evolution of regional fire-weather episodes, and will be used in future studies that will assess the potential impact of large-scale circulation changes in the atmosphere associated with a globally changed climate on the frequency of future wildland fire occurrences.

## STUDY 2: SURFACE PRESSURE PATTERN RELATIONSHIPS WITH FIRE OCCURRENCE IN THE NORTHEASTERN U.S.

In a companion study to the middle tropospheric circulation analyses performed in study #1, Takle et al. (1994) examined surface pressure patterns and circulations corresponding to reduced precipitation, high evaporation potential, and enhanced forest-fire danger for a portion of the northeastern U.S. Analyses of daily surface weather maps resulted in the identification of eight surface pressure or weather patterns (Yarnal 1993) that describe distinctive flow situations over the northeastern U.S. throughout the year. Three particular surface pressure patterns were found to occur most frequently during severe fires in the four-state region of West Virginia, Ohio, Pennsylvania, and New York: 1) an extended region of high surface pressure over the eastern and central U.S., with light surface winds, 2) a high pressure system situated off the Atlantic coast (Bermuda high pressure system) resulting in southerly flow over the eastern U.S., and 3) a high pressure system centered over the western Great Lakes region with northerly surface flow over the northeastern U.S. Of these pressure patterns, the Bermuda high pressure pattern was found to be associated with a disproportionately large amount of fire-related damage in the West Virginia area. Evaporation and precipitation data indicate that these three patterns along with a fourth pressure pattern described by a high pressure system centered over the northern Gulf of Mexico all lead to drying conditions over the northeastern U.S. and enhance fire potential.

Simulation results from the Canadian Climate Centre's (CCC) general circulation model (GCM) for the present climate and a doubled atmospheric CO<sub>2</sub> climate were examined to determine whether there may be a tendency for more surface pressure patterns conducive for fire occurrence in the northeastern U.S. to develop under increased atmospheric CO<sub>2</sub>. The results of the CCC GCM suggest a tendency for increased frequency of "drying" pressure

patterns in the northeastern U.S. under a globally changed climate, although the results were not statistically significant.

### STUDY 3: ATMOSPHERIC SYNOPTIC EFFECTS ON THE MESOSCALE DYNAMICS OF FIRE-WEATHER SYSTEMS

Determining the role of synoptic-scale atmospheric processes in affecting severe fire occurrence in a particular region of the country requires a fundamental understanding of the atmospheric dynamics associated with mesoscale or regional fire-weather systems. Mesoscale weather events that produce atmospheric conditions favorable for severe wildland fires develop and evolve, to a large extent, in response to the larger-scale circulation, temperature, and moisture patterns identified in studies #1 and #2. The development and evolution of mesoscale weather events conducive for fire occurrence can be examined through the use of atmospheric mesoscale modeling techniques that can also translate atmospheric conditions into estimates of fire risk.

As a precursor to actual mesoscale simulations of fire-weather episodes, a suitable but simple index of severe fire risk based on surface atmospheric conditions was developed by Potter (1995). He performed statistical analyses of eight meteorological variables on fire days and non-fire days throughout the U.S. and found that surface dew-point depression is the best overall discriminator of fire and non-fire days. A fire-weather index suitable for implementation in atmospheric mesoscale models for fire-weather simulation was then developed by Potter (1995) and is based on elevation-adjusted dew-point depression values at the earth's surface. Unlike other indices of fire-weather, this index does not require upper-air measurements and can be easily measured at any location. This index has been implemented in the Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992), a sophisticated computer model used for simulating atmospheric processes with spatial scales on the order of 2-2000 km. Mesoscale simulations of specific fire-weather episodes are currently being performed with RAMS to examine how typical large-scale circulation, temperature, and moisture patterns associated with regional fire occurrence influence the development and evolution of mesoscale weather systems that favor severe wildland fires. The new fire-weather index developed in this study serves as a useful tool for examining the spatial and temporal characteristics of fire-weather systems as they evolve over different regions of the country and for determining the potential for severe wildland fires.

### STUDY 4: SIMULATIONS OF SOIL-MOISTURE AND VEGETATION EFFECTS ON FIRE-WEATHER DEVELOPMENT

The development of regional fire-weather systems in response to the large-scale atmospheric circulation, temperature, and moisture fields is also influenced by atmospheric processes taking place at the earth's surface. Surface fluxes of heat and moisture can modify air masses and alter the atmospheric dynamics of weather systems that tend to enhance or inhibit the occurrence of severe fires. In particular, the presence of inhomogeneous distributions of soil-moisture and vegetation can significantly influence circulations and the heat and moisture budgets in the lower atmosphere, which in turn can lead to modifications in the overall impact of the larger-scale circulation, temperature, and moisture fields. Fast (1994) examined some of the fundamental characteristics of the atmospheric secondary circulations that can result from different soil-moisture and vegetation distributions. He also examined their impact on the lower atmospheric temperature and moisture fields which are very important variables in determining wildland fire potential.

Fast (1994) performed a series of numerical simulations with RAMS for the May 5-17, 1989 and October 25-November 16, 1987 periods when severe wildland fires occurred in Minnesota, Florida, and West Virginia, and abnormally dry and wet soil conditions existed in various regions of the eastern half of the country. For these particular periods, the simulations indicated that the use of realistic soil-moisture significantly affects the near-surface temperatures and moisture fields, and affects the cloud cover, precipitation, and wind speeds to a lesser extent. The largest effects due to soil-moisture usually occur at locations where the soil is sufficiently moist, but there are occasions when moisture evaporated from wet soil can be transported downwind and affect locations that

are characterized by much drier soils. Soil-moisture variations were found to have a significant impact on local diurnal temperatures and relative humidities, with wet soils decreasing daytime temperatures and increasing daytime humidity values. The simulations also indicated that surface vegetation moderates the transfer of water from the soil to the atmosphere. Vegetation reduces the amount of water evaporated into the atmosphere where the soil is wet, and increases the amount evaporated where the soil is relatively dry. Changes in the lower atmospheric temperature and moisture fields resulting from soil-moisture and vegetation variations were also found to affect the Lower Atmospheric Severity Index (LASI), an indicator of suitable conditions for severe fire occurrence (Haines 1988). Numerical simulations suggest that the LASI is usually reduced over moist-soil regions, so that the potential for wildland fires is diminished. The LASI was found to be mostly affected by evapotranspiration which reduces the dew-point depression within the atmospheric boundary layer.

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## SYNOPTIC CIRCULATION AND TEMPERATURE PATTERN DURING SEVERE WILDLAND FIRES

Warren E. Heilman<sup>1</sup>

Large-scale changes in the atmosphere associated with a globally changed climate and changes in climatic variability may have important regional impacts on the frequency and severity of wildland fires in the future. Identifying the relationships of large-scale middle and lower atmospheric processes to regional-scale fire-weather systems is critical for understanding how a changing climate or climate variability can potentially influence wildland fire activity. Three very important middle and lower atmospheric variables that influence the development of regional fire-weather systems are wind, temperature and moisture.

In this study, empirical-orthogonal-function (EOF) analyses were performed on the middle and lower atmospheric circulation and temperature fields at the onset of past severe wildland fire episodes. These EOF analyses were used to identify the synoptic circulation and temperature patterns at the 500 mb and 850 mb levels in the atmosphere, respectively, that are prominent at the onset of severe fires in six different regions (NW, NC, NE, SW, SC, and SE) of the U.S. Lower atmospheric relative humidity patterns corresponding to the EOF-derived circulation and temperature patterns during severe fires were also identified. The analyses suggest that there are two or three distinct synoptic circulation, temperature, and moisture patterns that tend to be associated with severe fires in each region. Additional studies are examining how these large-scale patterns influence the mesoscale dynamics of fire-weather systems.

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ATMOSPHERIC MESOSCALE SIMULATIONS OF REGIONAL WILDLAND FIRE EPISODES: LOOKING  
FOR WEATHER-RELATED FACTORS AND SCALES OF INTERACTION

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The Regional Atmospheric Modeling System (RAMS) is a sophisticated computer model for the simulation of atmospheric processes on scales from a county to a country. It can accurately represent winds, air moisture, and air temperature. In the study of fire-weather episodes, this information must somehow be translated into an estimate of fire risk. We performed statistical analyses of eight meteorological variables on fire days and nonfire days, and found that dewpoint depression differs between the two types of days throughout the United States (except Hawaii). By adjusting dewpoint depression for the surface elevation at a particular site, this measure of humidity becomes a fire-weather index that RAMS can easily compute. The model can subsequently produce maps showing the distribution of this fire-weather index at user-specified intervals for simulation of wildfire episodes. This new index serves as a useful tool for examining how large-scale atmospheric processes influence the development of regional weather systems conducive to fire occurrence.

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