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PLANT PHENOLOGY IN CANADA and CHINA:
BIOMONITOR FOR CLIMATE CHANGE

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ABSTRACT: The timing of spring plant development can be considered to be the most sensitive and easily-observed indicator of the biotic response to climate change. Spring bloom and leafing dates for perennial plants are largely controlled by heat accumulation, and trends in these dates can help reveal the rate of climate warming. These phenology data have been recorded in Canada for over a century, while the record in China goes back 3000 years. Analyses of phenology data show trends to an earlier onset of spring development in many temperate areas of the world, particularly over the last three decades. This trend has been detected also by remote sensing. Impacted sectors of society and the environment could include agriculture, forestry (including carbon sequestration), human health (for example, allergy seasonality), and biodiversity. Ecological implications include impacts at the level of species, populations, communities and ecosystems. Canada's Plantwatch program (www.plantwatch.ca) is coordinated by the Canadian government, educational institutions and non-profit organizations, and targets the public to report phenology for selected indicator plants. The Chinese Meteorological Agency currently has 400 stations tracking phenology. Future cooperation to establish observation of key indicator plant species on a wide geographic basis could greatly enhance our understanding of the effects of climate change.

Keywords: Agriculture, Bloom timing, Canada, China, Climate change, Forestry, Health, Phenology, Plantwatch, Remote sensing

1. Introduction

Plant phenology provides a useful tool to measure the effects of climate change. The rate of species development in spring is largely influenced by temperature, and trends to earlier development are being seen across much of our globe's temperate zone (Peñuelas and Filella 2001). Phenological data gathered by networks date back a century in Canada, and the current Plantwatch program has the potential to engage many Canadians in tracking the "green wave of spring" (Schwartz and Beaubien, 2003). In China the phenological record goes back 3000 years. It has been used to create calendars to guide farmers, and more recently to reveal historic climate change. Plant phenology and remotely sensed NDVI (normalized differential vegetation index) data for northern China have been linked to predict the effects of increased temperatures on the lengthening of the growing season.

Observed shifts in phenology have potential impacts on the economy through effects on sectors as diverse as agriculture, forestry, and human health. If this cost-effective method of tracking environmental change can be enhanced with cooperation between Canada and China, it will greatly increase our ability to track biotic change in space and time.

2. Plant Phenology

Phenology, the study of the seasonal timing of life cycle events, provides data useful in a variety of applications. The timing of spring plant development is considered to be the simplest, most sensitive and easily-observed biotic response to climate change. These data can also assist in decision-making and adaptation to change for agriculture, forestry, human health and tourism, and as validation for remote sensing imagery.

The variables tracked by phenology studies include stages of plant development such as timing of bud break, leafing, first bloom, full bloom and leaf colouring. In the zoological realm, examples of events recorded include timing of bird arrival, nesting and fledging, as well as insect development stages and mammal migration, reproduction and hibernation.

The timing of spring development of perennial plants in temperate zones of the earth is largely driven by accumulated temperature above a threshold value (Rathcke and Lacey, 1985). Photoperiod plays a greater role in the timing of late summer stages such as fruiting and leaf colouring. Moisture seems to have little effect on phenology in temperate zones (Menzel, 2003b). Because other organisms such as insects also develop in spring in response to temperature, the sequence of species development across trophic levels is largely consistent and predictable (Lieth, 1974).

3. Phenology in Canada

3.1 History in Canada

After deglaciation approximately 10,000 years ago, Canada was occupied by aboriginal peoples who depended on hunting, fishing, and collection of berries, roots and other plant products. Knowledge of the best timing for these activities enhanced these First Nations' chances of survival. Traditional knowledge of phenological calendars, or the timing and sequence of natural events, was passed down orally to successive generations. In British Columbia, ethnobotanic research has found over 140 phenological indicators among more than 20 First Nation linguistic groups, where a growth stage of one organism was used to predict a phase of another organism that was an important resource. Examples included prediction of the spawning time of salmonid fish, readiness for harvesting (in terms of adequate fat content) of certain animals, and availability of clams, berries or seaweed (Lantz and Turner, 2003).

In 1891, the Royal Society of Canada launched the first extensive survey of phenology in Canada (where extensive is defined as a survey involving many observers, for many years, and over a wide geographic area). Events tracked by volunteers included the timing of plant blooms, bird arrivals, freeze and thaw of lakes and rivers, and thunderstorms. The Botanical Club of Canada coordinated the survey until 1910, followed by the Canadian Meteorological Survey until 1922. Results were published annually in the Proceedings and Transactions of the Royal Society of Canada.

The next large survey was Canadian involvement in the United States' Regional Agricultural Experiment Station Regional projects. The projects began in the USA in the 1950's. In 1970, stations in several eastern Canadian provinces were added and continued at some stations through 1986. Phenological observations of lilac and honeysuckle continued until 1977. At that time, the Canadian province of Quebec had the largest participation of any state or province with 300 locations, of which about 50 were located at meteorological stations. This data was used by Dr. P. A. Dubé of Laval University to define bioclimatic and agricultural taxation zones in Quebec (Schwartz and Beaubien, 2003).

3.2 Plantwatch

Plantwatch in Canada began at the University of Alberta in 1995, a natural addition to the Alberta Wildflower Survey initiated by Beaubien in 1987. Plantwatch engaged Canadians in tracking bloom times of eight key species and reporting via the Internet, at www.devonian.ualberta.ca/pwatch (Beaubien and Freeland, 2000). One of the species, the common purple lilac (Syringa vulgaris), was tracked internationally. A teacher's guide was posted on this website in 2001, providing curriculum adaptations in science, mathematics, and social studies.

Beginning in 2000, PlantWatch expanded with assistance from Environment Canada's Ecological Monitoring and Assessment Network Coordinating Office and the Canadian Nature Federation. There are now coordinators who work on a volunteer basis in each of Canada's 13 provinces and territories. Promotional materials have been produced including a booklet "Plantwatch: Canada in Bloom" and a website is maintained where data is reported and the results can be viewed immediately on a map (www.plantwatch.ca). Canadians can choose to observe up to 15 widespread indicator plant species and many other regional species as well.

Global circulation modeling predicts that global warming will show the largest and fastest increases in northern ecosystems (Maxwell, 1992). To boost observation of the plant response, the northern Plantwatch coordinators have successfully combined forces and secured funding from Environment Canada's Northern Ecosystem Initiative program. Plantwatch North posters and booklets (Morin et al., 2003) have been produced in the English, French and Inuktitut languages. However, the progress of Plantwatch on the national scale is currently hindered by a lack of funding. There is no funding for coordinators to do the annual tasks of promotion and fundraising, as well as volunteer and data management, and progress is therefore intermittent.

3.3 Trends in phenology

Trends to an earlier spring have been noted in western Canada. An index of spring flowering was calculated as an annual mean of first bloom dates for three woody species, *Populus tremuloides* (aspen poplar), *Amelanchier alnifolia* (saskatoon or service berry) and *Prunus virginiana* (chokecherry). Data for the period 1936-1996 for Edmonton, Alberta revealed that bloom time has become earlier by eight days, while the tree species that blooms at the very start of spring, *P. tremuloides,* is blooming earlier by almost a month over the last century. Alberta's prevailing winds come from the west from the Pacific Ocean, and El Niño climatic events have an influence on the phenological response. Years of medium or strong El Niño events are also years of early bloom in Alberta (Beaubien and Freeland, 2000). Bloom time of Macintosh apples in Summerland, British Columbia shows a five day trend to earliness over the years 1936 to 2000 (Beaubien and Hall-Beyer, 2003).

In eastern Canada shifts to earlier bloom have as yet not been reported in keeping with temperature and other climate variables. In Nova Scotia

Plantwatch data for 1996-1998 were compared with historic data from the early 1900's, and significant differences in bloom time were not found for most plant species (Vasseur et al., 2001). Schwartz and Reiter (2000) show results for trends in eastern Canada over the 1959-1993 period.

These trends are not limited to plants. The timing of egg-laying in tree swallows *(Tachycineta bicolour)* across North America showed an advance in dates of up to nine days (1959-1991), which is attributed to increased temperatures during that period (Dunn and Winkler, 1999). Data from southern Ontario suggests that climate warming of 5 degrees Celsius in May could result in tree swallows laying eggs about one week earlier (Hussell, 2003).

4. Phenology in China

4.1 Observation networks

Modern phenological observation and research in China started in the 1920s with Dr. Kezhen Zhu (1890-1974). Beginning in 1921, Zhu observed spring phenophases of several trees and birds in Nanjing, China. (A phenophase is an easily observed growth stage). In 1931, Zhu summarized phenological knowledge from the last 3000 years in China. He also introduced phenological principles developed in Europe and the United States from the mid eighteenth to the early twentieth century (Zhu, 1931).

In 1934, Zhu organized and established the first phenological network in China. Observations of some 21 species of wild plants, nine species of fauna, some crops, and several hydro-meteorological events continued until 1937 when they ceased at the start of the War of Resistance against Japan (1937-1945). Twenty-five years later, in 1963, the Chinese Academy of Sciences (CAS) established a countrywide phenological network which continued until 1996. In 2003, phenological observations resumed again with a reduced number of stations. This observation program included a total of 173 observed species. Of these, 127 species of woody and herbaceous plants had a localized distribution. There were 33 species of woody plants, two species of herbaceous plants, and 11 species of fauna observed widely across the network (Institute of Geography, Chinese Academy of Sciences, 1965).

The Chinese Meteorological Administration (CMA) established another countrywide phenological network in the 1980s. This network is affiliated with the national-level agrometeorological monitoring network. The phenological observation criteria for woody and herbaceous plants and fauna were adopted from the Chinese Academy of Sciences network. In addition to phenological observations of native plant species, the network also carries out phenological observation of crops (National Meteorological Administration, 1993). There were 587 agrometeorological measurement stations in 1990. As the phenological and meteorological observations are parallel in this network, the data are especially valuable for understanding phenology-climate relationships. These data can also be used to provide agrometeorological services with predictions on crop yield, soil moisture and irrigation amounts, plant diseases and insect pests as well as forest fire danger (Cheng et al., 1993).

4.2 Traditional research

Traditional phenology research in China focuses mainly on compiling phenological calendars, defining phenological seasons, phenological mapping, detecting historical climate using phenological data, as well as phenological modeling and prediction.

Zhu and Wan (1973) compiled a phenological calendar based on observational data from 1950 to 1972 in Beijing, China consisting of the average, earliest, and latest dates of 129 phenological events. In the 1980s, the Institute of Geography at the Chinese Academy of Sciences devised uniform criteria to compile phenological calendars at stations of the Chinese Academy of Sciences network. Altogether 45 phenological calendars in China were published (Wan, 1986; 1987). In each calendar, the main phenological events of plants and fauna, together with hydro-climatic events, were chosen to represent an ordinal succession of phenophases in the annual cycle at each station.

In order to detect the spatial difference of phenological occurrence dates in a relatively small area, a specific observation network of ~17,000 km^2 was established in the Beijing area. Based on the observed data for 1979-1987 of this network, 16 phenological calendars were published (Yang and Chen, 1995). In order to represent the most detailed and continuous succession of phenophases, each phenological calendar in this area included almost all observed phenological occurrence dates. The results showed that the spatial difference of the average occurrence dates of a spring phenophase was three to seven days between urban and rural areas on the plain, but increased to ten days to one month between plain and mountain areas. Generally speaking, phenophases during spring and summer appeared first in the urban area and then in rural and mountainous areas. In contrast, phenophases during autumn and early winter appeared first in mountainous and rural areas and then in the urban area.

An earlier method for determining phenological seasons was developed by Wan (1986). In order to be able to compare phenological seasons among different stations, both temperature and phenology indicators were used. Daily mean temperatures of 3 degrees Celsius and 19 degrees Celsius were thresholds indicating the beginning dates of spring and summer, whereas 19 degrees Celsius and 10 degrees Celsius were thresholds indicating the beginning dates of autumn and winter. Beginning dates of sub-seasons were also defined using other specific temperature thresholds. Phenological indicators for the beginning dates of the temperature seasons were determined by reference to the local phenological calendar. However, the same plant phenophase occurred under different air temperatures in different areas (Japanese Agrometeorological Society, 1963; Reader et al., 1974).

In order to determine phenological seasons accurately, a new procedure called "phenological frequency distribution pattern" was developed at Beijing, China (Chen and Cao, 1999). The mixed data set was composed of phenological

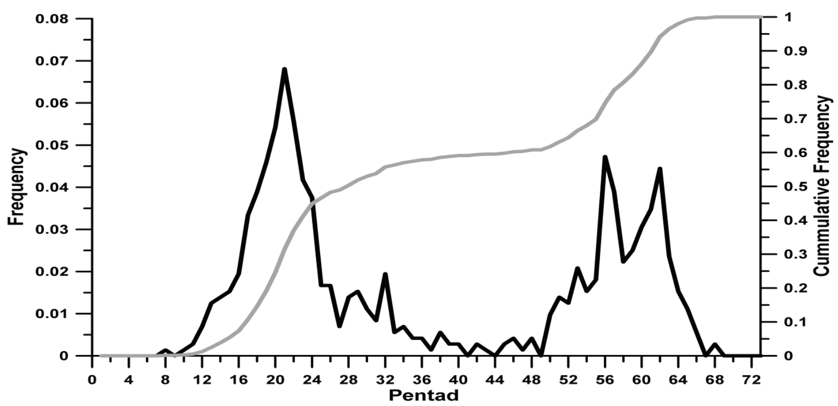

FIGURE 1

Frequency (black, left scale) and cumulative frequency curve (gray, right scale) of phenophases in Beijing (1979-1987).

occurrence dates of all observed deciduous trees and shrubs, including bud-burst, first leaf unfolding, 50 percent leaf unfolding, first bloom, 50 percent bloom, the end of blooming, fruit or seed maturing, fruit or seed shedding, first leaf coloration, full leaf coloration, first defoliation and the end of defoliation. Sequential and overlapping occurrences of phenophases represent seasonal succession of the local plant community. From these data, the frequency and cumulative frequency of phenophases in every five-day period, or pentad, throughout the year are calculated. Phenological seasons could be identified according to the turning point of the empirical cumulative frequency curve, the changing rates of phenological cumulative frequency, and fluctuation patterns of phenological frequency (see Figure 1).

Zhu (1973) pioneered revealing historical climate change using phenological evidence in China. Using ancient phenological data and other data, he reconstructed a temperature series of the past 5000 years in China. Three main results were shown. Firstly, during the initial 2000 years, the annual mean temperature in most eras may have been 2 degrees Celsius higher than the present with the winter temperature being 3-5 degrees Celsius higher. Secondly, there were several fluctuations towards lower temperatures in 1000 B.C., 400 A.D., 1200 A.D. and 1700 A.D. with an amplitude of 1-2 degrees Celsius. Thirdly, in each period of 400-800 years, several smaller cycles of 50-100 years with an amplitude of 0.5-1 degrees Celsius could be identified. A strong agreement was found between Zhu's temperature series and the temperature series obtained by variations of the isotope O^{18} content of the Greenland ice sheet during the last 1700 years (Zhu, 1973).

Approximately 200 kinds of archaic personal diaries remain in the Chinese literature, and 10-20 percent of them contain phenological data. Using the historical phenological data and other evidence, as well as the modern phenological data since 1950, Gong et al. (1984) reconstructed the spring phenological series from 1849 to 1981 in Beijing, China. The statistical analyses indicated that there were 7.4-year, 4-year, and 2-year cycles in the time series.
Statistical models can simulate temporal and spatial phenological performance. In order to predict flowering dates, linear regression equations were established between flowering dates of different trees in Beijing (Yang and Chen, 1985) and in North China (Chen and Yang 1988; Chen 1990). Another kind of statistical model was constructed between the average occurrence date of a phenophase and geographical coordinates at different stations.

Based on a linear regression equation established between average occurrence date of a phenophase and annual mean temperature at all stations, the possible effects of a temperature rise of 0.5 degrees Celsius, 1.0 degrees Celsius, 1.5 degrees Celsius, 2.0 degrees Celsius, and the doubling of the atmospheric carbon dioxide concentration scenario on plant phenology were extrapolated. Results showed that the corresponding phenophases may advance 4-6 days in spring and summer, and delay 4-6 days in autumn under the scenario of doubled carbon dioxide concentration in the atmosphere (Zhang, 1995).

4.3 Growing season and climate change

The climate of the earth has warmed by about 0.6 degrees Celsius over the last century. The period of warming from 1976 onwards shows the fastest rate of increase of any warming period over the last 1000 years (IPCC, 2001). A temperature-related shift in response was detected in a survey of 143 studies of plants and animals, and over 80 percent of these species showed changes or shifts in the expected direction (Root et al., 2003).

In recent years, determining the growing season of land vegetation at a large scale has become an important scientific question for global climate change research. Several studies have shown a lengthening of the growing season in the Northern Hemisphere (Keeling et al., 1996; Myneni et al., 1997; Zhou et al., 2001). These results are also supported by surface phenological observation of individual plant species in Europe (Menzel and Fabian, 1999; Peñuelas et al., 2002) and North America (Schwartz and Reiter, 2000). However, before a detailed integrative comparison between surface vegetation dynamics and remote sensing reflectance values (such as the normalized difference vegetation index or NDVI) can be carried out, a relationship between these measurements must be established at the regional scale. Therefore there is merit in first determining the temporal relationship of surface green wave phenology with NDVI phenology (Schwartz, 1994). Because current understanding of how well satellite sensor-derived greenness actually represents ground phenology is relatively poor (Markon et al., 1995), Chen et al. (2000, 2001) proposed a new statistical procedure to determine the growing season based on plant phenological and NDVI data at three sample sites, and assessed its feasibility in extrapolating the growing season from the sample sites to other sites in northern China (see Figure 2).

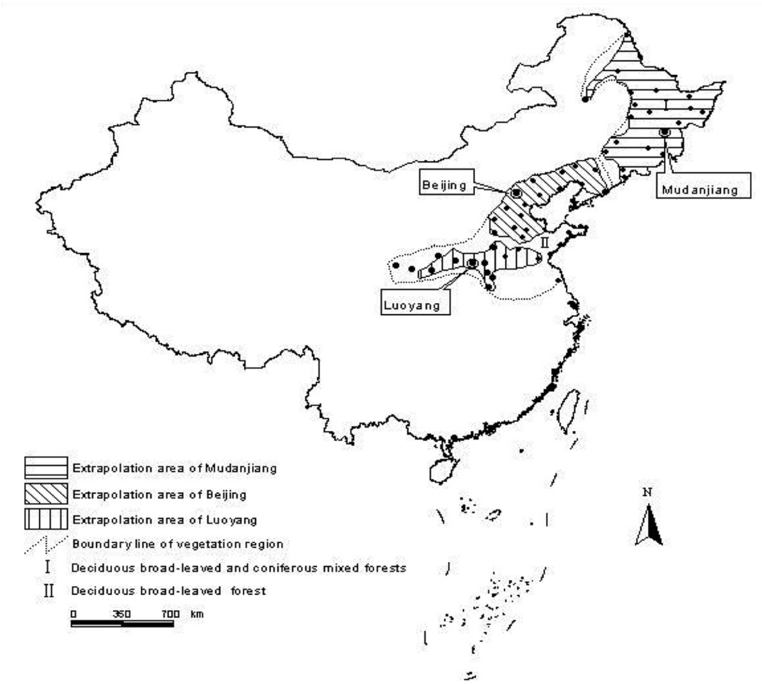

FIGURE 2

Sample sites and spatial extrapolation areas of the growing season in northern China (1983)

In order to explore phenology-climate relationships at the plant community level, a correlation analysis was undertaken to compare the beginning of the growing season, the end of the growing season, the length of the growing season, and seasonal climate variables (Chen and Pan, 2002). The beginning of the growing season is influenced mainly by mean air temperature and growing degree days above 5°Celsius from January to March at Beijing and Luoyang, China and from February to April at Mudanjiang, China. The overall negative correlation indicates that higher mean temperatures and growing degree day totals in late winter and spring may induce an earlier onset of the phenological growing seasons of local plant communities. However there is no significant correlation between the beginning of the growing season and seasonal precipitation.

On average, if annual mean temperature and mean temperature during late winter and spring increase by 1 degree Celsius, the growing seasons would lengthen 6.7-7.2 days and 10.4-11.5 days, respectively, while if annual total growing degree days increases 100 degree days, the growing seasons would lengthen 4-5 days. Since the growing season length models were based on the spatial-temporal series of all three sample sites, they should not only be useful to estimate the response of the growing season to climate change at the sample sites but also at other adjacent sites with similar vegetation dynamics and climate conditions.

5. Trends in phenology from other parts of the world

Schwartz and Reiter (2000) used modeled and actual lilac data for 1959-1993 and found an average 5 to 6 day advance in onset of spring in North America. The greatest trend noted was in the northeast and northwest. In the western USA, increases in temperature of 1 to 3 degrees Celsius began in the 1970's, coincident with earlier streamflow pulse dates, and with earlier bloom of lilac and honeysuckle of 0.15 to 0.35 days per year (Cayan et al., 2001). Bradley et al. (1999) found an average of 0.12 days per year advance in phenological data for plants and birds in southern Wisconsin from 1936 to 1998. These data included a 30 year gap.

Over the last decades a lengthening of the growing season is evident in the phenological record, and also in remote sensing data, temperature data, and atmospheric carbon dioxide concentration records (Menzel, 2003b). In the mid 1970's there is a flex point in both temperature and phenological data, where temperatures started an upward swing and phenological events shifted to earlier onset (Peñuelas and Filella, 2001). A study of precise phenological data obtained from International Phenological Gardens from Scandinavia to Greece (1959-1993) showed an 11 day trend to a longer growing season. An earlier arrival of spring by six days was also seen (Menzel and Fabian, 1999). In northern and central Europe the timing of some spring events such as growing season start can be correlated with values of the NAO (North Atlantic Oscillation) index related to winter climatic conditions (Menzel, 2003a).

Phenological responses to temperature are similar in plants and birds, as shown by data on spring arrival of birds, hatching of flycatchers, and leaf unfolding in birch and horse chestnut trees in Germany (Walther et al., 2002). Regional climate trends can also be different even within a small area (Schwartz, 1999).

While for most of Europe Spring is arriving earlier, certain areas such as southeastern Europe are showing a delayed spring response (Menzel and Fabijan, 1999).

Europe has much long-term data in phenology as shown in the review by Menzel (Menzel, 2003a). In the last decade, two vigorous new observation networks, both called "Nature's Calendar" and involving thousands of observers, have been created in the United Kingdom (www.phenology.org.uk) and the Netherlands (www.natuurkalender.nl).

6. Implications of shifts in phenology

Environmental change is one major possible result of shifts in phenology. Using observed and predicted shifts in climate and in phenology, Lechowicz (2001) notes that species could respond in three possible ways. Firstly, they could migrate to climatic areas that suit their suite of phenological responses. Movement of plant species is limited by many factors including reproductive strategies and suitability of the substrate in the new region. In temperate and Arctic zones there could be a shift of vegetation communities upwards in altitude, and towards the Poles. These shifts have occurred across a wide range of taxonomic groups including high latitude plants, many species of butterflies, and red and arctic foxes. As well the position of treeline has moved (Walther et al., 2002).

Secondly, plant species can stay where they are and exploit what genetic variability they have to adapt to the changing conditions. Thirdly, if species are unsuccessful in adapting to new conditions of climate and habitat, they will lose their dominance position in the plant community, or disappear. Changes at the species level will impact communities and ecosystems in unknown ways. The synergism of temperature increases, habitat destruction, and other possible stresses such as pollution and invasive species will result in differential species responses and lead to many extirpations and possibly extinctions (Root et al., 2003).

Species respond to abiotic factors in different ways. Changes in ecological partnerships such as decoupling of species interactions, including pollination, predator-prey relations, etc., can be expected. For many birds, photoperiod, which is unaffected by climate change, triggers the start of migration. If their food supply is available earlier over time as a result of climate warming, nestling survival could be jeopardized.

There are a number of other implications of shifts in phenology. Climate change, including warming, results in changes in carbon uptake and sequestration and has impacts on the global carbon cycle. In the area of human health, changes in the timing of pollen seasons and potential lengthening of the growing season could extend the allergy season in temperate climates. In agriculture, changes in climate and the phenological response affect the incidence of new pests and diseases, timing of fertilization and irrigation, suitability of new crops, timing of crop protection, and quality of produce. In forestry, changes in phenology will impact fire incidence and fuel availability. Phenology data is essential for modeling of mixed forest growth (Rötzer et al., 2004) and for modeling the future distribution of tree species (Chuine and Beaubien, 2001).

7. Benefits of future cooperation between Canada and China and with other countries

The tracking plant phenology provides a cost-effective way to track ecological changes resulting from climate change. Other changes such as shifts in species distributions, populations or communities will be more difficult and costly to detect (Menzel, 2003b).

Phenological research is essential to understand the dynamics of climate change. To track biotic response change over a wide geographic area, networks of public observers combined with more technical observers should be sought. These skilled observers could be found at research stations for meteorology, agriculture, or forestry, at university biological stations and at national parks and botanic gardens.

Phenological data are useful to monitor ecosystems and understand the dynamics of plant communities and thus animal communities. These data can be used to plan landscape design, prevent garden and crop pests and diseases, optimize the timing of farm activities, provide ground validation for remote sensing images, and even assist in planning for tourism. China has experience in the application of phenological calendars and data modeling that may help agriculture become more sustainable.

What is needed is a global observation system of common plants, including both native plants and cloned cultivars, integrated into the meteorological services around the world (Schwartz, 2003). This program would likely be most useful in the temperate zone where phenology is largely driven by temperature.

A Global Phenological Monitoring (GPM) program was started in 1998 using cloned plant cultivars and 15 gardens now exist for this purpose in Asia, Europe, and the United States (Bruns et al., 2003).

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