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ORIGINAL ARTICLE

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Monitoring global change with phenology: the case of the spring green wave

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Abstract The centuries-old practice of recording plant and animal events that take place at specific times each year (phenology) should play an important role in monitoring mid-latitude global changes. At least three problems related to the detection of biosphere changes could be investigated using this information. Firstly, the technique can be generalized from the local to global scale. Secondly, an integrated approach could be developed to represent biome diversity effectively. Lastly, physical mechanisms responsible for the events can be deduced in order to incorporate the phenological information into global-scale models, and detect changes in related environmental factors. With these goals in mind, regional phenological data collection networks were initiated in eastern North America during the early 1960s, using cloned lilacs and several species of honeysuckle. This paper reviews research projects which address the problems outlined above, using first leaf data (associated with spring green-up or "green wave" in mid-latitudes) gathered from these networks. The results of such studies in North America have demonstrated the potential of phenology as an efficient monitor of global change throughout mid-latitude regions. Future research efforts will concentrate on the development of a coordinated strategy to link phenological information from satellites, indicator plants (such as the lilac), and representative species from each biome.

Key words Phenology · Green wave · Global change

Introduction

Phenological information on various plant and animal species has been gathered for a number of centuries, and in a few locations far precedes the availability of regular weather observations. While efforts continue to understand thoroughly the physical connections of environmental factors to these events, phenological observations already serve as valuable sources of information about interactions at the Earth's surface (Lieth 1974). The collection of phenological data, especially from plants, allows the observed species to act as integrating monitors of the atmosphere, biosphere, and lithosphere.

Recently, the scientific community has become concerned with the prospects for global change. At first these interests were tied directly to predictions of profound anthropogenic climate change (due to "greenhouse gas" emissions) from early global climate models (IPCC 1990). Currently a broader-based definition is emerging, which emphasizes changes within the hydrosphere and biosphere, as well as the atmosphere. Perhaps more importantly, it is also generally recognized that a number of feedback mechanisms are at work between the "spheres", and even subtle changes in one may have long-lasting effects on the entire system.

In principle, therefore, plant phenological data are well suited as monitors of global change in mid-latitudes, because of their ability to represent the integrated dependency of the biosphere to changes within the atmosphere and hydrosphere (especially in areas of strong seasonal contrasts). To achieve this goal, however, at least three practical problems need to be addressed. Firstly, the data must be able to be generalized from the local to global scale. Ideally, this would mean collecting phenological events from a small set of plant species whose ranges cover the major portion of mid-latitude continental areas.

Secondly, biome diversity should be represented, an objective that is somewhat at odds with the first one. In order to have the broadest geographical coverage, a smaller number of species are suitable for use, while to best represent biome diversity requires greater numbers of species, with more limited ranges. The best compromise might be to use a few wide-ranging plant species as "indicators", and then describe their relationship to the representative species within each major biome. Lastly, physical mechanisms responsible for the phenological

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events must be well understood, if the information gathered is to be put to best use (i.e. as diagnostic information on the Earth's systems, as well as input for integrated global models). The first steps have been taken towards addressing the above three problems in North America using phenological events representing the onset of plant photosynthetic activity in the spring ("green-up"). Preliminary results suggest that much more can be achieved both in this region and throughout the mid-latitudes.

Previous and current research

History of regional phenology projects in North America

(Note: this information for the period up to 1985 was provided by M.T. Vittum in a personal communication) Much of the phenological data that are being used for regional studies in North America (and to address some of the "problems" of using these data for global change monitoring) have come from regional USA. Agricultural Experiment Station phenology projects. A brief history of these networks follows, in order to provide the background for an understanding of the currently available data. Figure 1 represents the extent of the data collection in eastern North America. Northeast regional research project NE-35, "Climate of the Northeast–Analysis and Relationships to Crop Response", was initiated in 1956. When the project was revised in 1965, R. Hopp at the University of Vermont was instrumental in incorporating a specific phenology objective. This allowed establishment of a phenological observation network in the Northeast, which would parallel and supplement similar networks previously established in the Western and North Central states.

J.M. Caprio at Montana State University initiated lilac phenology research in the United States under project W-48, "Climate and Phenological Patterns for Agriculture in the Western Region" in 1957. He developed a network of approximately 1000 volunteer observers scattered throughout 11 Western states. Existing purple common lilac (*Syringa vulgaris*) plants were used to study and record seasonal plant development. Later, two cultivars of honeysuckle (*Lonicera tatarica* 'Arnold Red' and *L. korolkowii* 'Zabeli') were added as indicator plants, the number of cooperators was increased, and plantings were expanded into Texas. Phenological observers in the 12 Western states numbered about 2500 in 1972.

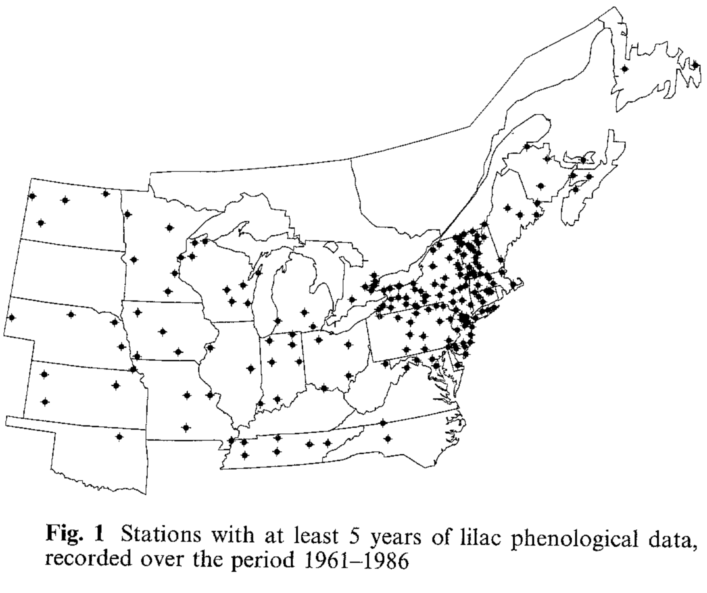

Fig. 1 Stations with at least 5 years of lilac phenological data, recorded over the period 1961–1986

Caprio's program in W–48 provided impetus for the North central states to initiate a similar project in 1961. This was part of project NC-26 "Weather Information for Agriculture", and W.L. Colville at the University of Nebraska headed the phenology portion of the project. Rather than use native lilacs of varied genetic background, Colville obtained all the plants used in the NC-26 lilac phenology network from Plumfield Nurseries of Fremont, Nebraska. The cultivar was *S. chinensis* 'Red Rothomagensis', and it is assumed that all of the plants of this cultivar obtained from Plumfield Nurseries were of the same genetic clone (US/IBP Phenology Committee 1972; Fiala 1988). When phenology was incorporated into the revised project NE-35 in 1965, all cooperating observers were furnished with 'Red Rothomagensis' lilacs obtained from Plumfield. Unfortunately the source of 'Arnold Red' and 'Zabeli' honeysuckle varied over the years because several nurseries supplying these to the NC and NE projects went out of business. Hence it is doubtful that all plants of either of these two cultivars are from exactly the same clone.

In July 1970, phenological programs conducted under NC-26 and NE-35 were combined as one of the objectives in a new regional project, NE-69, "Atmospheric Influences on Ecosystems and Satellite Sensing". The program expanded, including approximately 300 sites in the eastern United States, and three individuals served unofficially as leaders: B. Blair at Purdue took care of observers in the North Central states, R. Hopp at Vermont handled Northeastern states, and P. Dube at Laval University coordinated a huge phenology network in Quebec.

In 1975 upon termination of NE-69, a new regional project, NE-95 "Phenology, Weather and Crop Yields" was initiated, which included Canadian sites in Ontario and the Maritime Provinces. The program was continued until it was replaced by a fourth project, NE-135 "Impacts of Climatic Variability on Agriculture", in 1980. M.T. Vittum at Cornell University coordinated this project until 1985, when responsibility for it was turned over to R.C. Wakefield at the University of Rhode Island. W. Kennard at the University of Connecticut briefly coordinated the project until its termination at the end of 1986. In 1986, the proposal (within NE-135) to continue phenological data collection in the eastern and north central US was rejected, and no data surveys were sent out in 1987. Dube's survey in Quebec was also discontinued at about the same time.

Subsequently in late 1987, M. Schwartz at San Francisco State University corresponded with W. Kennard, M.T. Vittum, and R.C. Wakefield asking for permission to contact all of the former NE-135 observers for inclusion in an interim network, pending new funding. Approximately 75 observers responded to a renewed survey sent out in March 1988, returning lilac and honeysuckle information for 1988, and in many cases 1987 as well. Currently "Eastern network" data collection continues from about 50 observers, but without permanent funding. L. Perry at Vermont has supplied lilac clones (from some of the original plants–Plumfield Nurseries has also gone out of business) and honeysuckles have been obtained from Jung Nurseries of Randolph, Wis. for re-expansions of the network over the past 2 years. This included an "extension" of four sites in Alberta through the cooperation of E. Beaubien, who heads a wildflower phenology survey in that province. Finally, all of the data collected in Eastern phenology projects since 1961 (except Quebec), are available in PC-computer compatible form.

Regional modeling and monitoring research

In order to be most effective as a global monitoring system, phenological data would ideally be available for all stations in a broadly distributed data gathering network over an extended period of time. Due to the changing character of phenological projects in eastern North America, relatively few stations have a continuous period of recording over more than 15 years. An example of these stations is Dickinson, North Dakota (46.88° N, 102.80° W), and this single site shows an intriguing trend toward earlier first leaf dates over the 1962–1992 period (Fig. 2).

When lacking complete period-of-record phenological information, one way of exploring trends on a regional basis is to develop analog models. While less accurate than actual plant data, such models can be designed to simulate phenological events using meteorological data. This allows missing data to be estimated, and also provides a means to explore phenological responses during historical periods when weather but not plant data are available. Schwartz and Marotz (1986) developed regional phenological models for the lilac first leaf event across eastern North America, using data collected by the regional phenology networks. The best predictive model incorporated the number of "high-degree-day accumulation events" (related to the passage of certain types of synoptic weather systems) as a better indicator of heat accumulation, rather than standard degree-day totals. Subsequently, Schwartz and Marotz (1988) recognized the important contribution of synoptic events that occur in the week before first leaf ("capstones"). Both studies demonstrated that regional phenological models can be produced with acceptable error (mean absolute error of 6.5 days or less), so that phenological information over large areas can be approximated from weather data. Schwartz (1990) combined models for the two honeysuckle clones with the lilac model, in order to produce a provisional "spring index" (the average first leaf date among the three plants), which was shown to be related to changes in springtime temperature trends in the lower atmosphere.

Schwartz and Karl (1990) and Schwartz (1992) began to explore the physical mechanisms in the atmosphere which might be interacting with first leaf (spring green-up or green wave) phenology. Significant changes in the characteristics of lower atmospheric thickness, moisture, visibility, and winds all occur in conjunction with green wave passage. A major implication of these studies is that when the mid-latitude biosphere "turns on" in the spring, the character of the lower atmosphere changes enough to be detectable as discontinuities in conventional weather records. Perhaps equally important, phenological data identified the timing of these changes in the physical nature of the lower atmosphere (e.g., Fig. 3). This suggests the important role that phenological information could play in detecting changes in the atmosphere, such as variations in the timing of the winter-spring seasonal transition.

Current research

The spring index model is currently being used to reconstruct a first approximation of the green wave in the eastern United States from 1908 to the present, using data from the daily Historical Climate Network (HCN;

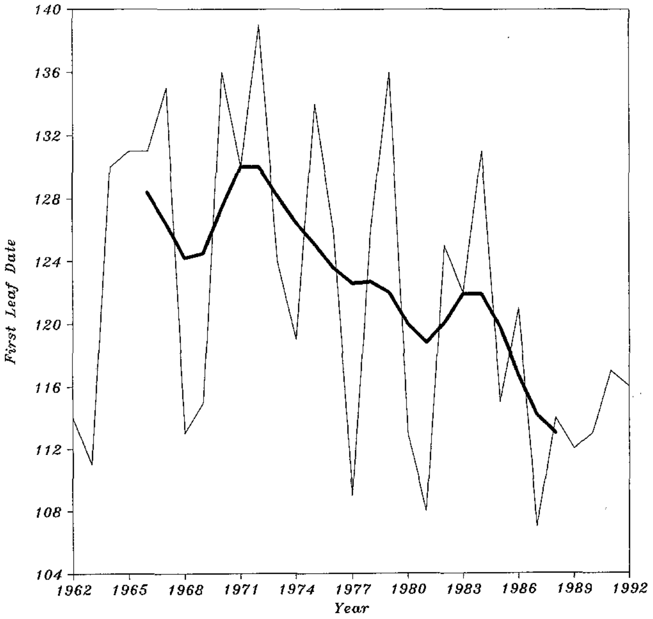

Fig. 2 First leaf date (days after previous 31 December) for Dickinson, ND 1962–1992 (the dark line shows a nine-year moving average)

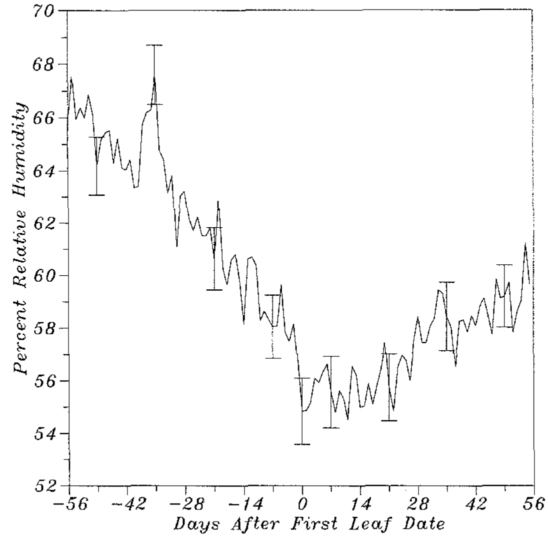

Fig. 3 Median p.m. relative humidity, averaged for twelve stations distributed across eastern North America over the period 1961–1986 by days after lilac first leaf date ($n=237$), for more information on the data base, refer to Schwartz 1992); ±1 standard error bars are shown at selected intervals

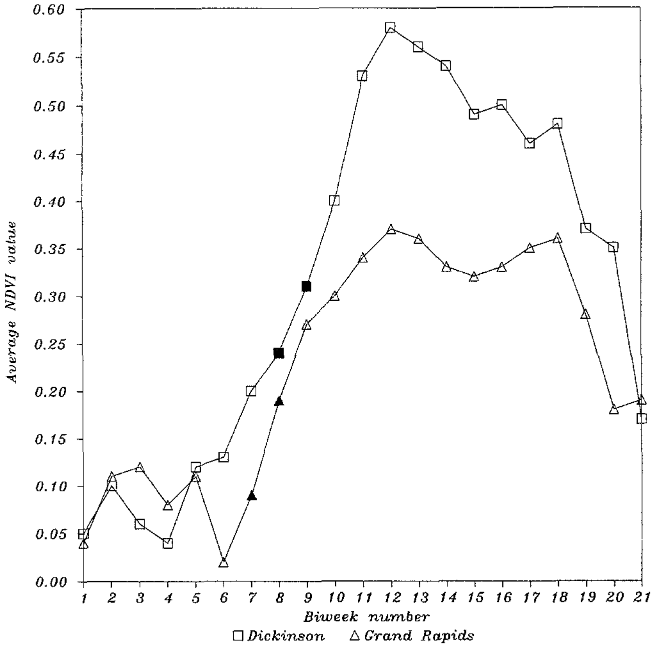

Fig. 4 An example comparison of lilac surface phenology to Normalized Difference Vegetation Index (NDVI) information derived from the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) series satellites. The first *darkened symbol* represents the time of first leaf emergence, and the second the time of 95% leaf emergence for lilac at Dickinson, North Dakota (46.88° N, 102.80° W) and Grand Rapids, Minnesota (47.23° N, 93.50° W) in 1987. Biweeks are roughly 2-week intervals over which the largest NDVI value from the satellite data is chosen, with biweek 1 corresponding with the first 2 weeks of the year. For more information on the NDVI, please refer to Goward (1989)

Hughes et al. 1992). The utility of this approach is being supplemented by additionally calculating the last −2.2° C frost date, and then combining the two dates to produce a new measure (spring index date minus last frost date) for each station-year. This difference is termed the "damage index" because yearly departures from its normal values (in days) should be related to the potential agricultural damage from frost. The main thrust of this research project is to look for trends in these green wave-related data, and so far the results are uncertain. Preliminarily, the most recent years show a noteworthy change toward earlier last frost dates, but less clear trends for the spring index and damage index.

Discussion and recommendations

The research projects discussed in this paper have barely explored a few of the potential applications of phenology to global change monitoring, and then only for the first leaf (green-up related) event. Additionally, much of the work had to be performed with phenological analog models, derived from weather data, because of the lack of complete phenological data sets. Little has been done to address agricultural applications, which were the initial driving force behind the North American phenological networks (Hopp 1978). Nevertheless, these results (together with numerous examples from phenological literature–summarized in Lieth 1974) show that phenological data have the potential to monitor long-term changes of the mid-latitude biosphere, and also detect annual variations in atmospheric features, such as the winter-spring seasonal transition.

With these potential applications in mind, several new research projects are well along in the planning process. Firstly the spring index model, although performing surprisingly well, was meant to be a "preliminary" model. Therefore, a new round of model building is needed to solidify the physical basis of the model and also improve its predictive accuracy. The new models will incorporate results from growth chamber experiments (underway by L. Perry at Vermont) and previous research (Schwartz and Karl 1990; Schwartz 1992). Secondly, perhaps the greatest contribution of phenology to studies monitoring global change will be in conjunction with remotely sensed satellite observations (using measures such as the Normalized Difference Vegetation Index, NDVI).

The satellite view is global and integrating, and therefore observes "broad-brush" changes in ecosystem dynamics. These features make them well suited for gathering many of the kinds of general biospheric information needed for global change models (Reed et al. 1994). What satellites cannot observe is the details driving the events they monitor; therefore unless global biospheric changes are quite profound, they are likely to be missed by satellite observations, and this is the area where phenology can contribute (e.g. Fig. 4). Satellite observations have to be typically combined into 2-week composites to deal with the problems of cloud cover

(Goward 1989; Reed et al. 1994). Over 14 days, the green wave in eastern North America travels an average of 300 km, and can travel as far as 450 km. The use of average (30-year normal) climate data as a method of estimating phenological responses could be problematic, since green wave passage at a single location can vary up to 1.5 months between years (Schwartz and Karl 1990). Actual phenological information, however, can be used to "calibrate" the satellite information at each site, and provide for a better physical interpretation of what is being seen through remote sensing.

Phenological data for a small set of indicator species (and corresponding physically based models) will supply the "missing link" for satellite-based observations of the mid-latitude biosphere, by showing the connection to "ground truth", and more importantly addressing the specific question of why (in terms of a physical connection) remotely sensed changes are occurring. A project is planned that will complement the investigation by Reed et al. (1994) of NDVI-derived phenology, by determining the relationship of surface green wave phenology with this NDVI phenology. Selected ground-based phenological events (in this case lilac and honeysuckle first leaf) will be "calibrated" in terms of their relationship to NDVI/derived phenology, and then used to extend the information-gathering capabilities of the satellite across several North American biomes. Within single biomes, the addition of representative species phenology (such as the wild flowers in Alberta's phenological survey) could be used, in principle, to convert general satellite data into specific and meaningful physical interpretations. The preliminary work has been done, and the potential contributions of phenology to global change studies are ready to be implemented throughout the mid-latitudes. In order to realize these goals, new networks for the collection of phenological data must be initiated. This will not be possible without the cooperation of a global network of interested scientists, and at least limited governmental support.

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