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EXAMINING SPRING AND AUTUMN PHENOLOGY IN A TEMPERATE DECIDUOUS URBAN WOODLOT

by

Rong Yu

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Abstract

EXAMINING SPRING AND AUTUMN PHENOLOGY IN A TEMPERATE DECIDUOUS URBAN WOODLOT

by

Rong Yu

The University of Wisconsin - Milwaukee, 2013
Under the Supervision of Distinguished Professor Mark D. Schwartz

This dissertation is an intensive phenological study in a temperate deciduous urban woodlot over six consecutive years (2007-2012). It explores three important topics related to spring and autumn phenology, as well as ground and remote sensing phenology. First, it examines key climatic factors influencing spring and autumn phenology by conducting phenological observations four days a week and recording daily microclimate measurements. Second, it investigates the differences in phenological responses between an urban woodlot and a rural forest by employing comparative basswood phenological data. Finally, it bridges ground visual phenology and remote sensing derived phenological changes by using the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) derived from the Moderate Resolution Imaging Spectro-radiometer (MODIS).

The primary outcomes are as follows: 1) empirical spatial regression models for two dominant tree species - basswood and white ash - have been built and analyzed to detect spatial patterns and possible causes of phenological change; the results show that local urban settings significantly affect phenology; 2) empirical phenological progression models have been built for each species and the community as a whole to examine how phenology develops in spring and autumn; the results indicate that the critical factor influencing spring phenology is AGDD (accumulated growing degree-days) and for autumn phenology, ACDD (accumulated chilling degree-days) and day length; and 3) satellite derived phenological changes have been compared with ground visual community phenology in both spring and autumn seasons, and the results confirm that both NDVI and EVI depict vegetation dynamics well and therefore have corresponding phenological meanings.

Dedication

TO MY PARENTS
AND TO MY GRANDPARENTS

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LIST OF ACRONYMS

ACDD: Accumulated Chilling Degree-days

AGDD: Accumulated Growing Degree-days

AP: Accumulated precipitation

AVHRR: Advanced Very High Resolution Radiometer

BBCH: Biologische Bundesanstalt, Bundessortenamt and Chemical Industry

CDD: Chilling degree-days

DBH: Diameters at breast height

DMA: Delayed moving average

DMSP-OLS: Defense Satellite Meteorological Program – Operational Linescan System

DOY: Day of Year

DTR: Diurnal temperature range

EOS: End of the growing season

EVI: Enhanced Vegetation Index

ET: Evapotranspiration

FBB: Full bud burst

GDD: Growing degree-days

IPCC: Intergovernmental Panel on Climate Change

LOS: Length of the growing season

LP: Landscape Phenology

LSP: Land Surface Phenology

MAE: Mean absolute error

MODIS: Moderate Resolution Imaging Spectro-radiometer

NDVI: Normalized Difference Vegetation Index

NOAA: National Oceanic and Atmospheric Administration

PPFD: Photosynthetic photon flux density

RMSE: Root mean squared error

RS: Remote sensing

SI: Spring indices

SMN: Seasonal midpoint NDVI

SOS: Start of the season

ST: Soil temperature

USA-NPN: USA National Phenology Network

UWM: University of Wisconsin-Milwaukee

VIs: Vegetation Indices

WMA: Wildlife Management Area

1. Introduction

Phenology is the study of the annual biological cycles of plants and animals, and their relationships to climate and other environmental factors (Zhu & Wan, 1973; Lieth, 1974). During the past two decades, phenological research, supported by developments in computer science, remote sensing techniques, and Geographic Information Science, has played an increasingly crucial role in the study of global environmental change (Schwartz, 2003). Results from phenological studies around the world clearly demonstrate the impacts of changing temperature on wildlife (Thomas *et al.*, 2004; Thuiller *et al.*, 2008) and the feedback between shifting phenology and climate change (Penuelas *et al.*, 2009; Walther, 2010). The 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that "Phenology – the timing of seasonal activities of animals and plants - is perhaps the simplest process in which to track changes in the ecology of species in response to climate change" (Parry, 2007). Therefore, phenology is considered to be a biospheric global change indicator (Schwartz, 2003).

"Phenophases" and "phenological events" are the two key terms in phenological studies, but their definitions vary. In this study of spring and autumn tree phenology, the definitions of phenophases and phenological events follow those of the USA National Phenology Network (USA-NPN). Phenophases, also known as phenological phases, are annually cyclical biological phases of plants and animals that can be described by a start and end date, such as the leafing out of a willow tree, the blossoming of a cherry tree, the leaves coloring on an oak tree, or the migration of the American robin. (http://www.usanpn.org/glossary/term/16). In contrast, phenological events are precise start and end points of phenophases, such as the first leafing of a willow tree, the first blossoming of a cherry tree, the last leaf fall of an oak tree, or the first appearance of an American robin (http://www.usanpn.org/glossary/term/15).

Phenology has been particularly associated with agricultural activities since ancient times, dating as far back as 3000 years ago (Zhu & Wan, 1973; Chuine *et al.*, 2004). Even today in some remote villages of southwest China, farmers still follow the tradition of planting rice when swallows first return to the village to build nests. Modern phenological observations and research can be traced back to Carl von Linne, who first organized a phenological observation network with 18 stations in Sweden from 1750 to 1752 (Schnelle & Yang, 1965). Subsequently, many systematic phenological observation networks, mostly located at agricultural-meteorological observation stations, were gradually established in major European countries, the USA, Canada, China, Japan, and others (Schnelle & Yang, 1965). These networks mainly served agriculture and forestry purposes until the 1990s.

Scientific studies have consistently shown that warmer temperatures significantly influence land surface physical processes and biogeochemical cycles, and consequently impact ecosystems and human society (McCarty, 2001; Penuelas & Filella, 2001; Scheffer *et al.*, 2001; Walther *et al.*, 2002; Hughes *et al.*, 2003; Parmesan & Yohe, 2003; Root *et al.*, 2003; Thomas *et al.*, 2004; Root *et al.*, 2005; Thuiller *et al.*, 2005; Visser & Both, 2005; Parmesan, 2006; Intergovernmental Panel on Climate Change. Working Group I., 2007; Rosenzweig *et al.*, 2008; Tylianakis *et al.*, 2008; Visser, 2008; Witze, 2008; Wood, 2008; Loarie *et al.*, 2009; Walther, 2010; Donnelly *et al.*, 2011).

From 1906 to 2005, global mean surface temperature rose by 0.74°C (Bernstein, 2008); the years from 2000 to 2009 were the warmest years in the instrumental temperature record (Zhao & Running, 2010) and 2010 reached a new global mean temperature record (Hansen *et al.*, 2010). As a result, global warming and related fields have been of growing interest to scientists, particularly since the 1990s. In addition, the media, the general public, and governments have paid increasing attention to global warming and its potential impacts on ecosystems and human society.

This recent interest in phenology has been driven by climate warming, as phenology is one of the most important indicators of ambient temperature change (Sparks & Menzel, 2002). Given the strong association between climate and phenology, many phenological studies have focused on the impact of a range of climate drivers on changes in the growing season from the local to global scale (Reed *et al.*, 1994; Chmielewski & Rotzer, 2001; Norby *et al.*, 2003; Schwartz, 2003; Zhang *et al.*, 2004a; Menzel *et al.*, 2005). In different regions and continents an earlier onset of spring and a longer growing season has been confirmed in recent decades (Keeling *et al.*, 1996; Myneni *et al.*, 1997; Menzel & Fabian, 1999; Chuine *et al.*, 2000; Piao *et al.*, 2006; Christidis *et al.*, 2007; Piao *et al.*, 2007; Miller-Rushing & Primack, 2008; Rich *et al.*, 2008). Strong relationships have also been detected between increasing air temperature and advanced spring phenology (Sparks & Carey, 1995; Forchhammer *et al.*, 1998; Schwartz, 1998; Menzel & Fabian, 1999; Schwartz & Reed, 1999; Saxe *et al.*, 2001; Fitter & Fitter, 2002; Badeck *et al.*, 2004; Walther, 2004; Zhang *et al.*, 2004b; Linderholm, 2006; Menzel *et al.*, 2006; Schwartz *et al.*, 2006). Furthermore, it has also been determined that phenological responses to climate change vary widely among species (Parmesan, 2007). As a consequence, shifts in phenology could introduce mismatches in the timing between interdependent species (such as plants and pollinators, predators and prey) or between species and their abiotic environment (Stenseth & Mysterud, 2002; Visser & Both, 2005; Donnelly *et al.*, 2011). Phenological mismatches could cause ecological problems in both terrestrial and aquatic ecosystems by influencing ecological networks (Edwards & Richardson, 2004; Donnelly *et al.*, 2011). However, these mismatches in timing may not always be negative as opportunities for presently weak interactions may be strengthened or new relationships formed. Furthermore, Chuine and Beaubien (2001) confirm that phenology can serve as a key determining factor in a process-based model to predict tree species distributions. Therefore, the analysis and forecast of species to biome level phenology, especially the determination of start and end dates of the growing season, are essential for further understanding the changes and feedbacks within ecosystems under global warming.

This dissertation is centered on tree phenology, which is a key indicator of variations on individual species, plant communities, and ecosystems in response to climate and environmental changes (Schwartz, 1999). This study focuses on intensive spring and autumn phenological observations and analysis of an urban woodlot on the University of Wisconsin-Milwaukee campus in Milwaukee, WI. Combining ground visual phenological observation data with detailed climate measurements and remote sensing images, the study begins to build a spatially intensive phenological observation time-series in an urban area. The study site is positioned to detect phenological responses to the meteorological variation at the local scale and to refine the understanding of in situ and remote sensing data in an urban setting. By comparing the results from this research project with phenological measurements gathered in a forested area in northern Wisconsin, it is expected that differential phenological patterns will be revealed in response to site location, meteorological variation, and landscape context (urban woods versus rural forest).

One of the novel aspects of this study is that comparable intensive phenological observation campaigns do not appear to have been conducted in an urban setting. A few studies have examined the differences in phenological response between urban and rural areas from remote sensing to confirm that higher temperatures will lead to earlier phenology (White *et al.*, 2002; Zhang *et al.*, 2004c). Urban areas are where most human activity occurs and are certainly among the most disturbed parts of the Earth's surface. The urban heat island effect raises the air temperature above that of the rural areas, which can have an indirect impact on humans living in urban areas by altering the timing of phenological events. For example, under warm conditions the timing of pollen release is earlier, which will have an effect on allergy sufferers (Chuine & Belmonte, 2004). Furthermore, it is in urban areas that anthropogenic climate change has the most profound influence on the timing of phenological events (Lu *et al.*, 2006; Rosenzweig *et al.*, 2008). Therefore, this study attempts to more closely examine tree phenology in an urban setting and compare it with tree phenology in rural areas.

A second novel aspect of this study is that autumn phenology, compared to spring phenology, remains relatively poorly studied. There are fewer publications based on data from ground visual observations, remote sensing, or modeling specifically relating to autumn phenology (Walther *et al.*, 2002; Parmesan & Yohe, 2003). Autumn phenology observations are considered to be more variable and complicated to record than spring phenology due to the overriding influence of other climatic factors (Sparks & Menzel, 2002; Walther *et al.*, 2002). Nevertheless, in global change research, spring phenology and autumn phenology are of equal importance in determining the start and end dates of the growing season (Morisette *et al.*, 2009). Both are needed to set the precise switch dates of CO_2 assimilation/fixation for each year, which critically control the calculation of primary productivity (Richardson *et al.*, 2010), land surface physical processes, and biogeochemical cycles (Lechowicz, 1984, 237-263; Jonsson & Eklundh, 2004; Estrella & Menzel, 2006; Friedl *et al.*, 2006; Delpierre *et al.*, 2009; Penuelas *et al.*, 2009; Richardson *et al.*, 2012; Schwartz *et al.*, 2012). Thus, my research initiates an intensive autumn phenological study, finds the most important driving factors, and contributes to the development of local, regional and global climate prediction and modeling. As a result, this study will add new knowledge and insight regarding the interaction between environmental factors and autumn phenology in an urban setting.

The final novel aspect of this study is to explore ways of extracting canopy information from remote sensing images. Satellite data plays a crucial role in climate change and phenological research, because of their availability as sequential time series with full coverage of the Earth's surface. Over the past 20 years, Land surface phenology (LSP), a new branch of phenological studies, has been introduced and developed along with the technical developments of Earth observation systems, geographic information analysis, and computer science. In LSP studies, the two most commonly used satellite-derived measures are the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). NDVI is calculated by taking a ratio of the near-infrared and red bands to detect greenness changes of vegetation (Jensen, 2000). EVI is modified from the NDVI by adding the blue band to correct aerosol scattering and adding a factor to adjust soil influences (Jensen, 2000). NDVI and EVI curves are used to distinguish vegetation cover from other surface features and describe generally the annual growing cycle of vegetation (Xu, 2005). Studies have shown that the growing season or the onset of seasons from satellite detection vary under the impact of warmer temperatures (White *et al.*, 2002; Zhang *et al.*, 2003; Jin *et al.*, 2005; Gazal *et al.*, 2008; White *et al.*, 2009). NDVI and EVI, however, are limited by the spatial and temporal resolutions and the characteristics of integrated surface spectral reflectance signals. Therefore, they cannot provide 'precise' assessments of the onset and end of the growing season, or 'precise' phenological responses to climate at a local or regional scale (Chen *et al.*, 2005). In fact, very few studies have examined how remote sensing images or vegetation indices (VIs) correspond to spatially comparable phenological events on the ground (Liang & Schwartz, 2009; Liang *et al.*, 2011). Meanwhile, ground observation data are always limited by an inadequate number of observation locations and their uneven distribution (Chen *et al.*, 2005; Cleland *et al.*, 2007; Morisette *et al.*, 2009). To achieve the upward scale transition of surface observations (from plot to landscape, to regional, and eventually to global) and provide satellite-derived canopy reflectance data with phenological meaning, it is important to develop methods that can combine these two kinds of data. This study, therefore, attempts to link remote sensing derived phenological changes to ground visual observations.

In view of the above, important questions which deserve further examination arise regarding changes in phenophases and the nature of their driving mechanisms. For example, how does plant phenology respond to warming during spring and autumn in an urban setting? Since strong relationships have been reported between air temperature and some specific phenophases, such as bud burst and flowering, questions arise as to how air temperature influences the occurrence of the whole progression of spring phenology. Also, what are the major drivers triggering autumn phenology and how are these drivers influencing the whole progression of autumn phenology? How do we compare and combine the observational results from satellites and ground-based measures? According to the above and many other related questions, intensive and comprehensive phenological observations are needed in order to detect phenological patterns and processes, as well as the relationships between phenological events and their driving climatic and environmental factors. Specifically, the knowledge of how plant phenology corresponds to energy exchange, mass exchange, and climatic factors will provide more accurate contexts and parameters for plant development models and global or regional carbon budget calculations.

This study consists of three major sections related to tree phenology. The first topic concentrates on patterns and processes of spring and autumn phenology, explores their key climatic factors, and reveals their interrelationships. The second concerns different phenological responses to meteorological variation in an urban woodlot compared to a rural forest. The last topic explores ways to determine a meaningful link between satellite data and ground visual observations.

2. Literature Review

Current plant phenological research can be divided into three major fields: ground visual observation phenology, land surface phenology, and simulation phenology. Ground visual observation phenology involves in situ phenological observations conducted by the human eye or onsite camera sensing (Richardson *et al.*, 2007; Crimmins & Crimmins, 2008; Graham *et al.*, 2009; Richardson *et al.*, 2009). Land surface phenology (LSP), also known as remote sensing phenology, detects spatial patterns and temporal variations of vegetated surfaces by using remote sensing data (Friedl *et al.*, 2006). Simulation phenology examines spatial-temporal patterns in the past and forecasts spatial-temporal trends in the future by simulating phenology from climatic data.

For the purposes of this literature review, visual observation phenology and simulation phenology will be dealt with together as both are related to direct on site observation or recording of data. Hence, the literature review has been grouped into four sections. Section 2.1 introduces phenological studies based on ground observations and simulations. Section 2.2 presents phenological studies based on remote sensing data and analysis. Section 2.3 focuses on phenological studies of autumn phenophases. Finally, section 2.4 examines phenological studies in urban settings.

2.1 Ground visual observation and simulation phenology

Ground visual observation phenology is a traditional way to collect phenological data and can be categorized in three ways according to the size of the study area and the duration of the observation period: the “snapshot” study, the intensive study, and the extensive study (Schwartz & Beaubien, 2003, 61). Ground visual phenological observation is an activity consuming a large amount of time and labor, so most phenological observations have been conducted in an extensive way, "… in which a network of observers surveys a large area over a period of years" (Schwartz & Beaubien, 2003, 61). Only a few phenological studies concentrate on intensive phenological observations, "… in which one or a small number of people survey a small area over a period of one or more growing seasons" (Schwartz & Beaubien, 2003, 61). Simulation phenology is a way to extend spatial and temporal coverage of phenological analysis by using climate data to simulate the timing of particular phenophases.

Over the last three decades, traditional phenological studies have concentrated on detecting temporal trends and/or spatial patterns of phenology, as well as examining the relationships between the timing of phenological events (e.g. leaf unfolding, flowering) and lower atmospheric parameters (e.g. air temperature, relative humidity). Lower atmospheric parameters have long been thought of as important drivers triggering phenology, especially in mid-latitudes (Schnelle & Yang, 1965; Schwartz & Reiter, 2000). Most ground phenological studies focus on spring phenology because of its important and close relationship with agricultural activities (Zhu & Wan, 1973) and with climate change research in recent decades (Parmesan, 2007; Bertin, 2008; Schwartz *et al.*, 2012). Sparks and Menzel (2002) suggest that "… phenology is the most responsive aspect of nature to warming and the simplest to observe" (p. 1716). Therefore, the relationship between spring phenology and lower atmospheric parameters is an important issue in phenological research. On the other hand, despite the complexity of autumn phenology, scientists have also made efforts to look into its relationship with potential climatic drivers, such as temperature and CO_2 (Menzel *et al.*, 2006; Taylor *et al.*, 2008).

Shifts in the timing of phenophases have been demonstrated by numerous studies across different regions and continents. In North America, the onset of spring phenological events of plants and migratory birds showed an average advance of 0.12 days per year over a period of 61 years at a single-site in southern Wisconsin (Bradley *et al.*, 1999). Furthermore, *in situ* and modeled phenological data for lilac (*Syringa chinensis*) revealed an average 5-6 day earlier spring across North America with regional variations from 1959 to 1993 (Schwartz & Reiter, 2000). Regional differences of lilac phenology in spring advancement showed in northwestern USA-southwestern Canada, in the northeast USA-Canadian Atlantic provinces, and in the central USA. In the Western United States, the onset of spring, calculated by first flowering dates of lilac (*Syringa vulgaris*) and honeysuckle (*Lonicera tatarica*) and first major snowmelt records from 1957 to 1994, confirmed that since the mid-1970s, the onset of spring has advanced about 2 days per decade for lilacs, 3.8 days per decade for honeysuckle, and 2 days per decade for first major snowmelt (Cayan *et al.*, 2001). In addition, Zhao and Schwartz (2003) reported that the onset of spring advanced by 0.46 days per year in southwestern Wisconsin and 0.25 days per year in central/eastern Wisconsin over the period 1965-1998. The evaluation of spring phenology of lilac (*Syringa chinensis*), apple (*Malus domestica*), and grape (*Vitis vinifera*) during the 1965-2001 period in northeastern USA and confirmed an advancement of spring ranging from 0.092 to 0.20 days per year (Wolfe *et al.*, 2005).

Schwartz and his colleagues investigated the influencing climatic drivers of spring phenology. During the period from 1961 to 1980, significant relationships between the first leafing of cloned lilacs and average surface daily maximum temperatures were detected in the central and eastern United States (Schwartz & Karl, 1990). Furthermore, many lower atmospheric parameters have been examined during the green wave (spring onset of photosynthesis) in the central and eastern United States over the period from 1960 to 1986; the results indicated that the time of spring leafing was connected with other lower atmospheric changes (lower-atmospheric lapse rate, surface vapor pressure, relative humidity, visibility, and the V wind component) besides air temperature (Schwartz, 1992). Schwartz (1996) also found that the diurnal temperature range (DTR) gradually increased before first leafing, and then stopped increasing during and after first leafing. In addition, initial examination of the phenology-energy relationship showed that the seasonal transition in spring in mid-latitudes was closely related to relative heat fluxes (Schwartz & Crawford, 2001). These empirical studies demonstrated that the onset of spring in mid-latitudes behaves as a modally abrupt transition related to meteorological changes in the lower atmosphere (Schwartz & Crawford, 2001). Other researchers have also concentrated on similar issues in the contiguous United States. Abu-Asab et al. (2001) examined the first flowering of 100 species in the Washington DC area during the period from 1970 to 1999, and 89 species showed that earlier flowering was linked with an increase in minimum temperature.

In Asia, the beginning of the growing season of *Ginkgo biloba* L. in Japan advanced by about 4 days while the end of the growing season was delayed by about 8 days from 1953 to 2000 (Matsumoto *et al.*, 2003). Both the budding event in spring and also the leaf-fall event in autumn show pronounced relations to air temperatures (Matsumoto *et al.*, 2003). Ibanez *et al.* (2010) reported a similar trend in the advancement in spring phenology and delay in autumn phenology during the 1953-2005 period in

Japan and South Korea. Also, temporal trends of the onset and the end of the growing season were examined by employing the leaf unfolding and leaf fall data of Siberian Elm (*Ulmus pumila*) during the period from 1986 to 2005 in the temperate zone of China, and the start date significantly advanced by, on average, 4.0 days per decade and the end date was significantly delayed by, on average, 2.2 days per decade (Chen & Xu, 2012).

In Europe, the results of Menzel and Fabian's study (1999) showed that the average growing season lengthened by 10.8 days in Europe from 1959 to 1993 and the major contributor to this change was a rise in mean air temperature. Moreover, Menzel *et al.* (2006) confirmed, that consistent with the results of past single-site or single-species phenological studies, 78% of spring phenological records (leafing, flowering, and fruiting) showed advancement while only 3% of autumn phenological records showed significant delay according to analysis of mega phenological data for 542 plant and 19 animal species across 21 European countries during the 1971-2000 period. They analyzed the relationship between phenological records and temperature in the preceding months and estimated that the average advance of spring/summer is 2.5 days per ºC and the average delay of autumn is 1.0 day per ºC (Menzel *et al.*, 2006). In south-central England, the first flowering date of 385 plant species showed an average advancement of 4.5 days during the period 1991-2000 compared with the period 1954-1989 (Fitter & Fitter, 2002). In Estonia, 943 time series of plant, fish, and bird phenology during the 1948-1999 period showed more than 80% of spring phenological phases significantly advancing with a range from 5 to 30 days but no obvious changes in autumn phenology (Ahas & Aasa, 2006). These results also showed a trend toward significantly longer growing seasons in coastal regions of Western Estonia mostly due to the advancement of spring. In addition, a phenological dataset of 29 plant species during the 1943-2003 period in the Mediterranean region confirmed similar shifts of plant phenology under climate change (Gordo & Sanz, 2010).

At the global scale, 62% of 677 species showed an advancement of spring during time intervals that ranged from 16 to 132 years with an average shift to earlier spring of 2.3 days per decade (Parmesan & Yohe, 2003). At the same time, a meta-analysis on 61 studies, which looked into temporal variations of spring phenology for 694 species in the past 50 years, showed that spring phenology advanced by an average of 5.1 days per decade (Root *et al.*, 2003). Furthermore, during the 1955-2002 period, spring indices (SI) first leaf date, first bloom date, and last spring freeze date have universally advanced about from 1 to 1.5 days per decade in the Northern hemisphere, although the shifts in the onset of spring vary among different regions (Schwartz *et al.*, 2006).

Most articles reporting spatial patterns of growing season change have examined and discussed phenological variations at the regional or global scale. According to these articles, most terrestrial ecosystems have experienced a lengthening of the growing season and have exhibited spatial variations in this lengthening (Moulin *et al.*, 1997; Fitzjarrald *et al.*, 2001; Menzel *et al.*, 2001; Zhang *et al.*, 2004a; Schwartz *et al.*, 2006; Doi & Takahashi, 2008). Few detailed observations at the local scale have examined spatial autocorrelation, spatial variations, and responses to climate change at the landscape level. Liang and Schwartz (2009) conducted intensive tree phenological observations and analysis in a Northern Wisconsin forest and concluded that there was no significant spatial autocorrelation or variations at the landscape level. Furthermore, they introduced the Landscape Phenology (LP) index, integrating plant phenology and landscape heterogeneity, to bridge the gap between land surface phenology and ground visual observation phenology (Liang *et al.*, 2011).

These efforts helped establish the foundations for vegetation-climate models with vegetation feedback to the lower atmosphere. However, most of these studies were conducted in an extensive way, that is, research sites were distributed over a large area and only one or several species were examined at each site. The results gained from a site were always regarded as representative of the whole area. So we still have little knowledge about the responses of different species to climate change, as well as the spatial autocorrelation and patterns of phenological events. Intensive phenological observation and analysis are a suitable means by which to explore how phenology responds to meteorological variations.

2.2 Land surface (remote sensing) phenology

Remote sensing (RS) is "… the art and science of obtaining information about an object without being in direct physical contact with the object" (Jensen, 2007, xiii). The sensors, fixed on specific platforms, gather information from an electromagnetic spectrum reflected or emitted from the Earth's surface. By processing and interpreting electromagnetic spectrum information, the objects, areas, or other phenomena of interest on the Earth's surface can be detected, monitored, and analyzed.

Compared with directly observed phenological data, remotely sensed data have advantages of large spatial coverage (usually at a global scale), continuous temporal sequences, and real time acquisition (Table 1). RS data can potentially monitor every point on the Earth’s surface daily, weekly, bi-weekly, or monthly at a spatial resolution from 1 to 8000 meters. The data have been preprocessed and are readily available to be used to draw contrasts of phenological changes and responses among different areas, regions, and continents. Compared with traditional phenological observations and studies, RS based phenological research can readily provide comparisons between the dates of “green wave” (spring onset of photosynthesis) and “brown wave” (autumn end of photosynthesis) at local to global levels (Schwartz, 1998). This information can be further matched with climate models in global change research. As a result, RS data and methods have become more powerful tools for detecting regional and/or global scale phenological changes and their response to global warming (Reed *et al.*, 1994; Thomas & Goudie, 2000; White *et al.*, 2002; Zhang *et al.*, 2004b; White & Nemani, 2006; White *et al.*, 2009; Liang *et al.*, 2011; Chen & Xu, 2012).

Despite those advantages, RS data are limited by inadequate spatial and temporal resolutions and the characteristics of integrated surface spectral reflectance signals. Meanwhile, traditional phenological research has its own disadvantages, being limited by the scarcity and uneven distribution of stations. Additionally, ground observation is an expensive activity requiring much time and labor. Recently, inexpensive networked digital cameras have been used to automatically detect phenological variations hourly or daily (Richardson *et al.*, 2009). In the future, phenological research should focus on integrating RS based data, ground visual observations, and near-surface remote sensing monitoring in order to enhance both spatial and temporal resolution of phenological data.

Table 1: Comparisons between RS data-based phenology and ground data-based phenology

Characteristics	RS Based Data	Ground Based Data
Spatial coverage	From local to regional to global (from 1 to 8,000 meters)	Selected sampling plots from local to regional
Temporal coverage	From daily to monthly to yearly; 40 years at most	Objective-oriented intervals during a certain period; much longer data series
Data size	Very large or mass amount	Small or moderate amount
Limitation	Integrated electromagnetic spectrum information in a heterogeneous pixel; cloud contamination; need high level of expertise, technology, and equipment to handle data	Time and labor consuming in observation
Related to high technology	Data monitoring and processing limited by hardware and software	Normally conducted by observers

Vegetation indices (VIs) are composite indices calculated by optical measurements from sensors and they can reflect the coverage, greenness, and health conditions of vegetation. Many VIs have been generated to fulfill different research requirements. In phenological studies, NDVI and EVI have been widely used to assess vegetation phenology. Both are extracted from reflectance values of remote sensing data and both can provide comprehensive vegetation information at different scales (Huete *et al.*, 2002).

Many approaches have been developed to detect variations of land surface phenology by using VIs. White *et al.* (2009) employed ten widely used methods (Table 2) to estimate the onset of spring from satellite data from 1982 to 2006. These methods have been grouped into four categories by White *et al.* (2009): conceptual-mathematical methods, global threshold methods, local threshold methods, and hybrid methods.

Table 2: Methods for calculating the start of spring (source: White et al. 2009)

Method	Full Name	Algorithm: SOS Estimate
Quadratic	Quadratic	Conceptual-mathematical: first composite period of growing degree accumulation best fitting the observed NDVI time series
NDVI 0.2	NDVI 0.2	Global threshold: NDVI exceeds 0.2
NDVI 0.3	NDVI 0.3	Global threshold: NDVI exceeds 0.3
DMA	Delayed Moving Average	Conceptual-mathematical: smoothed NDVI exceeds expected value of near-term historical NDVI
HANTS-FFT	Harmonic Analyses of NDVI Time-Series – Fast Fourier Transform	Conceptual-mathematical: maximum increase on Fourier approximation of NDVI
Timesat	Timesat	Conceptual-mathematical: high amplitude divergence from a multiplemodel NDVI fit
Midpointpixel	Midpointpixel	Local threshold: NDVI exceeds locally tuned threshold; run for every pixel
PAT	Percent-Above-Threshold	Local threshold: NDVI exceeds locally tuned threshold; run for the group behavior of all pixels within an ecoregion
Gaussian	Gaussian	Hybrid: average date when Gaussian fit of NDVI exceeds three global thresholds
Midpointcluster	Midpointcluster	Local threshold: NDVI exceeds locally tuned threshold; run for time series aggregated to a cluster level

Conceptual-mathematical methods always fit the VI curves into a mathematical model and use the turning points (or thresholds) as the onset or end of the season. The advantage of these types of method is that the turning points are objectively calculated and determined. However, this type of methods is largely influenced by data quality. Conceptual-mathematical methods also may fail to detect the change of seasons in regions with two or three growing seasons a year, such as in some Asian countries, where farmers plant rice twice a year. Moreover, the turning points have no clear biological meaning, so scientists cannot identify the phenological events on the ground corresponding to these turning points. Is it bud burst? Is it leaf out? Or is it something else? This is the most common limitation of the use of RS methods in phenological studies.

Threshold methods include global threshold methods and local threshold methods. They share the similarity of setting up thresholds subjectively, but they differ in the way they define the thresholds. In global methods the threshold is constant for the whole research region, such as setting 0.2 as a threshold for NDVI. For local methods, the threshold varies by pixels, ecoregions, or clusters within a research region. The advantage of these types of methods is that they can always assess the onset and end of the growing season and that they can be utilized to analyze spatial patterns and temporal trends. The disadvantage is that the threshold is subjectively defined and, therefore, it is hard to impart biological meaning to the threshold. Hybrid methods combine threshold and conceptual-mathematical approaches.

Of all the methods, the delayed moving average (DMA) method (Reed *et al.*, 1994), the seasonal midpoint NDVI (SMN) method (Schwartz, 2003), and the logistic model approach (Zhang *et al.*, 2004a) are most widely used. The delayed moving average method, first applied by Reed (1994), is used to determine the onset of spring by comparing the predicted values (the sliding mean of previous n values) with the actual NDVI values and determining the time when a significant increase is detected. Occasionally, the DMA method cannot identify the turning points because of bad data quality or latitude influence (Reed *et al.*, 1994). The SMN method was developed by

White (2003), who set up the midpoint of the minimum and maximum NDVI values as the onset of spring. This determined threshold is largely dependent on land cover type as well as being significantly influenced by the minimum and maximum NDVI values. Schwartz *et al.* (1999; 2002) conducted comparative research on the DMA, the SMN, the Spring Indices (SI) models, and ground visual observation data in deciduous forest and mixed woodland stations in the conterminous USA. The results showed that the three methods can all detect the relative variation in the start of the season (SOS) among years. SMN SOS dates were close to SI first bloom dates, while DMA SOS dates were about 30-60 days earlier than SI first bloom dates. Only the SI approach significantly correlated with native species bud burst at Harvard Forest. The DMA onset of spring may be closely related to understory green-up, while the SMN onset of spring may detect late spring phenology better (Schwartz & Reed, 1999; Schwartz *et al.*, 2002). The logistic model approach, employed by Zhang (2003), uses a logistic growth sigmoid function with a moving window to fit the MODIS (Moderate Resolution Imaging Spectro-radiometer) EVI annual curves. It calculates the minima and maxima of the curvature change rate, which correspond to the transition dates of green-up, maturity, senescence, and dormancy of terrestrial vegetation. This method can detect phenological seasons accurately, but it may be heavily influenced by understory change.

Most phenological studies have focused on RS phenology or traditional ground phenology, respectively, except studies conducted by Fisher *et al.* (2006), Liang and Schwartz (2009), and Liang *et al.* (2011). Fisher *et al.* (2006) attempted to fill the scale gap between Landsat data and ground measurements in southern New England. They integrated 57 Landsat images from 1984 to 2002 to provide an average for the research area, whereas ground validation data was acquired in Arcadia Wildlife Management Area (WMA) in RI and Douglas Forest and Buck Hill WMA at the CT/MA/RI tristate junction from Apr 7th to May 18th 2005. Fisher and his colleagues found a way to combine remote sensing and ground data, but more accurate and real-time data comparison and combination are needed.

Remote sensing data and ground data were compared at the landscape level by using a hierarchical method (Liang & Schwartz, 2009; Liang *et al.*, 2011).Liang *et al.* (2011) used bi-daily spring observations data of 864 trees in two 625 × 625 m study areas in the Park Falls Range District of the Chequamegon-Nicolet National Forest in Wisconsin and MODIS NDVI/EVI 250 m spatial resolution/16-day temporal resolution datasets for the same areas in 2008 and 2009. The observation phenology was scaled up from individual organism to population, then to community, finally to a Landscape Phenology (LP) index (Liang *et al.*, 2011). The phenological markers derived from MODIS EVI were close to the full bud burst (FBB) of the whole LP as well as the FBB of deciduous LP. Ground phenological development in spring may have increasing influence on land surface phenology, especially when leaves are out. This effort helped bridge the gap between ground visual observation phenology and land surface phenology, but, one important concern remains how to increase labor, time, and funding efficiency. Another concern is how to acquire remote sensing data with finer spatial and temporal resolutions. A third concern is how to assign the biological significance to land surface phenology.

Above all, RS data and methods in phenological studies have the virtues of full coverage of the whole Earth’s surface, consecutive time series, near real-time accessibility, and spatial pattern and temporal trend tracking. They can contribute to global change research for the same reasons. However, the limitations of RS data cannot be ignored. The most widely used VI data are measured at weekly or biweekly temporal resolutions and 250 to 8000 meter spatial resolutions. Although RS data is efficient and effective for analyzing phenological patterns and trends at regional, continental or global scales, it is still not precise enough with clear biological and physical meanings. It calls for enormous efforts to effectively combine the advantages of these two kinds of data and methods.

2.3 Autumn phenology

Autumn phenology is as important as spring phenology in calculating the length of the growing season and determining the timing of carbon assimilation (Delpierre *et al.*, 2009). Commonly, air temperature is thought of as the key driver for spring phenology, but the key driver(s) for autumn phenology is still unclear, because autumn phenology has complicated characteristics and intricate relationships with both climatic and environmental parameters. Therefore, in direct observation phenology, most attention has been devoted to spring phenology and only a few articles have concentrated on autumn phenology, primarily in Europe and Asia.

In Germany, Estrella and Menzel (2006) examined the relationships between the timing of leaf coloring of four tree species and the potential climate triggers during the period from 1951 to 2003, but they didn’t find enough statistical evidence to confirm the triggers of leaf coloring. In Japan, negative relationships between autumn phenology responsiveness and latitude, and positive relationships between autumn phenology and air temperature were found in a study of the leaf coloring and fall data of two tree species over 53 years in a range of latitudes between 31° and 44° N (Doi & Takahashi, 2008). Two years of autumn phenology of *Populus* in two Free Air CO_2 Enrichment Experiments in the US and Italy showed that the increase of CO_2 leads to the delay of leaf coloration and leaf fall (Taylor *et al.*, 2008). However, this study was of limited duration, suggesting that conclusive trends cannot be established. In Puerto Rico, the relationships between leaf fall patterns and climate drivers in a subtropical wet forest were examined and showed that the patterns were largely influenced by solar radiation, photosynthetic photon flux density, day length, and air temperature (Zalamea & Gonzalez, 2008). In France, Delpierre *et al.* (2009) leaf coloring were modeled for three tree species at 51 deciduous forest sites by using photoperiod and air temperature, and a delay of leaf coloring was predicted at the rate of 1.4 and 1.7 days per decade in *Fagus* and *Quercus* during 1951-2099.

These studies from Europe and Asia focused on autumn phenological observations and attempted to address the important climatic factors driving autumn phenology at the regional scale. Further efforts in autumn phenological research are still needed, such as conducting direct autumn observations, examining the potential climatic factors, building efficient autumn phenological models, and validating satellite derived autumn senescence.

2.4 Phenological studies in urban settings

In most phenological studies, observation sites in rural and urban areas have not been differentiated, and a few articles have differentiated and examined remote sensing and in situ vegetation phenology in an urban setting. White *et al.* (2002) used 10-year NDVI data from the Advanced Very High Resolution Radiometer (AVHRR) to examine the phenological differences between urban and rural areas in deciduous broadleaf forest regions in the eastern United States. Their results showed that the onset of the growing season has advanced and the whole growing season has extended in urban areas compared with rural areas (White *et al.*, 2002).The spatial resolution of the study area is 1°latitude by 1°longitude. The results of the study, therefore, showed general differences of the growing season between urban and rural areas due to the very coarse spatial resolution. Moderate or high spatial resolution data is needed for future studies comparing phenology in urban and rural areas.

Zhang *et al.* (2004c) addressed the variations in remote sensing phenology of urban core areas and surrounding rural areas according to EVI from the Moderate Resolution Imaging Spectro-radiometer (MODIS). Results suggested that the length of the growing season increased in urban areas versus the adjacent rural areas, and that urban heat islands had a significant effect on vegetation phenology in eastern North America. MODIS NDVI and EVI are valuable datasets to examine vegetation phenology at the regional to global scales. Fisher *et al.* (2006) also employed a logistic-growth curve to examine how the onset of spring changes with increasing distance from a metropolitan area, showing that Rhode Island metropolitan areas have an earlier spring onset than comparable rural areas.

SPOT NDVI and an urban index derived from the Defense Satellite Meteorological Program – Operational Linescan System (DMSP-OLS) showed no significant relationship between the phenological transition dates and urbanization (Xu *et al.*, 2008). None of these studies of remote sensing phenology conducted in an urban setting has included ground validation to verify/confirm the phenological meaning of the satellite data.

As for *in situ* phenology conducted in an urban setting, traditional extensive phenological observation data of three woody plant species during the period from 1962 to 2004 in Beijing, China showed that the growing season extended with urbanization (Luo *et al.*, 2007). A comparison of leaf flushing in seven cities showed that budburst started earlier in three of four temperate cities and one of three tropical cities; however, only one temperate city followed the classic urban phenology paradigm, which is that higher land surface temperature and lower vegetation fraction cover lead to earlier budburst Gazal *et al.* (2008).

There appear to be no articles focusing on intensive phenological observations in an urban area, although, urbanization has been shown to be the major factor influencing surface temperatures (Kalnay & Cai, 2003). Studies at local, regional, or global scales have confirmed urban heat island effects, and diurnal temperature ranges in urban areas showed to be significantly narrower compared to surrounding rural areas in the United States (Gallo *et al.*, 1996). Zhou *et al.* (2004) identified 0.05ºC per decade of mean surface temperature increasing due to rapid urbanization in southeast China. Studies on differences of phenology between urban and rural areas could be both a way to test climate warming influences on phenology (White *et al.*, 2002; Zhang *et al.*, 2004c) and to accurately estimate the start and end of the growing season.

3. Research Questions

This dissertation examines three major topics. The first is the patterns and processes of spring and autumn phenology and their relationships to key climatic factors in an urban woodlot located in Southeastern Wisconsin. An intensive phenological observation campaign of this kind has not been conducted in an urban area. The second topic is a comparison of the responses of tree phenology to climatic factors in an urban woodlot versus a rural forest. How to bridge the gap between direct observation phenology and satellite-derived land surface phenology has always been a key issue in phenological research. The third topic is an exploration of methods to combine direct observation phenology and land surface phenology, and effectively use RS reflectance information as well as direct observation data. In the context of these topics, the following questions are posed and addressed.

The first questions addressed concern both spring and autumn phenology and their interaction with key climatic factors. The relationships between plant phenology and climatic factors are a basic issue in global warming and phenological research. Temperatures, including surface layer air temperature and soil temperature, usually serve as the key driving factors for spring phenology and as important driving factors for autumn phenology; light, moisture, and wind conditions are also possible factors for autumn phenology. Therefore, the first general question is what are the spatial patterns, progressions, and dominant climatic factor(s) of spring and autumn phenology in Downer Woods. Six sub-questions related to the first topic are addressed: 1) What are the spatial patterns of spring and autumn phenology in this urban woodlot? 2) Is there any spatial autocorrelation in the appearance of phenophases? 3) What are the annual variations of spring and autumn phenology at this location? 4) What are the progressions of spring and autumn phenology in this urban woodlot? 5) What are the relationships between the phenological phases and climatic factors? 6) Are there any differences in response to microclimate variations among individual species?

Few phenological studies are conducted in urban areas because of their complex surroundings. However, urban areas cannot be ignored in phenological research because they are an integral part of the Earth's surface and are greatly impacted by anthropological global warming. The urban heat island effect is expected to greatly influence phenological events (Gazal *et al.*, 2008), possibly causing significant differences between the growing seasons of urban woodlots and rural forests. Therefore, the second general question is how tree phenology in an urban woodlot responds to climate variation versus tree phenology in a rural forest. Two sub-questions will be addressed related to the second research topic: 1) At the species level, how is the phenological response to climate variations in an urban woodlot different from that in a rural forest, and why? 2) Is there a significantly different response of plant phenology to climate variation in an urban setting versus a rural setting?

Researchers still lack knowledge about the types of ground canopy information reflected by remote sensing data. Therefore, this is another critical issue for global warming and phenological research. Researchers have detected relative changes in integrated phenological information derived from remotely sensed data; however, it is very important to understand how the data reflect actual ground phenological information. The data provide important initial parameters for global or regional circulation models and set more reasonable and accurate growing season lengths for carbon cycle research. In relation to the third topic, two sub-questions will be addressed: 1) What are the onset and end of growing season (calculated by using Zhang’s approach from MODIS NDVI and EVI)? 2) Which phenophases of actual ground phenology do these results reflect?

4. Study Area

4.1 Downer Woods

The study site is Downer Woods (43º4′52″N, 87º52′51″W), which is a 4.495 ha (11.1 acre) fenced secondary forest located in the northern part of the University of Wisconsin-Milwaukee (UWM) campus. The UWM campus is situated in the northeastern corner of the city of Milwaukee, approximately 850 meters from the western shore of Lake Michigan (Figure 1). Since 1998, Downer Woods has been managed by the UWM Field Station to encourage its return to a natural state (http://www4.uwm.edu/fieldstation/naturalarea/downerwoods.cfm). There are two reasons for choosing Downer Woods as the study site for this research. First, it is easily accessible and is convenient for conducting regular intensive observations (bi-daily) because of its on-campus location. Second, the woods is in an urban setting, surrounded by campus buildings, residential houses, and roads. This makes the observational data unique and valuable for tracking urban phenology.

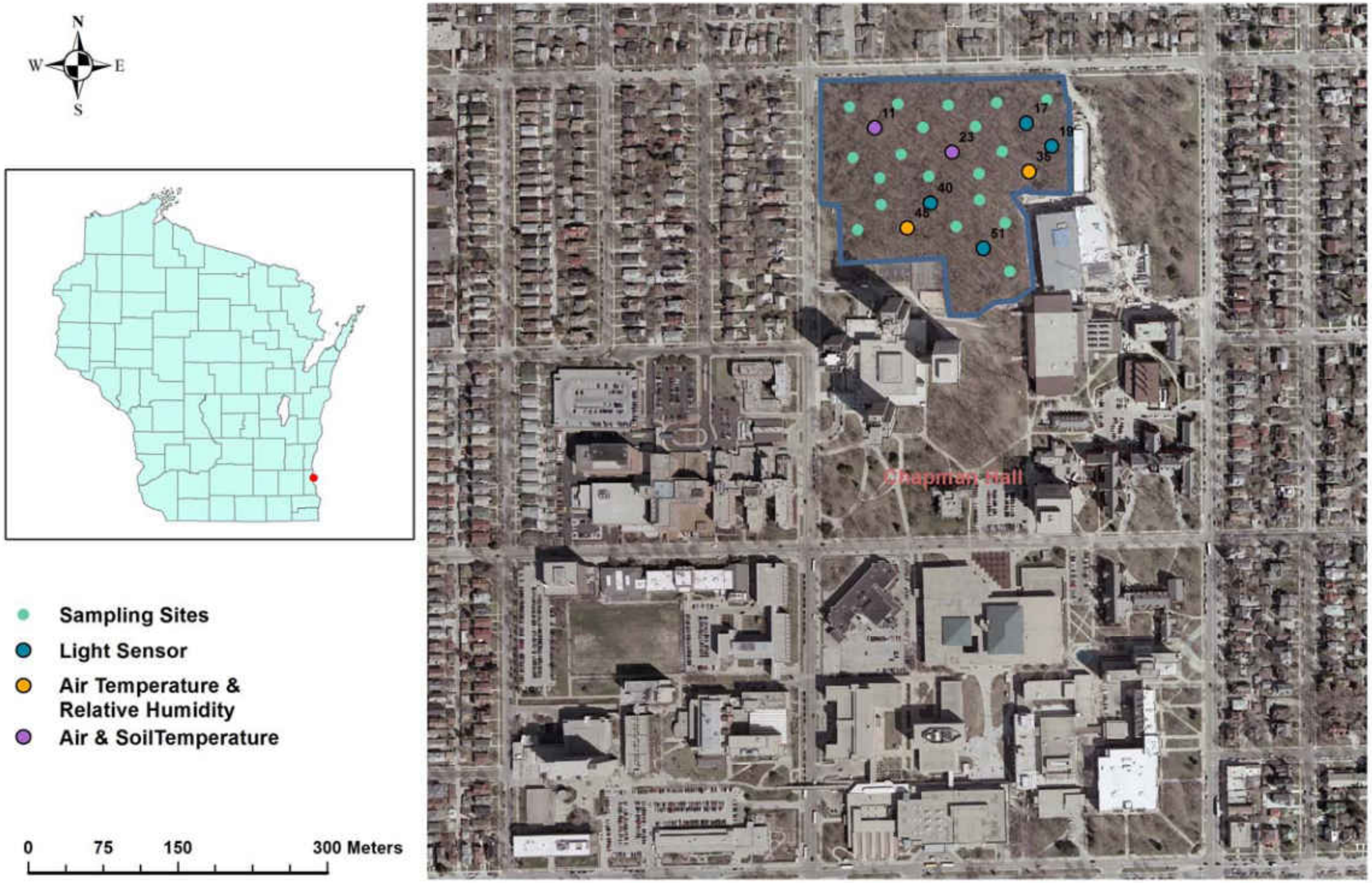

Figure 1: The main study site – Downer Woods (Source: UWM Field Station)

Milwaukee is located in a continental climatic zone with a long winter, moderate summer temperatures, and a short spring and autumn. This climatic type is typically classified as Dfb, which represents snow, full humid, and warm summer under the Köppen Climate Classification System. The climate of Milwaukee, especially the area close to the lakeshore, is influenced by Lake Michigan, which mitigates cold weather in winter and hot weather in summer. The annual average temperature in Milwaukee is 7.8 °C. January is the coldest month with an average temperature of -7.3 °C and July is the warmest month with an average temperature of 21.6 °C. Milwaukee's annual precipitation of 836 mm and annual snowfall of 1,196 mm leads to relatively high humidity. Spring gets the most of the precipitation of the year. (http://www1.ncdc.noaa.gov/pub/orders/IPS-B494C070-228B-4E39-83A3-B9B3042AF362.pdf).

The botanical history of Downer Woods was summarized in a UW-Milwaukee Field Station Bulletin report (Salamun, 1972). The documented records of Downer Woods can be traced back to 1896. Before 1896, the Pfister family owned a dairy farm in the area including Downer Woods. From 1896 to 1921, the Pfister family gradually deeded different portions of this area to the Milwaukee-Downer College, eventually donating a total of approximately 45 acres (18.21 ha). In 1964, it was sold to UW-Milwaukee as 30-35 acres (12.14-14.16 ha) of woodland, named Downer Woods. By 1972, only about 15 acres of the land was wooded or partially wooded. Between 1964 and 1971, oaks were the dominant trees in the woods, but very few oak seedlings and saplings were found, while, ash and basswood trees were abundant with adult trees as well as seedlings and saplings. Ash and basswood are now the dominant trees in term of abundance in the woods, rather than oaks. The ages of ashes, basswood, hawthorns and oaks were determined in 1965. Tree rings were counted to determine the ages of ashes, basswood, and hawthorns, while inference was used in the case of oaks. The adult ash and basswood trees were about 35-50 years old, the hawthorns about 40-70 years old, and the oaks about 180-200 years old. Thus, currently, some of the ash and basswood trees should be about 75-90 years old, the hawthorns about 80-110 years old, and the oaks about 220-240 years old.

The topography of Downer Woods is relatively flat and the average elevation is about 200 meters above mean sea level. Two small creeks run through the woods. Various animals live in the woods, such as squirrels, raccoons, deer, and many birds. The vegetation type is characterized as temperate deciduous broad-leaved forest. The dominant tree species are *Fraxinus americana.* (American white ash) and *Tilia americana.* (American basswood) (James Reinartz, UWM Field Station, unpublished data, 1998 and 1999). These two dominant tree species were selected as sample trees for this research, as well as five species with lesser frequency in the woods, *Quercus rubra* (red oak), *Quercus alba* (white oak), *Acer negundo* (boxelder), *Crataegus spp.* (hawthorn), and *Ostrya virginiana* (American hophornbeam) (Table 3). With the exception of *Crataegus spp.* (hawthorn), the distribution of species among sample trees is closely proportionate to that among the larger population reported in the 1999 survey (Table 4). The eastern and southern edges of the woods are bordered by university buildings and two small grassy areas. The northern edge is adjacent to East Edgewood Avenue, and the western edge is adjacent to North Maryland Avenue. The surroundings are residential houses with small lawns.

Table 3: Observed tree species in Downer Woods

Latin Name	Common Name	N	Percentage of the total sample (%)
Acer negundo	Boxelder	5	4.6
Crataegus spp.	Hawthorn	2	1.9
Fraxinus americana	White Ash	45	41.7
Ostrya virginiana	American Hophornbeam	1	1
Quercus alba	White Oak	8	7.4
Quercus rubra	Red Oak	4	3.7
Tilia americana	American Basswood	43	39.8
	Total	108	100.0

Table 4: General tree species information in the 1999 Downer Woods survey

Latin Name	Common Name	N	Percentage of the total sample (%)
Acer negundo	Boxelder	15	3.8
Acer platanoides	Norway Maple	1	0.3
Acer saccharum	Sugar Maple	0	0.0
Crataegus spp.	Hawthorn	23	5.9
Fraxinus americana	White Ash	177	45.3
Fraxinus nigra	Black Ash	2	0.5
Ostrya virginiana	Hophornbeam	2	0.5
Prunus serotina	Black Cherry	0	0.0
Quercus alba	White Oak	13	3.3
Quercus rubra	Red Oak	7	1.8
Tilia americana	Basswood	151	38.6
	Total	391	100.0

* Source: J.A. Reinartz, UWM Field Station

4.2 Park Falls Range District

The Park Falls Range District is located in the Chequamegon-Nicolet National Forest in northern Wisconsin (Figure 2) and serves as a general research site to conduct comparisons of phenological responses to climate between an urban woodlot and a rural forest. Prof. Mark D. Schwartz, Dr. Liang Liang, and other colleagues have established two study sites in the Park Falls Range District for conducting phenological observations. In this study, basswood phenology data from the northern study site were employed. Basswood is one of the prominent species in the upland forest in the northern study area and there are a total of 24 basswood trees sampled (Liang, 2009).

A 447-m tall AmeriFlux flux tower (45º56′46″N, 9016′19″ºW), which is run by the Chequamegon Ecosystem-Atmosphere Study (ChEAS) group, is adjacent to the study sites. The ChEAS is a multi-organizational program exploring biosphere-atmosphere interactions by gauging CO_2, water, and energy since 1995. The climate of the region is cool continental. The mean temperature in January is -12.9 ºC and in July is 18.9 ºC, with an average of 4.1 ºC (http://cheas.psu.edu/).

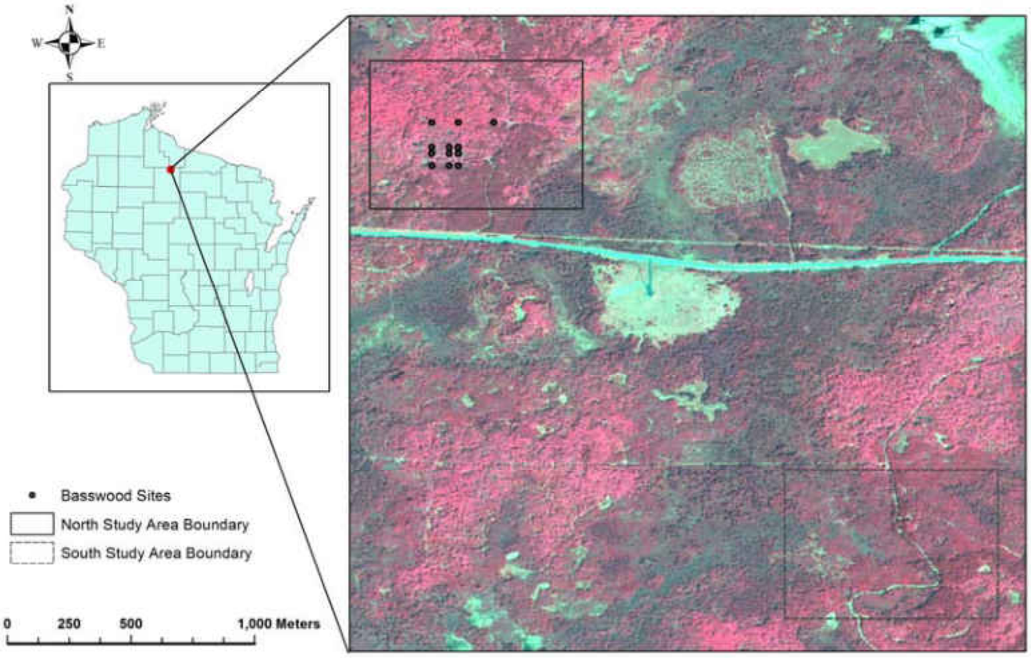

Figure 2: The contrast study site – Park Falls Range District, Wisconsin, USA (Data source: Prof. Schwartz and Dr. Liang)

5. Data and Methods

5.1 Data - Downer Woods

5.1.1 Tree sampling strategies

The study site is an area approximately 250 meters by 237 meters (Figure 1). Sample trees were selected and marked with pink plastic bands and wire tags in summer 2007. Dr. Gretchen Meyer from the UWM Field Station, an expert on the vegetation in the woods, helped to identify the sample species. Twenty-seven evenly distributed sites were selected from 56 sites identified in the 1998-1999 Field Station Survey to serve as phenological observation sites (Figure 1). At each site, four sample trees with the greatest diameters at breast height (DBH) and located within a 10-meter radius of the site center were selected. The distribution of species among sample trees was mainly determined by the distribution of species among the larger population reported in the 1998-1999 field survey. Therefore, the sample trees closely represent the general species composition of the woods.

5.1.2 Spring and autumn phenological observations

Intensive phenological observations and analysis have been conducted in Downer Woods by Prof. Schwartz's research group each spring and autumn since autumn 2007. The data from intensive observations of spring and autumn phenology plays the most critical role in this study. The spring phenological observation protocol for deciduous trees followed the observation protocol developed for use in the Park Falls Range District of the Chequamegon National Forest in northern Wisconsin by Dr. Liang and Prof. Schwartz (Liang, 2009). In the Park Falls Range District, Prof. Schwartz and Dr. Liang started intensive spring phenological observations in 2006. Their spring phenological observation protocol was adapted from the German Biologische Bundesanstalt, Bundessortenamt and Chemical Industry (BBCH) scheme (Sparks & Carey, 1995) and subsquently cross-referenced with J.C. Randolph's five dominant phenophases for weekly phenological observations at the Indiana Morgan-Monroe Forest AmeriFlux site (Randolph, personal correspondence). This spring protocol allows rapid-recording of continuous phenophases corresponding to tree growth, instead of the more traditional discrete phenological events records.

The spring protocol includes six key phenophases, each of which corresponds to a numerical ranking (Table 5): buds visible (100 level), buds swollen (200 level), buds open (300 level), leaves out (400 level), leaves fully unfolded (500 level), and leaf expansion (600 level) (Liang & Schwartz 2009). Each phenophase is further divided into four progressive categories. The categories of the first five phenophases are defined by the covering ratio to the whole canopy (<10%, 10~50%, 50~90%, and >90%). The categories of the last phenophase are defined by the ratio of leaf size to the size of mature leaf (<25%, 25~50%, 50~75%, and >75%).

Table 5: Spring phenological protocol for deciduous trees

Code	Deciduous Phenophase	Percentage
0	No Buds Visible	
100	Buds Visible	<10%
110	Buds Visible	10~50%
150	Buds Visible	50~90%
190	Buds Visible	>90%
200	Buds Swollen	<10%
210	Buds Swollen	10~50%
250	Buds Swollen	50~90%
290	Buds Swollen	>90%
300	Buds Open(leaves visible)	<10%
310	Buds Open(leaves visible)	10~50%
350	Buds Open(leaves visible)	50~90%

390	Buds Open(leaves visible)	>90%
400	Leaves Out(not fully unfolded)	<10%
410	Leaves Out(not fully unfolded)	10~50%
450	Leaves Out(not fully unfolded)	50~90%
490	Leaves Out(not fully unfolded)	>90%
500	Leaves Fully Unfolded	<10%
510	Leaves Fully Unfolded	10~50%
550	Leaves Fully Unfolded	50~90%
590	Leaves Fully Unfolded	>90%
600	Leaf Expansion Level	<25%
625	Leaf Expansion Level	25%~50%
650	Leaf Expansion Level	50%~75%
675	Leaf Expansion Level	>75%

The autumn phenological observation protocol for deciduous trees was set up following similar theoretical and practical considerations to the spring protocol. It measures two critical phenophases in autumn (Table 6): leaf coloration (800 level) and leaf fall (900 level), and it uses the same types of progressive categories as the first five phenophases in the spring protocol. The categories of the two autumn phenophases are assigned to the covering ratio of the whole canopy (<10%, 10~50%, 50~90%, and >90%).

Table 6: Autumn phenological protocol for deciduous trees

Code	Deciduous Phenophase	Percentage
800	Leaf coloration	<10%
810	Leaf coloration	10~50%
850	Leaf coloration	50~90%
890	Leaf coloration	>90%
900	Leaf Fall	<10%
910	Leaf Fall	10~50%
950	Leaf Fall	50~90%
990	Leaf Fall	>90%

The approaches to observation in spring and autumn are different. Spring phenology is a visually continuous progression of plant growth, and the protocol attempts identify the newest phenological stage. Therefore, in spring, the most advanced phenophase is recorded on each individual tree. In contrast, autumn phenology is less studied and more complex than spring phenology. Leaf fall is not a continuous phenological stage after leaf coloration. They may, to some extent, occur concurrently. Therefore, two autumn phenophases are assessed and recorded simultaneously so as to fully track and understand autumn phenological process. In order to maintain the intensity and accuracy of phenological observations, they are recorded at least every other day during the periods of spring and autumn. Generally, spring observations were undertaken from April through June, lasting for about 2 months overall, while autumn observations were undertaken from September through November, lasting for about 2 to 2.5 months. Following these guidelines, five years of spring phenological observation data (2008-2012) and six years of autumn phenological observation data (2007-2012) have been collected in this study.

5.1.3 Measurements of microclimatic parameters

Climatic elements in the lower atmosphere are primary factors influencing vegetation phenology. Air temperature is the major element triggering spring phenological events (Abu-Asab *et al.*, 2001; Menzel *et al.*, 2006; Schwartz *et al.*, 2006; Christidis *et al.*, 2007; Thompson & Clark, 2008), and although the factors influencing autumn phenophases are more complicated, air temperature likely plays an important role in leaf coloration and leaf fall. In Downer Woods, air temperature (at breast height), soil temperature (20 cm depth), and relative humidity were derived from temperature series connected to data loggers recording every ten minutes. HOBO[1] loggers were deployed at sites 11 and 23 for microclimate recordings of air and soil temperatures, and at sites 35 and 45 for microclimate recordings of air temperature and relative humidity (Figure 1). Precipitation data were derived from a Shorewood meteorological dataset (located 3 kilometers northwest of Downer Woods, recorded by Prof. Mark D. Schwartz). The photosynthetic photon flux density (PPFD) is recorded by light sensors. Sites 19 and 51 are equipped with light sensors detecting light intensity under basswood canopies whereas sites 17 and 40 detect light intensity under white ash canopies. A reference light sensor was also set up on the roof of Chapman Hall, a campus building about 100 meters southwest of Downer Woods (Figure 1). Other micrometeorological variables, including wind speed and wind direction were acquired from the Milwaukee Mitchell Airport weather station records in the National Climatic Data Center archives. Table 7 illustrates the meta-data for this study.

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[1] HOBO: a series of battery powered data logger products from Onset Company measuring and recording temperature, humidity, light, energy, and a variety of other parameters.

Table 7: Basic information for phenological and climatic data

Category	Type	Time Interval	Source
Phenological data	phenological phases	at least every other day	Ground visual observation
Climatic data	air temperature	every ten minutes	HOBO
	soil temperature	every ten minutes	HOBO
	relative humidity	every ten minutes	HOBO
	photosynthetic photon flux density (PPFD)	every ten minutes	Pendant light sensor
	air temperature precipitation	daily	Shorewood data from Prof. Schwartz (1994-2012)
	day length	daily	Naval Oceanography Portal
	air temperature wind speed wind direction	daily	Milwaukee airport station (National Climatic Data Center) (2007-2012)

In order to better detect the relationship between phenology and microclimate, the microclimatic data were divided into four groups as shown in Table 8. These four groups of microclimatic data are examined together to identify the critical factors influencing tree phenology at the plot scale. Temperature data included the accumulated growing degree-days and the daily maximum, minimum, and mean temperature calculated from onsite air and soil temperature data. Also included was the accumulated chilling degree-days calculated from the Shorewood air temperature data. Moisture data included daily water balance, daily precipitation, and accumulated precipitation calculated from the Shorewood precipitation data. Light data included daily light intensity and photoperiod (day length). Wind data included daily wind speed and daily wind direction.

Table 8: Summary of microclimatic parameters

Group	Variable
Temperature	air and soil temperature (daily maximum, daily minimum, daily mean, accumulated growing degree days) (HOBO data) air temperature (accumulated chilling degree days) (Shorewood data)
Moisture	water balance (daily) precipitation (daily, accumulated)
Light	light intensity (daily) photoperiod (day length)
Wind	wind speed, wind direction (daily)

Temperature data analysis

Four HOBOs were deployed at sites 11, 23, 35, and 45 to record air and soil temperatures at ten-minute intervals in spring and autumn during the phenological observation period from 2007 to 2012. One HOBO was deployed in winter to continue tracking temperature in the woods, and one HOBO was deployed at site 56 to detect possible heat effect since 2011, because site 56 is close to the UWM Klotsche Center building, which may potentially influence air temperature nearby. Daily air temperature data recorded by Prof. Mark D. Schwartz in Shorewood and daily air temperature data for Milwaukee, downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service Forecast Office (http://www.nws.noaa.gov/climate/index.php?wfo=mkx), were also used to compensate for the absence of summer and long-term air temperature data in the study area.

Daily temperature

Daily maximum, minimum, and mean air and soil temperatures were calculated from ten-minute interval air and soil onsite temperatures. The differences of daily mean air temperature among the four sites with HOBOs by year were calculated by subtracting the mean daily temperature of all four HOBO sites from the daily temperature at each HOBO site.

Mean air temperature comparison among HOBO data, Shorewood data, and Milwaukee weather station data

In contrast to the onsite HOBO weather data extending from autumn 2007 to autumn 2012, onsite summer weather data were only collected during summer 2011 and 2012. The Shorewood weather records (-87.893W, 43.0977N, 1994-2012) and Milwaukee weather station data (-87.9044W, 42.955N, 1948-2012) were employed to compensate for the lack of long-term data and summer data in Downer Woods.

Growing degree-days and chilling degree-days

The growing degree-days (GDD) method is a widely used measure of heat accumulation for plant growth in agricultural and ecological fields (Hamilton *et al.*, 2007). Physiological studies show that specific plant growth stages are reached only when enough effective temperature accumulation is achieved (de Beurs & Henebry, 2005; Brown & de Beurs, 2008). Hamilton *et al.* (2007) found that physiologically based models involve more parameters and are more complicated than accumulated degree-day based models, which have been proven to be more accurate predictors. The growing degree-days measurement is calculated by taking the difference between the daily mean temperature ($\mathrm{T_{mean}}$) and the base temperature ($\mathrm{T_{base}}$) when $\mathrm{T_{mean}}$ is greater than $\mathrm{T_{base}}$. Normally, the base temperature for the GDD is set between 0°C and 10°C, although it may vary by species and locations. In this study, GDDs were calculated with base temperature from 0°C to 10°C in 1°C increments. Accumulated growing degree-days (AGDD) is the sum of GDD from day of year $\mathrm{DOY_1}$ to $\mathrm{DOY_2}$ (equation as below). In this study, $\mathrm{DOY_1}$ was set as January 1st. According to correlation analysis between AGDDs and spring phenological development, 3°C was chosen as the optimal base temperature.

$$AGDD = \sum_{i=DOY_1}^{DOY_2} \left(\begin{matrix} (\overline{T_i} - 3) for\ \overline{T_i} > 3 \\ 0\ for\ \overline{T_i} \leq 3 \end{matrix} \right)$$

Chilling degree-days (CDD) are used to examine chilling requirements for plant growth in spring (de Beurs & Henebry, 2005; Betancourt *et al.*, 2007). The study area has long and cold winters, thus the chilling requirements are expected to be fulfilled long before spring (Schwartz & Hanes, 2010), and therefore, it is not necessary to consider chilling requirements in spring phenology. Although there is still a lack of published research focusing on the relationships between autumn phenology and climatic factors, a preliminary study by Richardson *et al.* (2006) showed that the accumulated CDD using 20°C as the base temperature demonstrated a relatively strong connection with autumn phenology at the Hubbard Brook Experimental Forest in central New Hampshire. Therefore, in the current study, the ACDD was examined as a potential factor influencing autumn phenology. In this study, CDDs were calculated with base temperature from 10°C to 30°C in 2°C increments. Similar to the AGDD, accumulated chilling degree-days is the sum of CDD from day of year $\mathrm{DOY_1}$ to $\mathrm{DOY_2}$ (equation as below). In this study, $\mathrm{DOY_1}$ for CDD was set as August 1st. According to correlation analysis between ACDDs and autumn phenological development, 20°C was chosen as the optimal base temperature.

$$ACDD = \sum_{i=DOY_1}^{DOY_2} \left(\begin{matrix} (20 - \overline{T_i}) for\ \overline{T_i} < 20 \\ 0\ for\ \overline{T_i} \geq 20 \end{matrix} \right)$$

Moisture data analysis

Precipitation

Precipitation is also a critical factor in climate change research. Because it influences soil moisture, which can be closely related to plant emergence and growth (Thomas *et al.*, 1973). In this study, daily precipitation from the Shorewood data records was used. Accumulated precipitation (AP) served as an important moisture parameter and was calculated by summing all precipitation from day of year $\mathrm{DOY_1}$ to $\mathrm{DOY_2}$ (equation as below). In this study, $\mathrm{DOY_1}$ is set as January 1st.

$$AP = \sum_{i=DOY_1}^{DOY_2} Precipitation$$

Water balance

Water balance is used to examine soil water storage conditions. If there is a water surplus, the excess will result in surface flow. If there is a water deficit, there will be a water shortage in regard to the needs of plant growth (Thomas *et al.*, 1973), and therefore water balance may be a potential factor influencing plant phenology.

In this study, the American climatologist C. W. Thornthwaite's bookkeeping method was employed to calculate water balance as follows (Oliver, 2002).

$$\boldsymbol{ST_i} = \begin{cases} \mathbf{100}\ \ (for\ P_i \geq ET_i\ and\ ST_{i-1} + P_i - ET_i \geq 100) \\ \boldsymbol{ST_{i-1} + P_i - ET_i}\ \ (for\ P_i \geq ET_i\ and\ ST_{i-1} + P_i - ET_i < 100) \\ \boldsymbol{ST_{i-1} + P_i - ET_i}\ \ (for\ P_i < ET_i\ and\ ST_{i-1} + P_i - ET_i > 0) \\ \mathbf{0}\ \ (for\ P_i < ET_i\ and\ ST_{i-1} + P_i - ET_i \leq 0) \end{cases}$$

Here, ET_i is evapotranspiration in mm, P_i is precipitation in mm, ST_i is the amount of water stored in the soil in mm, and i is the *i*th day. The initial *ST* was normally set as 10 cm. The calculation was from March 1st to November 30th each year. The daily evapotranspiration data was provided by Prof. Mark D. Schwartz through personal correspondence with Joe Russo and his colleagues. It is a set of data modeled on a grass surface, but it may still be useful in measuring annual variation of water balance for an urban woodlot.

Light data analysis

Photosynthesis is the process by which green plants absorb solar energy and fix it to produce plant carbohydrates (Rosenberg *et al.*, 1983). “Photosynthesis is solely a daytime phenomenon” (Thomas & Goudie, 2000, 369). Photoperiod is “…the length of time that an organism is exposed to sunlight each day, generally equivalent to day length” (Cleland *et al.*, 2007, 357). Therefore, day length heavily influences photosynthesis, and consequently influences plant growth and development. So these are potentially important factors influencing the timing of plant phenology. Day length data was downloaded from the United States Naval Observatory website (http://aa.usno.navy.mil/data/docs/Dur_OneYear.php).

Light intensity, which is the strength of sunlight to which plants are exposed and is another factor influencing photosynthetic efficiency. Light intensity in units of lux was recorded by a HOBO pendant temperature/light data logger. A light sensor deployed in nearby full sun (not shaded) locations (Chapman Hall roof for Downer Woods) was used to parameterize light strength exposure for the tree canopies.

Wind data analysis

I found no references in the literature discussing the relationships between wind and autumn phenology, although wind may be a possible climatic factor for autumn phenology, especially leaf fall. Two wind parameters were selected: average wind speed and direction of the fastest 2-minute wind.

5.1.4 Satellite data

This study employed the Collection 5 VI product, from the MODIS (Moderate Resolution Imaging Spectro-radiometer) Terra satellite, acquired from the Oak Ridge National Laboratory Distributed Active Archive Center (http://daac.ornl.gov/MODIS/modis.html). The Collection 5 VI product (MOD13Q1), which includes both NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index) data, has a 250 m spatial resolution and a 16-day temporal resolution (Table 9). The downloaded dataset was from July 2007 to December 2012, which covered the whole period of the ground visual observation campaign.

Table 9: Summary of satellite data

Science Data Set	Units	Spatial Resolution	Temporal Resolution
NDVI	NDVI	250 m	16 days
EVI	EVI	250 m	16 days
VI Quality detailed QA	Bits	250 m	16 days
Composite day of the year	Day of year	250 m	16 days

5.2 Data - Park Falls

5.2.1 Tree sampling

Since 2006, Prof. Schwartz's research group has conducted intensive phenological observations in a 625m × 275m study area in the Park Falls Range District, and subsequently expanded this area to 625m × 625m and added another study area of similar size (Liang, 2009). The spring phenological observation protocol for deciduous trees was adapted and introduced by Prof. Schwartz and Dr. Liang. During spring of 2008, in order to examining differences of phenological response to climate between an urban woods and a secondary mix temperate forest, a total of 24 basswood trees were chosen as part of phenological observations in the northern study area (Figure 3). Because the observations in the Park Falls Range District rely on restricted funding, the direct observation dataset is not as extensive as the one in Downer Woods. Table 10 summarizes the availability of basswood phenological data.

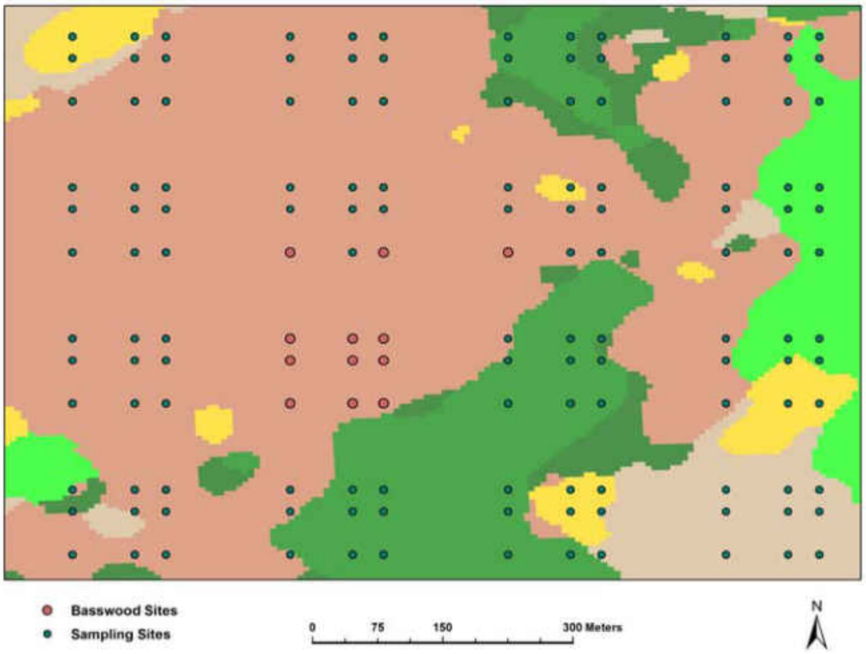


Figure 3: Sampling sites with basswood, Park Falls Range District, Wisconsin, USA (Data Source: Prof. Schwartz & Dr. Liang)

Table 10: Summary of the availability of basswood phenological data in Park Falls

Data Availability	Spring	Autumn
2008	Y	N
2009	Y	N
2010	Y	Y
2011	N	N
2012	N	Y

*Y: Data available; N: Data unavailable

5.3 Methods

5.3.1 Preprocessing

5.3.1.1 Outliers in phenological data: checking and cleaning

The focus of this study is on the phenology of healthy trees, because unhealthy trees or outliers could heavily mislead the analysis and results. Therefore, trees that were considered to be unhealthy due to disease, damage (wind, insect, etc.), age or some other factor were identified by two preprocessing diagnoses and removed from the phenological dataset. These two preprocessing diagnoses were only employed to identify unusual individuals of basswood and white ash trees because of the large total number of individuals of these species.

In the first diagnostic method, the corresponding dates of 200 (buds swollen), 400 (leaves out), 600 (leaf expansion), 850 (leaf coloration), and 950 (leaf fall) phenophase levels were extracted. A box plot of each phenophase level was drawn to determine the extreme outliers. In the second diagnostic method, the corresponding phenophase levels at the ¼ quartile, median, and ¾ quartile of observation dates were selected. The box plot for each of these three particular observation dates was drawn to determine the extreme outliers. These extreme outliers were considered to be samples with values more than 3 times the inter-quartile range from the ¼ quartile or the ¾ quartile.

Two white ashes (sample tree 2 at site 13 and sample tree 4 at site 31) were consistently determined to be extreme outliers according to both diagnostic methods. Also, these two white ash trees were extremely unhealthy with sparse leaves and always exhibited very late spring phenology, and finally died in 2012. Therefore, the phenological records of these two sample trees were removed from the data analysis. There were also a few other extreme outliers, but none of them appeared very often or consistently. These were retained in the dataset and saved for future analysis.

In addition, sample tree 1 at site 1 (a white ash) was felled during a thunderstorm in autumn 2007 and the two hawthorns contracted a viral disease. Thus, they were not included in the dataset.

5.3.1.2 Descriptive summary of the phenological data

The corresponding day of year (DOY) for each phenophase of each sample tree was extracted from the ground phenological observation data. The general extraction rule was that the corresponding DOY was set as the first date when the sample tree reached a specific phenophase; or if this specific phenophase was skipped, the corresponding DOY was set as the date when the sample tree reached the nearest phenophase. The basic descriptive statistics, including number of cases, mean, median, minimum, maximum, range, standard error of mean, and standard deviation, were summarized for each species individually, in addition to the entire community for each phenophase using mean corresponding DOY for autumn periods between 2007 and 2012 and spring periods between 2008 and 2012.

5.3.1.3 Phenological data transformation

The phenological observation records are ordinal data, but they include valuable information beyond the ranking. The data were converted into interval data in order to keep as much information as possible and conform to statistical evaluation requirements. Phenophase levels falling into the interval from 0 to 10% are set as 5%, from 10% to 50%

as 30%, from 50% to 90% as 70%, and greater than 90% as 95%. Most of the following analysis is based on these transformed phenological data.

5.3.1.4 Satellite data preprocessing

The boundary of Downer Woods (approximately 250×237 m polygon) in a Lambert conformal conic projection was transformed to a sinusoidal projection, which is the default projection for global MODIS products. The Downer Woods study area was overlain on the 250×250 m MODIS VI grids and eventually five pixels overlapped on the study area (Figure 4). Each 16-day VI value in those five pixels was extracted to calculate the mean VI value for the study area by using the ratio of the area of each pixel to the whole study area as weight. The corresponding VI quality assurance data were extracted to make sure that VIs used in this study were of useable quality. Moreover, the composite day of the year (actual image acquisition date) was extracted to comply with VI data instead of using the start date of the 16-day composite period.

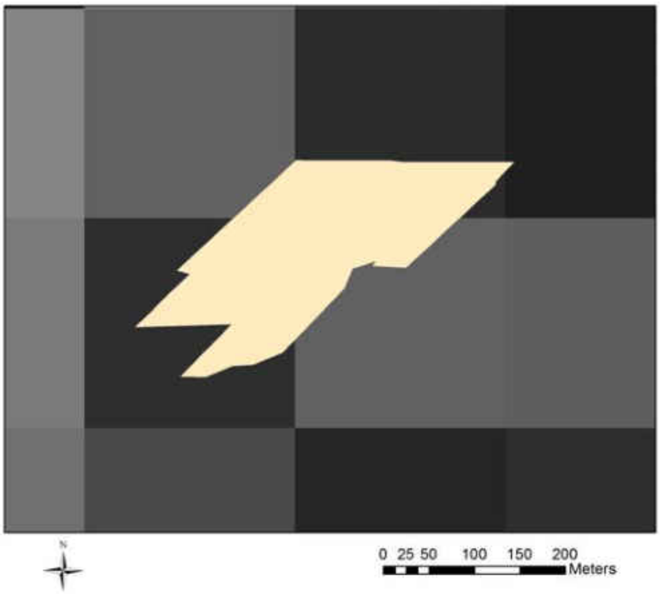


Figure 4: Study area (Downer Woods) overlaying MODIS pixel grids (250×250m)

I generated MODIS NDVI and EVI time series (2007.07-2012.12) for the study area, which is critical to connect to ground visual phenology. MODIS VI quality assurance has been divided into four categories to define overall pixel quality: 0 means good data; 1 means useful data; 2 means snow/ice covered data; and 3 means cloud covered data. In order to ensure the entire reliability of all pixels in the study area, only those assigned to a quality value of 0 or 1 were used in this study.

5.3.2 Spatial pattern analysis

5.3.2.1 Spatial autocorrelation analysis

Waldo Tobler's (1970) first law of geography states, "Everything is related to everything else, but near things are more related than distant things." (p 236) Therefore, if spatial autocorrelation exists among sample trees of individual species, care must be taken when using statistical analysis to describe and explain a particular phenological phenomenon. A basic requirement for most traditional inferential statistical tools is that samples should be random and independent from each other.

The Global Moran's I statistic is widely used to examine the degree of autocorrelation in spatial data (Rogerson, 2006) and was employed in this analysis to detect spatial autocorrelation among white ash and basswood. Other species did not have enough samples to permit meaningful spatial autocorrelation analysis.

In ArcGIS, Global Moran's I statistic is calculated as follows:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \qquad S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j}$$

Where n is the total number of spatially distributed cases, i and j are individual cases, and w_{ij} is the weight of spatial adjacency between case i and j. Results close to 1 indicate strong positive spatial autocorrelation, results close to -1 indicate strong negative spatial autocorrelation, and 0 indicates a random pattern (Rogerson, 2006).

For basswood and white ash, the corresponding DOY on which each phenological level (200, 250, 290, 300, 350, 390, 400, 450, 490, 500, 550, 590, 600, 650, 800, 850, 890, 900, 950, and 990) was recorded has been extracted by using MATLAB software. At each site, if the number of the same species was greater than one, the mean date of the same species is used to represent the average DOY of this site. Phenophase level 800 (first leaf coloration) in autumn 2009 for basswood and phenological level 800 in autumn 2008 and 2009 for white ash had less than 20 values each. Therefore, in order to assure the accuracy of the spatial autocorrelation statistic, these records have been removed from the analysis. Global Moran's I statistical tool in ArcGIS was employed to perform spatial autocorrelation analysis for each phenological level of basswood and white ash separately.

5.3.2.2 Spatial regression modeling and trend analysis

In order to examine the relationships between the phenological phases of dominant species and site location, multiple regression analysis was employed. Multiple regression analysis is a commonly used method to examine "…the relationship between a dependent variable and a set of independent, explanatory variables" (Rogerson, 2006, 193). The regression equation is as follows:

$$\hat{y} = a + b_1x_1 + b_2x_2 + \cdots + b_px_p$$

Where $\hat{y}$ is the predicted value of dependent variable and x_1, …, x_p are independent variables. The values of the parameters a, b_1, …, b_p are calculated by minimizing the sum of the squared residuals (Rogerson, 2006).

This method was also conducted on the two dominant species, basswood and white ash. Phenophase level was the dependent variable. Latitude, longitude, and the nearest distance from each site to the woods edge (in meters) all served as explanatory parameters of location. This spatial pattern analysis was conducted at the site scale and the latitude and longitude values were only used as the variables for location, so, the results cannot be extrapolated to a large scale. In regression analysis, there is an assumption that there is no multicollinearity among independent variables. For better spatial regression modeling, multicollinearity was checked by computing correlations among latitude, longitude, and the nearest distance to the edge.

5.3.3 Relationships between phenology and microclimate

5.3.3.1 Correlation analysis

Simple correlation analysis was conducted to detect possible relationships between phenology and climatic factors. Pearson's product-moment correlation coefficients were calculated to evaluate the strength of linear associations between phenology and climatic factors. Pearson's product-moment correlation coefficient is calculated as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y}$$

Where s_x and s_y are sample standard deviations of variables x and y, respectively (Rogerson, 2006).

5.3.3.2 Regression models for phenology and microclimatic factors

After defining potential climatic factors, phenological progression models were built to examine how specific climatic factors influence phenology as well as to predict the phenological progress influenced by various climatic factors. In this study, the phenological data and related climate data were used as multi-dimensional data, which contain observations on sequential phenological phases over multiple years for the same individual species. The general regression equation is:

$$\hat{Y} = b_0 + b_1 X_1 + \cdots + b_i X_i$$

Where $\hat{Y}$ is the predicted phenophase level, X_1, …, and X_i are climatic factors, b_0 is constant, and b_1 ,…, and b_i are coefficients for the corresponding independent variables.

5.3.4 Breakpoint detection

Piecewise logistic functions have been broadly applied to land surface phenology to determine seasonal transition dates since Zhang et al. (2003) first employed this method to deal with MODIS EVI data sets. This logistic model has already been proven to be a valid and effective approach to tracking the annual cycle of vegetation phenology (greenup, maturity, senescence, and dormancy), which was used to create MODIS Global Land Cover Dynamic products (Ganguly *et al.*, 2010). However, I found that the relationships between VI and ground visual phenology also comply with the logistic curves; therefore, this approach was applied to track the breakpoints and further detect the connections between VI and ground visual phenology. The logistic function was adopted from Zhang *et al.* (2003) as follows:

$$\mathrm{y}(VI) = \frac{c}{1 + e^{a+b*VI}} + d$$

where *VI* is the vegetation index, *y*(*VI*) is the ground visual phenophase value to the corrpesponding *VI*, *a* and *b* are fitting parameters, *c*+*d* is the maximum VI value, and *d* is the initial background VI value.

Breakpoints were assigned to the largest or smallest rate of change (corresponding to the point from steep curve to gentle curve) in the curvature of the fitted logistic models. The curvature *K* and the rate of change of the curvature *K′* are calculated as follows:

$$K = \frac{\mathrm{d}\alpha}{\mathrm{d}s} = -\frac{b^2cz(1-z)(1+z)^3}{[(1+z)^4 + (bcz)^2]^{\frac{3}{2}}}$$

$$K' = b^3cz\left\{\frac{3z(1-z)(1+z)^3[2(1+z)^3 + b^2c^2z]}{[(1+z)^4 + (bcz)^2]^{\frac{5}{2}}} - \frac{(1+z)^2(1+2z-5z^2)}{[(1+z)^4 + (bcz)^2]^{\frac{3}{2}}}\right\}$$

Where $z = e^{a+b*VI}$, α is the angle (in radians) of the unit tangent vector at the corresponding *VI* along a differentiable curve, and *s* is the unit length of the curve.

6. Results

6.1 Descriptive summary of the phenological data

6.1.1 Downer Woods

Community level autumn phenology

Table 11 presents the basic descriptive statistics for each individual tree species together with the community as a whole for each autumn phenophase between 2007 and 2012. Included in the table are the number of observations, and the means, minima, maxima, and standard errors of the means.

Table 12 presents the durations (number of days) between each of the phenophases that represent leaf coloration and leaf fall, as well as the duration of the entire autumn season. Figure 5 illustrates the mean day of year (DOY) of each phenophase for each species. Additionally, Figures 6 and 7 represent the mean DOY of each phenophase for each species for each year. Leaf coloration and leaf fall were observed simultaneously, therefore there are overlaps in the phenophase dates for leaf coloration and leaf fall.

Leaf coloration phenophases were represented by 800, 810, 850, and 890 as leaf color increased progressively. The overall average leaf coloring started (phenophase 800) on DOY was 263 and very little variation was observed between the species (Table 11, Figures 5 and 6). On average, the subsequent levels of leaf coloration (810, 850, and 890) were reached on DOY 269(±0.34), nearly one week later, DOY 278(±0.41), two weeks later, and DOY 282(±0.44), ~19 days later, respectively (Tables 11 and 12).

Leaf fall phenophases were represented by 900, 910, 950, and 990 as leaf fall progressed. The levels of leaf fall (900, 910, 950, and 990) were reached on average on DOY 269(±0.27), followed by DOY 278(±0.36), ~9 days later, DOY 286(±0.40), ~17 days later, and finally DOY 291(±0.45), approximately three weeks after the start of leaf fall (Tables 11 and 12). The autumn phenology season at the community level in Downer Woods, therefore, lasted for approximately 28 days.

Species level autumn phenology

In general, the timing of leaf coloration and leaf fall for white ash was consistently earlier than for the other species studied. For example, coloration phenophases 800, 810, 850, and 890 were reached on DOY 263(±0.43), 267(±0.50), 272(±0.51), and 275(±0.52) respectively whereas leaf fall phenophases 900, 910, 950, and 990 were reached on DOY 268(±0.38), 275(±0.52), 282(±0.49), and 286(±0.48) respectively with the total duration of the autumn phenological season of this species being 23 days (Tables 11 and 12). In contrast to this, the oak species, especially red oak, were always the last trees to reach each of the autumn phenophases. On average, red oak reached leaf coloration phenophases 800, 810, 850, and 890 on DOY 264(±1.30), 274(±1.55), 290(±1.51), and 296(±1.36) respectively and leaf fall phenophases 900, 910, 950, and 990 on DOY 273(±1.38), 287(±1.35), 302(±1.28), and 313(±1.70) respectively with an overall autumn phenological season duration of 49 days (more than twice that of white ash). The difference in phenological timing of these two species increases as autumn phenology progresses. Both species begin to color (phenophase 800) at approximately the same time (DOY 263 and 264 for white ash and red oak respectively), but the difference increases substantially by the time of leaf fall (phenophase 990) which occurs with a gap of nearly one month (27 days). Overall, white ash was the first species to enter winter dormancy and red oak the last.

Basswood represents an intermediate phenology between the two previous species. On average, basswood began leaf coloration (phenophase level 800) on DOY 263(±0.41) and ended (phenophase level 890) on DOY 284(±0.57). Leaf fall for this species began on approximately DOY 269(±0.43) and ended on DOY 290(±0.57) resulting in an autumn phenology duration of approximately 27 days, similar to that of white ash (Tables 11 and 12).

Boxelder, which some individuals consider to be a shrub and which is not a dominant tree species in terms of abundance in Downer Woods, has a later autumn phenology than the majority of the dominant species but behaves more like the oaks. On average, boxelder reached the beginning of leaf coloration (phenophase level 800) on DOY 265(±1.08) and the end of leaf fall (phenophase level 990) on DOY 300(±1.31) with a total autumn phenological duration of 35 days.

Table 11: Case summaries of autumn leaf coloration and leaf fall phenophases from 2007 to 2012 (Number of cases/N, mean, minimum/Min, maximum/Max, and standard error of mean/SE). Note: 800 (start) to 890 (end) of leaf coloration phenophase; 900 (start) to 990 (end) of leaf fall phenophase.

		Leaf Coloration				**Leaf Fall**			
Observed Species		**800**	**810**	**850**	**890**	**900**	**910**	**950**	**990**
Basswood	N	249	249	256	258	258	258	258	258
	Mean	263	269	279	284	269	279	285	290
	Min	255	257	260	266	262	264	268	274
	Max	280	296	302	307	288	301	309	316
	SE	0.41	0.52	0.57	0.57	0.43	0.52	0.51	0.57
Boxelder	N	30	30	30	30	30	30	30	30
	Mean	265	274	288	293	273	284	295	300
	Min	257	257	267	278	262	269	278	288
	Max	277	292	300	305	287	305	310	312
	SE	1.08	1.72	1.36	1.34	1.45	1.79	1.42	1.31
Hophorn-beam	N	6	6	6	6	6	6	6	6
	Mean	263	271	286	293	270	284	293	301
	Min	257	264	277	285	262	278	285	295
	Max	275	280	294	299	282	291	306	311
	SE	2.75	2.55	2.86	2.12	2.99	2.19	3.12	2.71
Red Oak	N	24	24	24	24	24	24	24	24
	Mean	264	274	290	296	273	287	302	313
	Min	257	259	278	284	264	278	289	299
	Max	280	287	301	307	287	296	313	329
	SE	1.3	1.55	1.51	1.36	1.38	1.35	1.28	1.7
White Ash	N	201	201	225	240	240	240	240	240
	Mean	263	267	272	275	268	275	282	286
	Min	255	257	258	257	261	262	264	271
	Max	280	292	296	301	282	296	301	307
	SE	0.43	0.5	0.51	0.52	0.38	0.52	0.49	0.48
White Oak	N	48	48	48	48	48	48	48	48
	Mean	264	271	285	294	272	284	299	307
	Min	257	258	262	278	265	267	288	295
	Max	280	287	301	307	291	301	313	323
	SE	0.91	1.12	1.33	1	0.94	1.02	1.02	1.13
Total	N	558	558	589	606	606	606	606	606
	Mean	263	269	278	282	269	278	286	291
	Min	255	257	258	257	261	262	264	271
	Max	280	296	302	307	291	305	313	329
	SE	0.27	0.34	0.41	0.44	0.27	0.36	0.4	0.45

Table 12: The duration (number of days) between each phenophase of leaf coloration and leaf fall (2007-2012 average)

	Duration (days)								
Observed Species	**800-810**	**810-850**	**850-890**	**Leaf Coloration**	**900-910**	**910-950**	**950-990**	**Leaf Fall**	**Autumn**
Basswood	6	9	5	21	9	7	5	21	27
Boxelder	9	14	5	28	12	11	4	27	35
Hophornbeam	8	14	7	30	14	10	8	31	38
Red Oak	10	16	6	32	14	14	11	40	48
White Ash	4	5	3	12	7	6	4	18	23
White Oak	8	14	9	30	13	15	8	35	43
Total	6	8	5	19	9	8	5	22	28

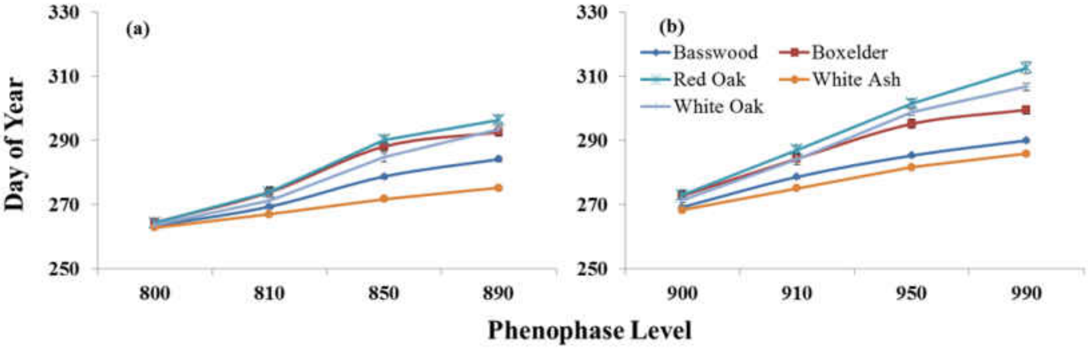


Figure 5: Average (2007-2012) DOY(±SE) by species (a) leaf coloration phenophase level (800-start to 890-end of phenophase); (b) leaf fall phenophase level (900-start to 990-end of phenophase)

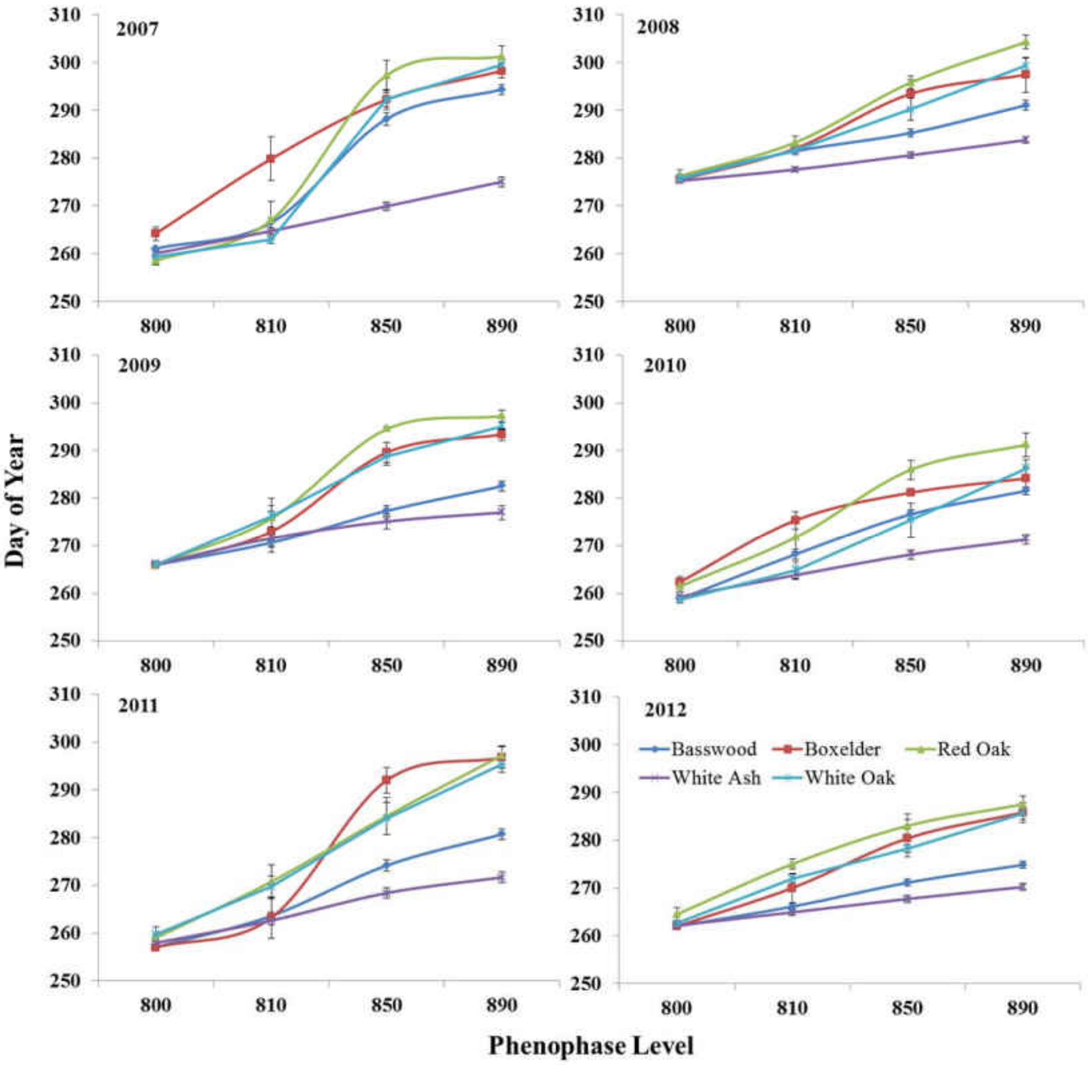


Figure 6: Average DOY(±SE) for leaf coloration phenophases in autumn (800 (start) to 890 (end)), by year and species

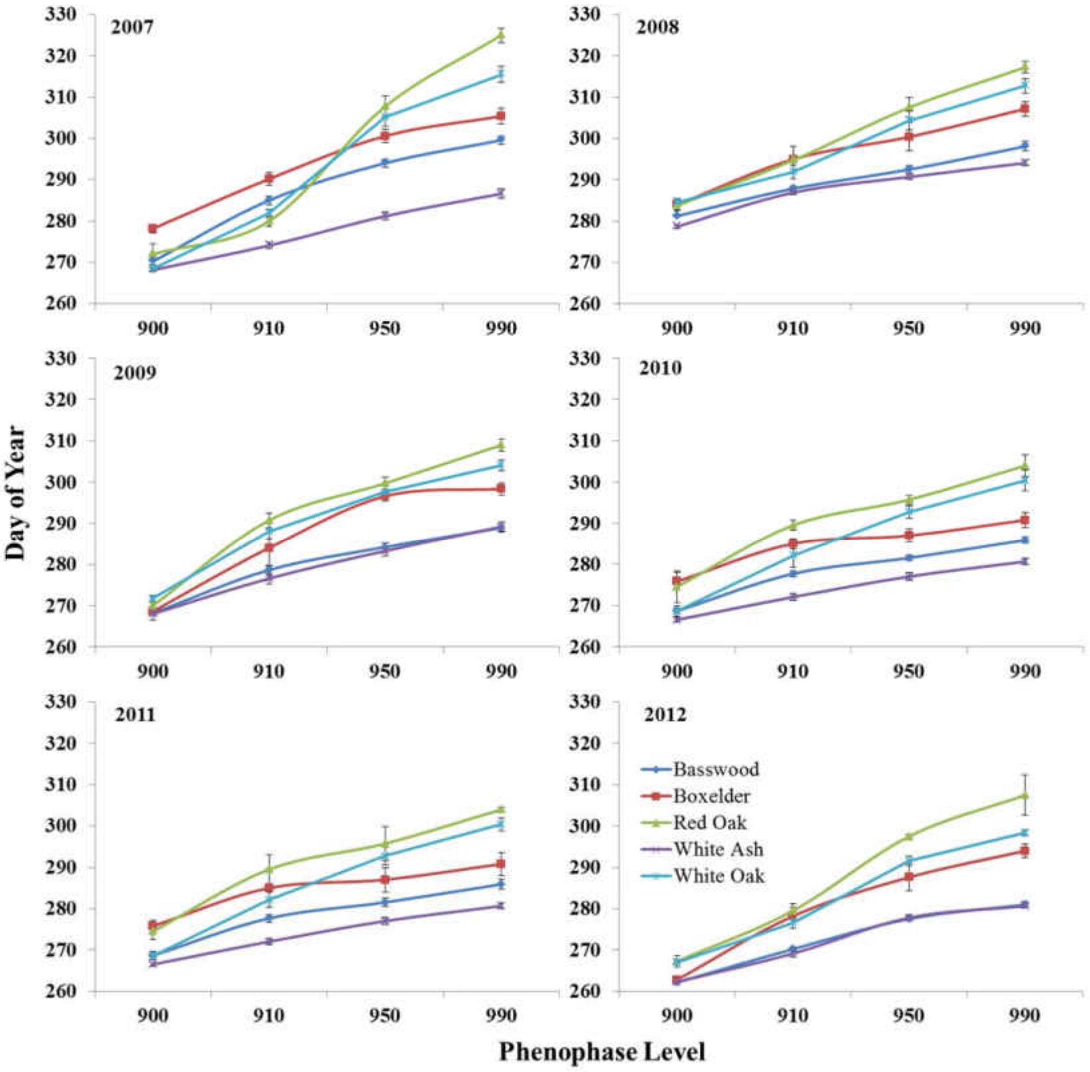


Figure 7: Average DOY(±SE) for leaf fall phenophases (900 (start) to 990(end)), by year and species

Community level spring phenology

Tables 13-1, 13-2, and 13-3 describe the basic statistics for each individual tree species and the community as a whole for each spring phenophase between 2008 and 2012. Included in these tables are numbers of observations, means, minima, maxima, and standard errors of the means. Table 14 presents the duration (number of days) between each of the major phenophases of spring as well as the duration of the entire spring season. Figure 8 shows the average DOY of phenophases for each species in spring. In addition, Figure 9 illustrates the average DOY of each spring phenophase for each species for each year.

Spring phenophases were assigned to 100, 110, 150, 190, 200, 210, 250, 290, 300, 310, 350, 390, 400, 410, 450, 490, 500, 510, 550, 590, 600, 625, 650, and 675 according to the development stages of bud (100-390) or leaves (400-675). Spring phenophases 100, 110 and 150 were not included in the analysis because, first, at the very beginning of spring, the buds of woody species are very difficult to observe because of their height in the canopy, and second, this study is primarily focused on leaf phenology. In addition, it was considered appropriate to focus on the intermediate phenophase levels only for clarity and convenience purposes, as to provide details on each phenophase level individually would be excessive. The overall average DOY when buds were considered to be fully visible was 104(±0.44) and the major phenophase levels of spring (290, 390, 490, 590, and 675) were reached on 115(±0.48), 11 days later, DOY 124(±0.38), 20 days later, DOY 131(±0.36), 27 days later, DOY 136(±0.40), approximately a month later, and DOY 145(±0.41), nearly six weeks later (Tables 13-1, 13-2, 13-3, and 14). Therefore, the total duration of the spring phenology season at the community level was approximately one and a half months.

Species level spring phenology

In contrast to species level autumn phenology, the timing of spring phenology of white ash was consistently later than the other species at the beginning of spring but subsequently caught up with the basswood and oaks around the time of leaves out

(Figures 8 and 9). Phenophase levels 190 (buds visible), 290 (buds swollen), 390 (buds open), 490 (leaves out), 590 (leaves fully unfolded), and 675 (leaf expansion level) were reached on DOY 110(±0.70), 120(±0.63), 127(±0.48), 132(±0.51), 138(±0.54), and 148(±0.57) respectively, with the total duration of the spring phenological season of white ash being ~5 weeks (Tables 13-1, 13-2, 13-3, and 14).

In contrast to white ash, boxelder was always the first species to green up and advanced through the spring phenophases at a faster rate than other species (Figures 8 and 9). On average, boxelder reached phenophases 190, 290, 390, 490, 590, and 675 on DOY 101(±1.13), 102(±1.91), 110(±1.92), 117(±1.98), 118(±2.19), and 130(±1.75) respectively, with an overall spring phenology duration of nearly a month (two weeks less than that of the community as a whole) (Tables 13-1, 13-2, 13-3, and 14).

The phenology of the basswood and oaks was more like boxelder at the beginning of spring and more like white ash at the end of spring (Figures 8 and 9). Basswood reached buds fully visible on DOY 100(±0.45) and full leaf expansion on DOY 143(±0.58) with the total phenology duration lasting six weeks (Tables 13-1, 13-2, 13-3, and 14). White oak exhibited the longest spring phenology season, lasting a total of seven weeks, beginning on DOY 101(±1.47) and ending on DOY 150(±1.22).

Table 13-1: Case summaries of spring phenophases 190-310 from 2008 to 2012 (Number of cases/N, mean, minimum/Min, maximum/Max, standard error of mean/SE). Note: 100 levels (buds visible), 200 levels (buds swollen), 300 levels (buds open).

Observed Species		**190**	**200**	**210**	**250**	**290**	**300**	**310**
Basswood	N	212	212	212	214	215	215	215
	Mean	100	104	106	108	112	116	118
	Min	88	88	90	94	94	95	97
	Max	110	114	118	125	126	129	134
	SE	0.45	0.56	0.61	0.65	0.69	0.66	0.61
Boxelder	N	11	11	11	19	20	20	20
	Mean	101	103	104	100	102	103	104
	Min	96	96	96	88	90	90	90
	Max	105	107	110	112	114	117	119
	SE	1.13	1.41	1.61	2.02	1.91	2.05	2.07
Hophornbeam	N	4	4	4	4	4	4	4
	Mean	98	100	100	102	107	110	112
	Min	88	88	88	90	92	92	92
	Max	105	107	109	110	114	118	123
	SE	3.57	4.29	4.6	4.44	4.99	6.14	6.92
Red Oak	N	20	20	20	20	20	20	20
	Mean	101	105	107	109	112	115	117
	Min	88	92	92	94	95	102	104
	Max	112	119	119	123	125	126	126
	SE	1.81	2.13	2.27	2.42	2.29	1.92	1.81
White Ash	N	203	203	203	204	205	205	205
	Mean	110	113	115	118	120	122	123
	Min	90	92	92	94	97	101	104
	Max	135	141	141	141	141	141	141
	SE	0.7	0.69	0.71	0.69	0.63	0.6	0.55
White Oak	N	37	37	37	40	40	40	40
	Mean	101	105	106	108	111	114	115
	Min	88	88	92	94	95	97	104
	Max	112	117	119	123	125	126	126
	SE	1.32	1.61	1.63	1.67	1.58	1.47	1.37
Total	N	487	487	487	501	504	504	504
	Mean	104	108	110	112	115	118	119
	Min	88	88	88	88	90	90	90
	Max	135	141	141	141	141	141	141
	SE	0.44	0.45	0.48	0.49	0.48	0.45	0.42

Table 13-2: Case summaries of spring phenophases 350-500 from 2008 to 2012 (Number of cases/N, mean, minimum/Min, maximum/Max, standard error of mean/SE). Note: 300 levels (buds open), 400 levels (leaves out – not fully unfolded), 500 levels (leaves fully unfolded).

Observed Species		350	390	400	410	450	490	500
Basswood	N	215	215	215	215	215	215	215
	Mean	120	124	125	126	129	130	131
	Min	102	104	106	108	110	110	114
	Max	136	140	140	140	142	147	147
	SE	0.58	0.56	0.52	0.5	0.49	0.5	0.51
Boxelder	N	20	20	20	20	20	20	20
	Mean	108	110	111	112	114	117	118
	Min	92	94	94	94	95	101	102
	Max	121	121	123	123	123	128	129
	SE	1.89	1.92	1.97	2.02	2.01	1.98	2.04
Hophornbeam	N	4	5	5	5	5	5	5
	Mean	115	114	116	116	118	119	120
	Min	94	95	101	102	104	106	106
	Max	125	126	126	126	128	129	129
	SE	7.15	6.27	5.39	5.26	5.37	5.1	5.24
Red Oak	N	20	20	20	20	20	20	20
	Mean	120	123	125	125	128	131	132
	Min	106	111	111	111	113	120	120
	Max	128	133	134	134	136	140	142
	SE	1.81	1.71	1.54	1.57	1.52	1.45	1.67
White Ash	N	205	205	205	205	205	205	205
	Mean	125	127	128	129	131	132	134
	Min	104	106	106	106	106	110	110
	Max	141	142	147	147	150	150	151
	SE	0.52	0.48	0.49	0.49	0.52	0.51	0.53
White Oak	N	40	40	40	40	40	40	40
	Mean	118	122	124	125	127	131	135
	Min	106	106	106	106	106	110	120
	Max	128	132	136	136	142	143	147
	SE	1.38	1.39	1.42	1.47	1.52	1.41	1.15
Total	N	504	505	505	505	505	505	505
	Mean	122	124	126	127	129	131	132
	Min	92	94	94	94	95	101	102
	Max	141	142	147	147	150	150	151
	SE	0.4	0.38	0.37	0.36	0.37	0.36	0.37

Table 13-3: Case summaries of spring phenophases 510-675 from 2008 to 2012 (Number of cases/N, mean, minimum/Min, maximum/Max, standard error of mean/SE). Note: 500 levels (leaves fully unfolded), 600 levels (leaf expansion level).

Observed Species		**510**	**550**	**590**	**600**	**625**	**650**	**675**
Basswood	N	215	215	215	215	215	215	215
	Mean	132	134	135	136	138	141	143
	Min	116	120	120	122	123	125	129
	Max	147	150	150	150	153	156	161
	SE	0.5	0.51	0.51	0.52	0.53	0.56	0.58
Boxelder	N	20	22	25	25	25	25	25
	Mean	118	119	118	120	123	126	130
	Min	102	104	104	104	106	110	116
	Max	129	131	133	136	140	142	143
	SE	2.05	2.12	2.19	2.24	2.12	1.98	1.75
Hophornbeam	N	5	5	5	5	5	5	5
	Mean	120	122	123	124	130	134	138
	Min	106	106	108	110	120	124	129
	Max	129	131	133	133	142	147	150
	SE	5.24	4.93	5.01	4.46	4	4.29	4.03
Red Oak	N	20	20	20	20	20	20	20
	Mean	133	134	137	138	141	143	146
	Min	120	122	125	125	130	134	134
	Max	142	147	150	150	152	152	154
	SE	1.67	1.7	1.81	1.73	1.61	1.55	1.6
White Ash	N	205	205	205	205	205	205	205
	Mean	134	136	138	139	143	146	148
	Min	110	112	120	122	124	128	130
	Max	151	153	153	154	160	168	168
	SE	0.52	0.54	0.54	0.55	0.52	0.54	0.57
White Oak	N	40	40	40	40	40	40	40
	Mean	136	139	140	142	145	147	150
	Min	120	124	128	130	132	134	138
	Max	147	150	152	154	154	161	163
	SE	1.17	1.12	1.12	1.05	1.08	1.15	1.22
Total	N	505	507	510	510	510	510	510
	Mean	133	134	136	137	140	143	145
	Min	102	104	104	104	106	110	116
	Max	151	153	153	154	160	168	168
	SE	0.37	0.38	0.4	0.4	0.4	0.41	0.41

Table 14: The durations between major phenophases of spring (2008-2012 average). Note: 190: fully buds visible; 290: fully buds swollen; 390: fully buds open; 490: fully leaves out; 590: leaves fully unfolded; 675: leaf fully expansion

	Duration (days)					
Observed Species	**190-290**	**290-390**	**390-490**	**490-590**	**590-675**	**Spring**
Basswood	12	12	6	5	8	43
Boxelder	1	8	7	1	12	29
Hophornbeam	9	7	5	4	15	40
Red Oak	11	11	8	6	9	45
White Ash	10	7	5	6	10	38
White Oak	10	11	9	9	10	49
Total	11	9	7	5	9	41

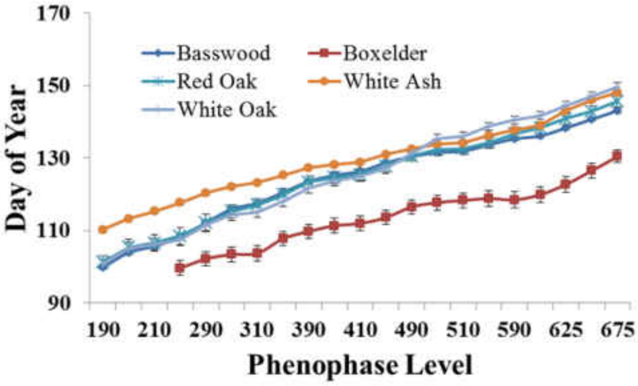


Figure 8: Average (2008-2012) DOY(±SE), by species

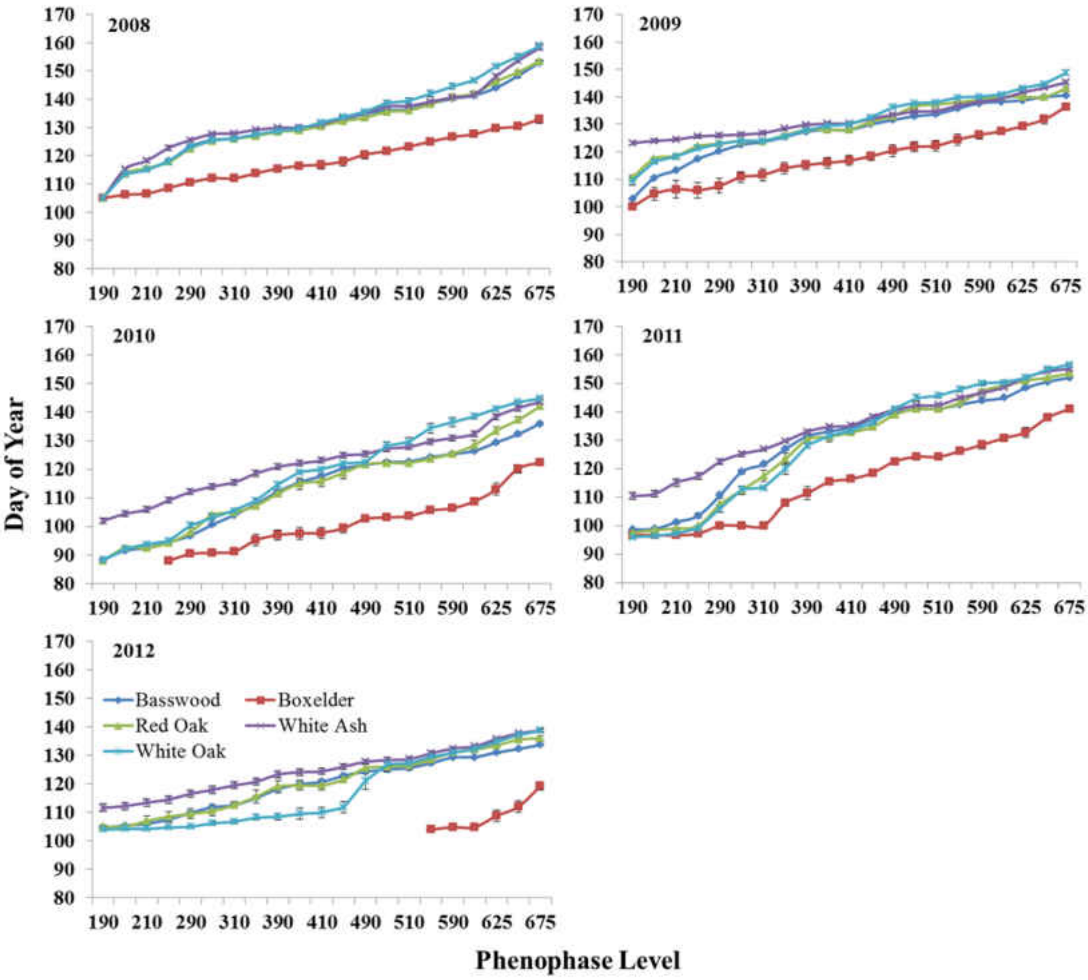


Figure 9: Average DOY(±SE), by year and species (2008-2012)

Summary

In general, autumn phenology in Downer Woods started approximately in mid-September and ended at the beginning of November, whereas spring phenology started approximately in late March and ended in late May. White ash was the last species to green-up in spring and the first species to yellow in autumn. The phenology of boxelder had a longer growing season than the dominant tree species in the Woods. The contrasting results between the individual species indicate substantial inter-species variation in both the progression and duration of each of the phenophases examined for both the autumn and spring phenology seasons.

Growing season

In this study, the start of the growing season (SOS) is defined as the date at which buds are fully open (leaves visible, phenophase level 390) and the end of the growing season (EOS) is determined by the date when leaves have reached full coloration (phenophase level 890). Therefore, the length of the growing season (LOS) is the duration between buds fully open (leaves visible, phenophase level 390) and leaves fully colored (phenophase level 890). This duration is approximately equal to the photosynthetic period of vegetation (Menzel, 2003; Xu & Chen, 2012).

On average (2008-2012), the growing season in Downer Woods started on DOY 124 and ended on DOY 281, a 157-day duration (Table 15). Boxelder was determined to have the longest growing season of 183 days, nearly a month longer than the growing season length at the community level (Table 15). The longer growing season of boxelder resulted from a two-week earlier start and a 10-day later end to the growing season. Red oak and white oak had the next longest growing seasons of 172 and 170 days respectively, which mainly resulted from a two week later EOS compared to the EOS at the community level (Table 15). Basswood had nearly the same SOS (DOY 124), EOS (DOY 282), and LOS (159 days) as at the community level (Table 15). White ash had the shortest growing season, 148 days, nine days less than the community, reflecting three days later in the SOS and 6 days earlier in the EOS (Table 15).

Table 15: Average DOY (2008-2012) of start of the growing season (SOS, 390), end of the growing season (EOS, 890), and length of the growing season (LOS), by species

Average (2008-2012)	SOS (DOY)	EOS (DOY)	LOS (days)
Community	124	281	157
Basswood	124	282	159
White Ash	127	275	148
Red Oak	124	295	172
White Oak	122	292	170
Boxelder	110	291	183

From 2008 to 2012, at the community level, the SOS advanced by 1.5 ($P > 0.10$) days per year, whereas the EOS advanced by 3.24 ($P \leq 0.05$) days per year; as a result, the LOS in Downer Woods declined at a rate of 1.7 days per year (Table 16 and Figures 10, 11, 12). Inevitably, there was significant variation observed in the LOS between individual species. All of the species showed an earlier start of the growing season, which varied from a rate of 1 day per year (white ash) to 4 days per year (white oak), but none of these trends were statistically significant. Basswood, white ash, and red oak showed an earlier end to the growing season at a rate of more than 3 days ($P < 0.10$) per year. Boxelder and white oak showed a longer growing season at a rate of 2.1 days per year and 1.4 days per year, respectively. In contrast, basswood, red oak, and white ash exhibited a shortened growing season at a rate of 1.77 days per year, 1.4 days per year, and 2.34 days per year, respectively. However, similar to the SOS, none of the trends for the LOS was statistically significant.

Overall, each species showed an earlier end to the growing season; therefore, the length of the growing season increased primarily due to an earlier start as opposed to a delay in the end of the growing season. In addition, some species showed a shortening of the growing season primarily driven by this earlier end to the growing season.

Table 16: Average DOY of the growing season (SOS, 390), end of the growing season (EOS, 890), and length of the growing season (LOS), by year and species

Community	SOS (DOY)	EOS (DOY)	LOS (days)
2008	128	290	161
2009	128	283	155
2010	115	279	164
2011	131	280	149
2012	119	275	156

Basswood	SOS (DOY)	EOS (DOY)	LOS (days)
2008	128	291	163
2009	127	283	155
2010	112	282	169
2011	131	281	149
2012	118	275	157

White Ash	SOS (DOY)	EOS (DOY)	LOS (days)
2008	130	284	154
2009	130	277	148
2010	121	272	151
2011	133	272	139
2012	123	270	147

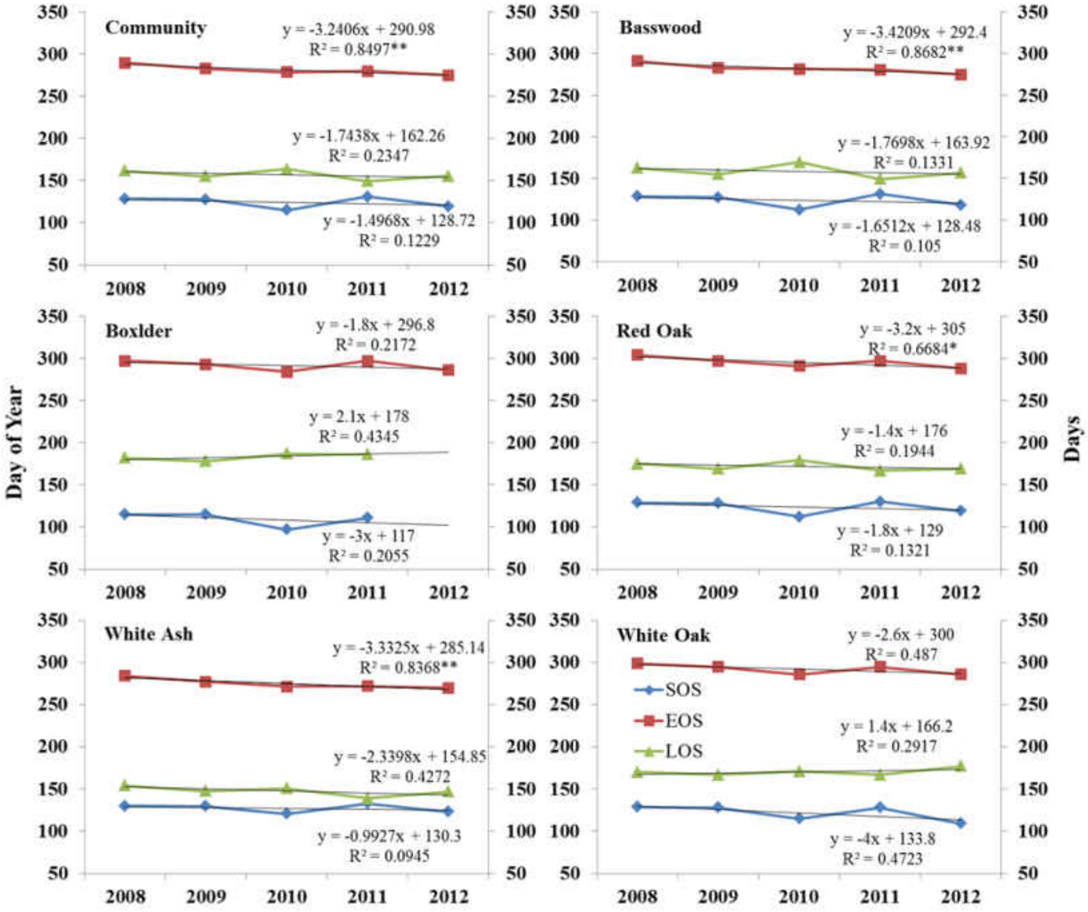
Red Oak	SOS (DOY)	EOS (DOY)	LOS (days)
2008	129	304	175
2009	128	297	169
2010	112	291	179
2011	130	297	167
2012	119	288	169

White Oak	SOS (DOY)	EOS (DOY)	LOS (days)
2008	129	299	170

2009	128	295	167
2010	115	286	171
2011	128	295	167
2012	109	286	177

Boxelder	**SOS (DOY)**	**EOS (DOY)**	**LOS (days)**
2008	115	297	182
2009	115	293	178
2010	97	284	187
2011	111	297	186
2012		286	

* In 2012, when the observation started, the SOS of boxelder was already reached.



*: The trend is significant at the 0.10 level; **: The trend is significant at the 0.05 level.

Figure 10: Annual variation and trend of the start of the growing season (SOS), the end of the growing season (EOS), and the length of the growing season (LOS), by species

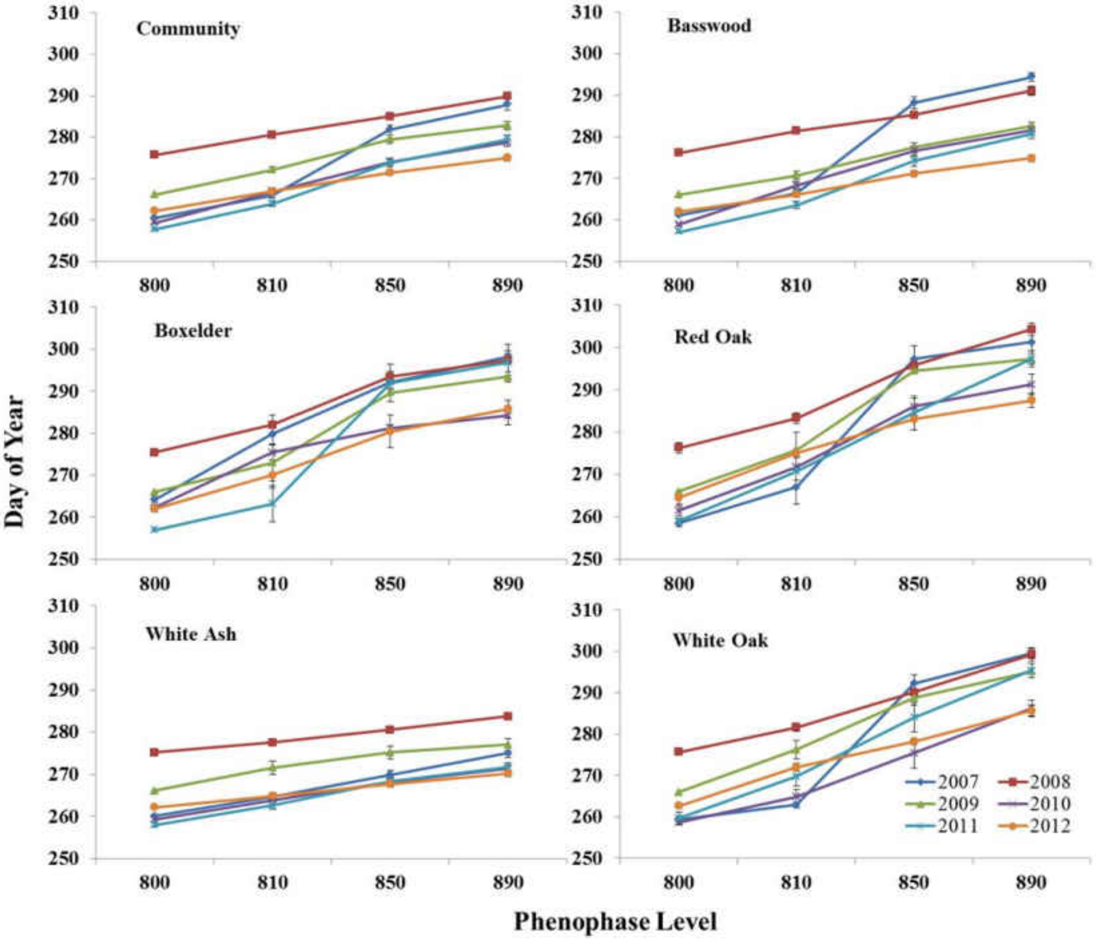


Figure 11: Average day of year (DOY) of leaf coloration phenophases in autumn, by species

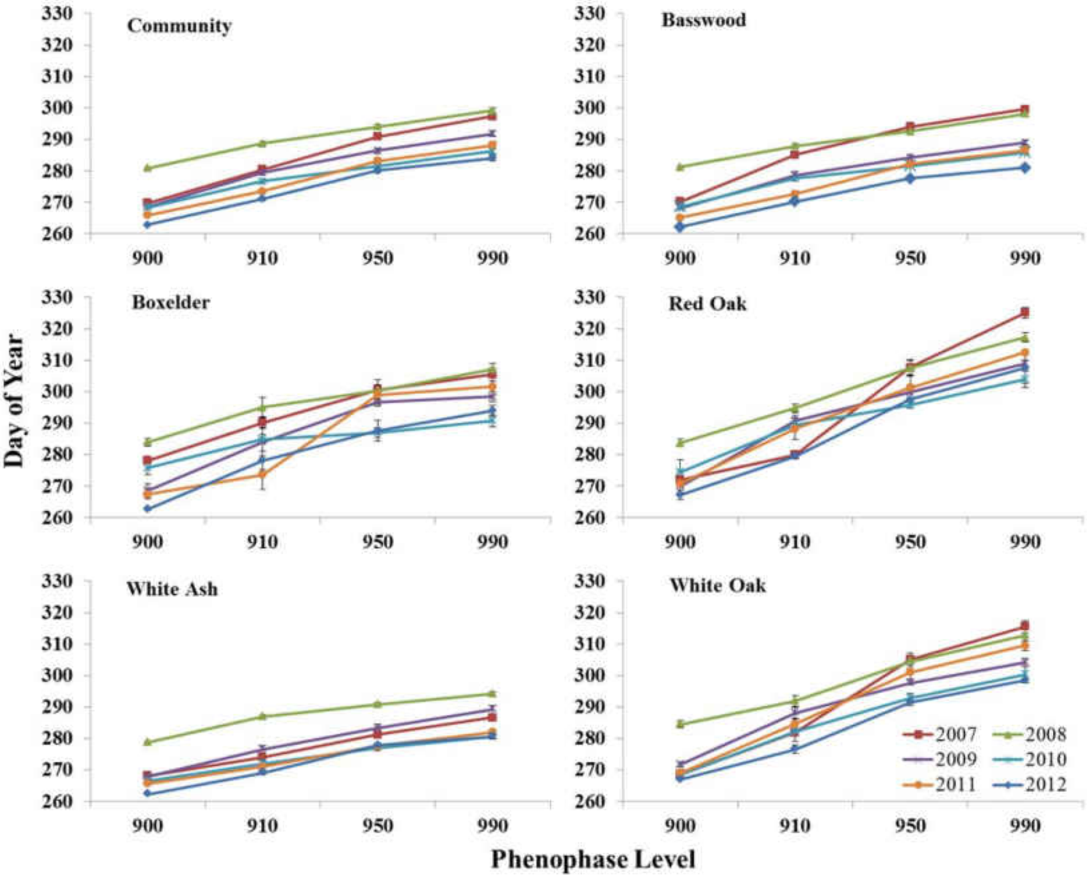


Figure 12: Average day of year (DOY) of leaf fall phenophases in autumn, by species

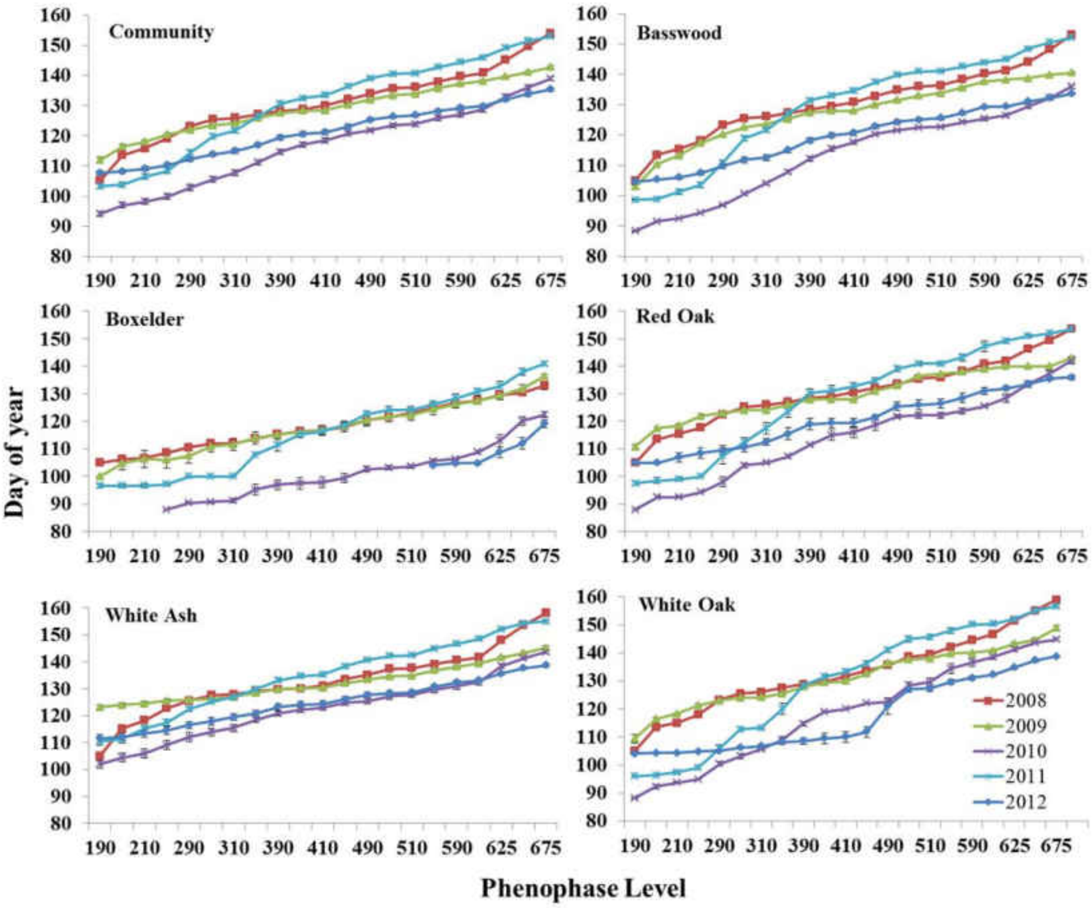


Figure 13: Average day of year (DOY) of phenophases in spring, by species

6.1.2 Parks Fall Range District

Autumn phenology

The timing of both leaf coloration and leaf fall of basswoods in the Park Falls study site were consistently earlier than those in Downer Woods (Tables 11 and 17). Leaf coloration phenophases 800, 810, 850, and 890 were reached on DOY 262(±0.23), 263(±0.38), 269(±0.40), and 273(±0.43) respectively whereas leaf fall phenophases 900, 910, 950, and 990 were reached on DOY 262(±0.22), 267(±0.47), 271(±0.49), and 275(±0.63) respectively.

Table 17: Case summaries of autumn leaf coloration and leaf fall phenophases for 2010 and 2012 (Number of cases/N, mean, minimum/Min, maximum/Max, and standard error of mean/SE). Note: 800 (start) to 890 (end) of leaf coloration phenophase; 900 (start) to 990 (end) of leaf fall phenophase.

		Leaf Coloration				Leaf Fall			
Observed Species		**800**	**810**	**850**	**890**	**900**	**910**	**950**	**990**
Basswood	N	29	47	48	48	46	48	48	48
	Mean	262	263	269	273	262	267	271	275
	Min	260	260	260	268	260	260	266	268
	Max	263	268	275	279	263	277	279	291
	SE	.230	.382	.396	.428	.224	.473	.486	.629

Spring phenology

In contrast to spring phenology of basswoods in Downer Woods, the timing of spring phenology of basswoods at the Park Falls study site was consistently later (Tables 13 and 18). Phenophase levels 190, 290, 390, 490, 590, and 675 were reached on DOY 124(±0.41), 129(±0.63), 135(±0.74), 140(±0.63), 142(±0.48), and 145(±0.40) respectively.

Table 18: Case summaries of spring phenophases 190-675 from 2008 to 2010 (Number of cases/N, mean, minimum/Min, maximum/Max, standard error of mean/SE).

Observed Species		**190**	**200**	**210**	**250**	**290**	**300**	**310**
Basswood	N	64	67	67	69	72	72	72
	Mean	124	125	126	128	129	130	132
	Min	118	118	118	118	118	120	120
	Max	131	131	133	135	139	139	142
	SE	.406	.405	.500	.574	.633	.610	.698
Observed Species		**350**	**390**	**400**	**410**	**450**	**490**	**500**
Basswood	N	72	72	72	72	72	72	72
	Mean	134	135	135	137	138	140	140
	Min	121	122	122	122	124	126	126
	Max	144	146	146	146	148	150	150
	SE	.741	.741	.737	.712	.673	.629	.600

Observed Species		**510**	**550**	**590**	**600**	**625**	**650**	**675**
Basswood	N	71	67	55	52	50	47	30
	Mean	141	140	142	143	143	145	145
	Min	127	0	134	138	140	141	142
	Max	150	150	150	150	149	150	148
	SE	.599	2.183	.484	.428	.395	.439	.403

Growing season

In spring 2008, 2009, and 2010, the differences of the SOS between basswoods in Downer Woods and Parks Falls were -12, -10, and -16 days, indicating an earlier start to spring in Downer Woods. However, in autumn 2010 and 2012, the differences between the two sites in the end of the growing season were 10 and 1 days, suggesting a later end to autumn in Downer Woods. In 2010 the length of the growing season was 21 days longer in Downer Woods than at Park Falls.

Table 19: Average DOY of the growing season (SOS, 390), end of the growing season (EOS, 890), and length of the growing season (LOS), by year

Basswood	**SOS (DOY)**	**EOS (DOY)**	**LG (days)**
2008	140		
2009	137		
2010	128	272	144
2011			
2012		274	

6.2 Spatial patterns of phenology in Downer Woods

Spring and autumn phenology vary spatially within Downer Woods, as represented by the two dominant tree species -basswood and white ash.

6.2.1 Spatial autocorrelation analysis

Spatial autocorrelation was carried out on all phenophase levels for basswood and white ash in all years to determine if spatial autocorrelation existed in each dominant species in Downer Woods. The results of this analysis revealed negative spatial autocorrelations (-0.41 and -0.43, $P \leq 0.10$) for basswood, phenophase levels 490 (leaves out) in spring 2008 and 200 (buds swollen) in spring 2009. In addition, phenophase levels 800 (leaf coloration) in autumn 2007 and 900 (leaf fall) in autumn 2010 showed positive spatial autocorrelation (0.30 and 0.30, $P \leq 0.10$). White ash, phenophase level 650 in spring 2008 showed positive spatial autocorrelation (0.47, $P \leq 0.05$). All others analyses showed no significant differences from zero, therefore, the null hypothesis was accepted that the phenophases of basswood and white ash were randomly distributed within Downer Woods.

6.2.2 Spatial regression model

Pearson correlation analysis was conducted in order to test for multicollinearity among the three locational parameters (latitude, longitude, and the minimum distance from each site to the edge). The results showed that there were no significant correlations among these parameters and thence no multicollinearity (Table 20). Therefore, the parameters can be used in the following spatial regression models.

Table 20: Correlations among latitude, longitude, and the minimum distance from each site to the edge

		Latitude	Longitude	Distance
Latitude	**Pearson Correlation**	1	.004	.043
	Sig. (2-tailed)		.985	.833
	N	27	27	27
Longitude	**Pearson Correlation**	.004	1	.282
	Sig. (2-tailed)	.985		.154
	N	27	27	27
Distance	**Pearson Correlation**	.043	.282	1
	Sig. (2-tailed)	.833	.154	
	N	27	27	27

Model 1used latitude and longitude as spatial explanatory variables, whereas model 2 used latitude, longitude, and the minimum distance from each site to the edge of Downer Woods. By comparing these two models, the existence of an edge effect in Downer Woods can be tested. Five out of 29 models of basswood were found to be statistically significant at the 0.05 or 0.10 level. For spring phenophases 650 and 675 (leaf expansion level), there was no obvious improvement in performance from model 1 to model 2. However, for spring phenophase 210 (buds swollen), autumn phenophases 890 (leaf coloration) and 990 (leaf fall), R-squared from model 1 to model 2 improved 0.084, 0.034, and 0.058, respectively (Table 21). Table 21 presents the statistical summary of R, R-squared, and p-values of spatial regression models for each phenophase level for basswood.

Table 21: Statistical summary of spatial regression models of basswood, by phenophase level

Phenophase Level	R		R-squared		*P*	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
SP_190	.253^{a}	.255^{b}	.064	.065	.517^{a}	.728^{b}
SP_200	.142^{a}	.233^{b}	.020	.054	.816^{a}	.779^{b}
SP_210	.467^{a}	.549^{b}	.218	.302	.085^{a}	.072^{b}
SP_250	.383^{a}	.385^{b}	.147	.148	.204^{a}	.372^{b}
SP_290	.312^{a}	.388^{b}	.098	.151	.358^{a}	.364^{b}
SP_300	.241^{a}	.257^{b}	.058	.066	.549^{a}	.723^{b}
SP_310	.279^{a}	.290^{b}	.078	.084	.446^{a}	.633^{b}
SP_350	.226^{a}	.258^{b}	.051	.067	.593^{a}	.718^{b}
SP_390	.318^{a}	.421^{b}	.101	.177	.344^{a}	.284^{b}
SP_400	.331^{a}	.413^{b}	.110	.170	.313^{a}	.303^{b}
SP_410	.398^{a}	.453^{b}	.158	.205	.179^{a}	.215^{b}
SP_450	.292^{a}	.300^{b}	.085	.090	.411^{a}	.605^{b}
SP_490	.203^{a}	.205^{b}	.041	.042	.658^{a}	.840^{b}
SP_500	.187^{a}	.188^{b}	.035	.035	.701^{a}	.873^{b}
SP_510	.237^{a}	.238^{b}	.056	.056	.561^{a}	.769^{b}
SP_550	.138^{a}	.145^{b}	.019	.021	.825^{a}	.937^{b}
SP_590	.253^{a}	.277^{b}	.064	.077	.516^{a}	.670^{b}
SP_600	.318^{a}	.319^{b}	.101	.102	.343^{a}	.553^{b}
SP_625	.421^{a}	.423^{b}	.178	.179	.142^{a}	.279^{b}
SP_650	.535^{a}	.537^{b}	.286	.288	.034^{a}	.085^{b}
SP_675	.506^{a}	.513^{b}	.256	.263	.052^{a}	.114^{b}
LC_800	.310^{a}	.373^{b}	.096	.139	.363^{a}	.404^{b}
LC_810	.180^{a}	.213^{b}	.032	.045	.720^{a}	.824^{b}
LC_850	.370^{a}	.403^{b}	.137	.162	.229^{a}	.327^{b}
LC_890	.510^{a}	.542^{b}	.260	.294	.049^{a}	.079^{b}
LF_900	.397^{a}	.424^{b}	.158	.179	.180^{a}	.278^{b}
LF_910	.247^{a}	.286^{b}	.061	.082	.533^{a}	.644^{b}
LF_950	.430^{a}	.471^{b}	.185	.222	.130^{a}	.180^{b}
LF_990	.525^{a}	.578^{b}	.276	.334	.040^{a}	.047^{b}

a. Predictors: (Constant), Longitude, Latitude
b. Predictors: (Constant), Latitude, Longitude, Distance
c. SP: spring; LC: leaf coloration; LF: leaf fall
d. Grey shading showed the significant models

The spatial regression models for all basswood phenophases are presented in Table 22 and the standardized coefficients of each model are shown in Table 23. In spring, phenophase 210 (buds swollen) and phenophases 650 and 675 (leaf expansion) displayed positive relationships with latitude and longitude. These results suggest that spring phenology of basswood occurs later at locations further west and further north within the study area. Temperature gradients by latitude showed a greater influence on spring phenology of basswood than temperature gradients by longitude, which means that the further north, the later the phenophase. However, the models only explain from 25.6% to 30.2% of the variation in the spatial pattern of spring phenophases of basswood.

In autumn, basswood leaf coloration 890 and basswood leaf fall 990 displayed negative relationships with latitude, longitude, and edge distance, suggesting that in locations further west, north, or with the greatest distance from the edge, the earlier the autumn phenology. In contrast to spring, temperature gradients by latitude showed less influence on autumn phenology of basswood than either temperature gradients by longitude or distance. The models explain from 29.4% to 33.4% of the variation in the spatial pattern of autumn phenophases of basswood.

Table 22: The spatial regression models, basswood

Phenophase Level	Model
SP_210	y=.078*Lon+.363*Lat-.020*Dis-80740.050
SP_650	y=.144*Lon+.489*Lat-121212.798
SP_675	y=.184*Lon+.457*Lat-128828.597
LC_890	y=-.940*Lon-.530*Lat-.060*Dis+379747.109
LF_990	y=-.886*Lon-.477*Lat-.075*Dis+354678.497

* Lon: longitude in seconds; Lat: latitude in seconds; Dis: nearest distance in meters from each site to the edge of Downer Woods; SP: spring; LC: leaf coloration; LF: leaf fall

Table 23: The standardized coefficients of each significant spatial regression model, basswood

Phenophase Level	**Standardized Coefficients**		
	Longitude	Latitude	Distance
SP_**210**	.169	.475	-.301
SP_**650**	.240	.493	-
SP_**675**	.289	.432	-
LC_**890**	-.440	-.149	-.191
LF_**990**	-.439	-.142	-.253

* Lon: longitude in seconds; Lat: latitude in seconds; Dis: nearest distance in meters from each site to the edge of Downer Woods; SP: spring; LC: leaf coloration; LF: leaf fall

According to these three spring models and two autumn models of basswood, similar rates of phenological advance across the study area by temperature gradients represented by latitude were revealed in both spring and autumn, ranging from 0.363 day/second to 0.530 day/second. In contrast, there was an obvious difference in the rate of phenological advance along a longitudinal gradient between autumn and spring. The rate of advance for autumn phenology was 0.9 day/second compared to 0.1 day/second for spring. Therefore, there is less spatial variation among basswood phenology in spring than in autumn, as shown in Figures 14 and 15, which provide examples of the spatial trends of basswood phenophases 625 (leaf expansion level) and 950 (leaf fall).

Figure 14: Spatial trend of phenophase level 625 (leaf expansion level) for basswood (a clear north/south trend towards later spring phenology is shown)

Figure 15: Spatial trend of phenophase level 950 (leaf fall) for basswood (a clear east/south trend towards later autumn phenology is shown)

Table 24 summarizes R, R-squared, and p-values of each spatial regression model of white ash by phenophase level. Similar to the above basswood models, latitude and longitude were the spatial explanatory variables in model 1, and edge distance was added as an extra explanatory variable in model 2. In contrast to the spring models of basswood, those of white ash were all statistically significant at the level from 0.001 to 0.05, except for phenophase 190 (buds visible). On the contrary, none of the autumn models of white ash were statistically significant. Model 2 showed great improvement in R-squared for early spring phenophases (200 to 600) compared to model 1 whereas later spring phenophases (625-675) showed no significant improvement between models 1 and 2.

Table 24: Statistical summary of spatial regression models of white ash, by phenophase level

Phenological phase	R		R-squared		*P*	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
SP_190	.296[a]	.468[b]	.087	.219	0.401	0.186
SP_200	.276[a]	.551[b]	.076	.304	0.454	0.07
SP_210	.381[a]	.638[b]	.145	.408	0.208	0.017
SP_250	.383[a]	.687[b]	.147	.471	0.204	0.006
SP_290	.497[a]	.764[b]	.247	.583	0.058	0.001
SP_300	.518[a]	.763[b]	.269	.582	0.044	0.001
SP_310	.515[a]	.782[b]	.265	.611	0.046	0
SP_350	.446[a]	.708[b]	.199	.502	0.109	0.004
SP_390	.439[a]	.736[b]	.193	.541	0.117	0.002
SP_400	.426[a]	.702[b]	.181	.493	0.135	0.004
SP_410	.445[a]	.675[b]	.198	.455	0.111	0.008
SP_450	.464[a]	.664[b]	.216	.440	0.088	0.01
SP_490	.398[a]	.664[b]	.158	.441	0.179	0.01
SP_500	.526[a]	.726[b]	.276	.527	0.039	0.002
SP_510	.531[a]	.718[b]	.282	.515	0.036	0.003
SP_550	.552[a]	.690[b]	.305	.476	0.026	0.006
SP_590	.553[a]	.669[b]	.306	.448	0.026	0.009
SP_600	.597[a]	.705[b]	.356	.497	0.012	0.004
SP_625	.709[a]	.755[b]	.503	.571	0.001	0.001
SP_650	.673[a]	.700[b]	.453	.490	0.002	0.004
SP_675	.635[a]	.659[b]	.403	.435	0.006	0.011
LC_800	.149[a]	.247[b]	.022	.061	0.798	0.747
LC_810	.071[a]	.077[b]	.005	.006	0.951	0.99
LC_850	.176[a]	.187[b]	.031	.035	0.731	0.874
LC_890	.203[a]	.212[b]	.041	.045	0.657	0.827
LF_900	.219[a]	.247[b]	.048	.061	0.611	0.746
LF_910	.150[a]	.246[b]	.023	.060	0.796	0.75
LF_950	.201[a]	.279[b]	.040	.078	0.663	0.663
LF_990	.239[a]	.320[b]	.057	.102	0.554	0.551

a. Predictors: (Constant), Longitude, Latitude
b. Predictors: (Constant), Latitude, Longitude, Distance
c. Grey shading showed the significant models

The significant spatial regression models of white ash are presented in Table 25 and the standardized coefficients of each model are shown in Table 26. Spring phenophases of white ash, from phenophase 200 (buds swollen) to phenophase 600 (leaf expansion), revealed positive relationships with latitude, longitude, and distance. This suggests that locations further west, north, or farthest from the edge displayed later white ash spring phenology. Locations closest to the edge of Downer Woods most influenced both early (200-290) and mid (300-510) spring phenology of white ash (Table 26).

Table 25: The spatial regression models, white ash

Pheno_phase	Model
SP_200	y=.083*Lon+.686*Lat+.188*Dis-132441.061
SP_210	y=.041*Lon+1.181*Lat+.213*Dis-196080.727
SP_250	y=.046*Lon+1.113*Lat+.230*Dis-187126.953
SP_290	y=.110*Lon+1.402*Lat+.218*Dis-251974.347
SP_300	y=.179*Lon+1.225*Lat+.183*Dis-246516.851
SP_310	y=.234*Lon+1.048*Lat+.180*Dis-236416.959
SP_350	y=.166*Lon+.853*Lat+.158*Dis-184637.901
SP_390	y=.209*Lon+.681*Lat+.157*Dis-171486.135
SP_400	y=.119*Lon+.813*Lat+.156*Dis-163559.605
SP_410	y=.154*Lon+.916*Lat+.150*Dis-190767.351
SP_450	y=.164*Lon+.983*Lat+.140*Dis-204346.466
SP_490	y=.121*Lon+.715*Lat+.144*Dis-148957.543
SP_500	y=.185*Lon+1.026*Lat+.135*Dis-217513.551
SP_510	y=.159*Lon+1.098*Lat+.133*Dis-220502.730
SP_550	y=.208*Lon+1.168*Lat+.116*Dis-246973.645
SP_590	y=.231*Lon+1.139*Lat+.103*Dis-249503.712
SP_600	y=.301*Lon+1.159*Lat+.101*Dis-274724.780
SP_625	y=.404*Lon+1.127*Lat-302648.978
SP_650	y=.352*Lon+.932*Lat-255827.576
SP_675	y=.378*Lon+.720*Lat-231116.263

* Lon: longitude in seconds; Lat: latitude in seconds; Dis: nearest distance in meters from each site to the edge of Downer Woods; SP: spring

Table 26: The standardized coefficients of each significant spatial regression model, white ash

Pheno_phase	**Standardized Coefficients**		
	Longitude	**Latitude**	**Dist_Edge**
SP_200	.038	.185	.488
SP_210	.018	.303	.524
SP_250	.021	.294	.582
SP_290	.053	.397	.593
SP_300	.099	.399	.572
SP_310	.139	.365	.602
SP_350	.105	.318	.563
SP_390	.142	.273	.604
SP_400	.077	.311	.571
SP_410	.095	.331	.519
SP_450	.101	.356	.485
SP_490	.081	.283	.544
SP_500	.124	.404	.512
SP_510	.105	.424	.494
SP_550	.134	.444	.423
SP_590	.152	.442	.385
SP_600	.203	.460	.383
SP_625	.347	.569	-
SP_650	.341	.531	-
SP_675	.394	.442	-

* Lon: longitude in seconds; Lat: latitude in seconds; Dis: nearest distance in meters from each site to the edge of Downer Woods; SP: spring

Temperature gradient by latitude was the second influencing factor used in the models. Temperature gradients by longitude showed the smallest influence on early and mid-spring phenology of white ash. The models explain from 30.4% to 61.1% of the variation in the spatial pattern of early and mid-spring phenophases of white ash. Spring phenophases, from phase 625 to phenophase 675 (leaf expansion level) displayed positive relationships with both temperature gradients by latitude and longitude. However, late in spring, temperature gradient by latitude was the most important spatial factor influencing phenology. The models explain from 43.5% to 57.1% of the variation of spatial pattern of late spring phenophases of white ash. However, none of the autumn models of white ash were statistically significant. According to the spring models, the rate of phenological advance across Downer Woods by latitude varied from 0.686 day/second to 1.402 day/second. This variation in spring phenology was greater than that of basswood, suggesting that spring phenology of white ash develops faster than that of basswood. Figures 16 and 17 provide examples of the spatial variation of white ash phenology.

Figure 16: Spatial trend of phenophase 625 (leaf expansion level), white ash

Figure 17: Spatial trend of phenophase 950 (leaf fall), white ash

6.3 Relationships between phenology and microclimate

It is well established that phenology is influenced by a range of local climatic factors, so here four groups of climatic factors, temperature, moisture, light, and wind are examined.

6.3.1 Microclimatic parameters

6.3.1.1 Daily temperature

From 2008 to 2012, the spring daily mean air temperature at site 45 (located in the southwestern corner of the woods) was consistently higher than the temperatures at the other three sites (Figures 18-1 and 18-2). The daily mean air temperature at site 23 (located near the center of the woods) was lower than the temperatures at the other three sites most of the time. In 2011, the HOBO at site 56 detected a slightly higher temperature than the HOBO at site 45. Most of the spring daily mean temperatures differences between sites were within ±0.60 °C.

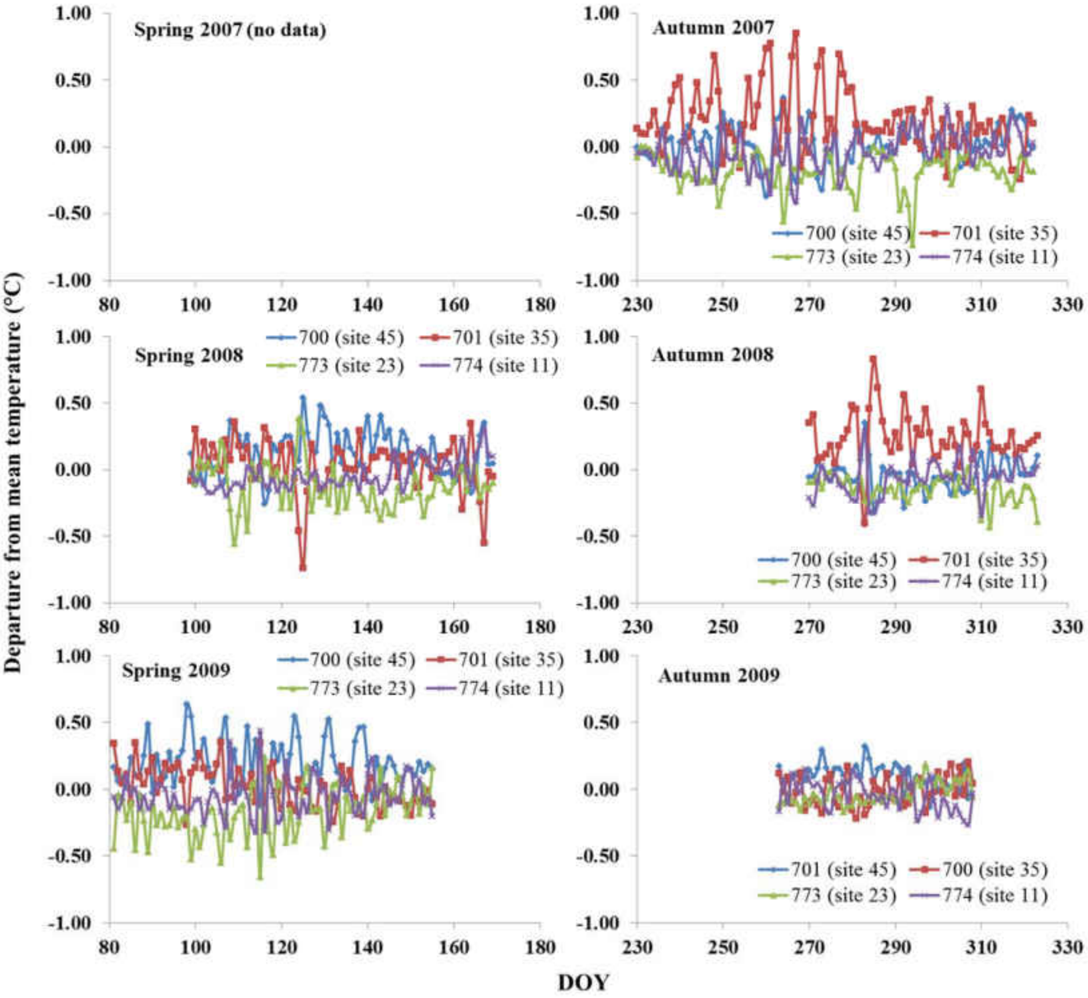


Figure 18-1: Daily mean air temperatures by HOBO sites (Note: spring 2008-spring 2009, autumn 2007-autumn 2009; 700, 701, 773, 774 are the HOBO numbers)

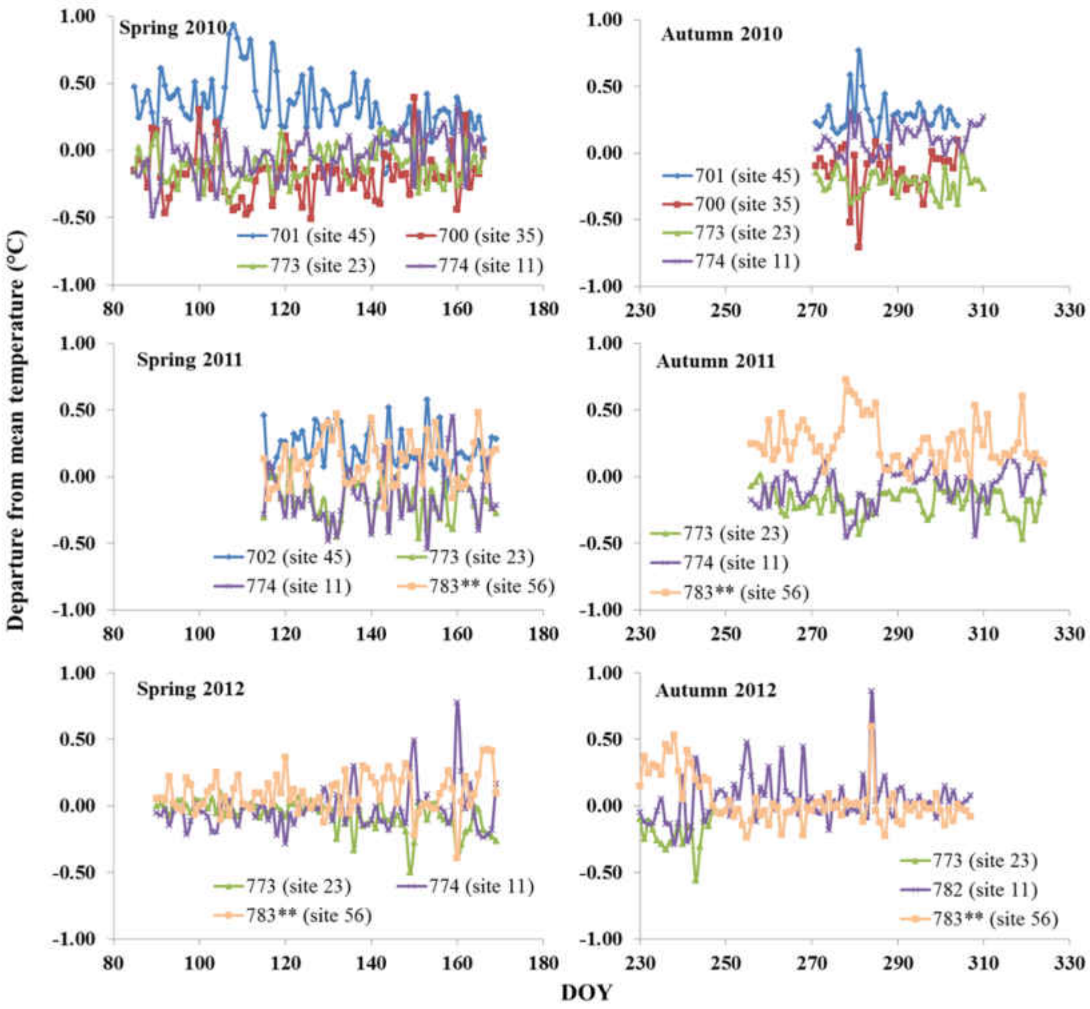


Figure 18-2: Daily mean air temperatures by HOBO sites (Notes: spring 2010-spring 2012, autumn 2010-autumn 2012; 700, 701, 773, 774, 783 are the HOBO numbers; ** means the HOBO close to the Klotsche Center)

In general, autumn temperatures did not vary as much as spring temperatures during the course of the study, as no consistent differences were detected between monitoring instruments (Figures 18-1 and 18-2). However, site 23 recorded the lowest temperature of all HOBO sites whereas site 56 showed higher temperatures than sites 11 and 23 in autumn 2011. Unfortunately, the HOBO data for site 45 was not available during this time. The differences in daily mean temperature between instruments in autumn were always within ±0.80°C of each other.

6.3.1.2 Mean air temperature comparison among HOBO data from Downer Woods, Shorewood data, and Milwaukee weather station data

Temperature data from Downer Woods was compared to the Shorewood data from Prof. Mark D. Schwartz and the Milwaukee weather station data, located at distances of 3 and 14 km from the study site respectively. Overall, temperature profiles for all years were very similar, with highest temperatures being recorded in summer and lowest in winter. The warmest temperatures were in 2012 and the coolest in 2007.

There were no obvious differences between monthly mean air temperatures in Downer Woods, Shorewood, and at the Milwaukee airport weather station (Figure 19). Air temperature at Downer Woods was always slightly lower than that of the other two locations, but most of the differences were less than 1°C. The largest differences occurred in June 2011, when air temperature in Downer Woods was 1.76°C cooler than that at Shorewood and 1.77°C cooler than that at the Milwaukee airport (Figure 19). Most of the time, air temperature recorded at the Milwaukee weather station was slightly lower than that at Shorewood, but again the differences were less than 1°C. These slight differences may be due to the fact that the Shorewood data were collected in a typical residential area in Milwaukee metro area and the airport is located on the south edge of the city of Milwaukee, in a transition zone between urban and rural areas. Downer Woods is an urban woodlot surrounded by the typical residential buildings and green spaces, but the woods itself create a specific microclimate due to the presence of the vegetation which typically acts to cool the area. There were no significant differences in air temperatures between the three locations, and only a slightly tendency for air temperature to decrease from Shorewood to the Milwaukee airport to Downer Woods (Figure 19).

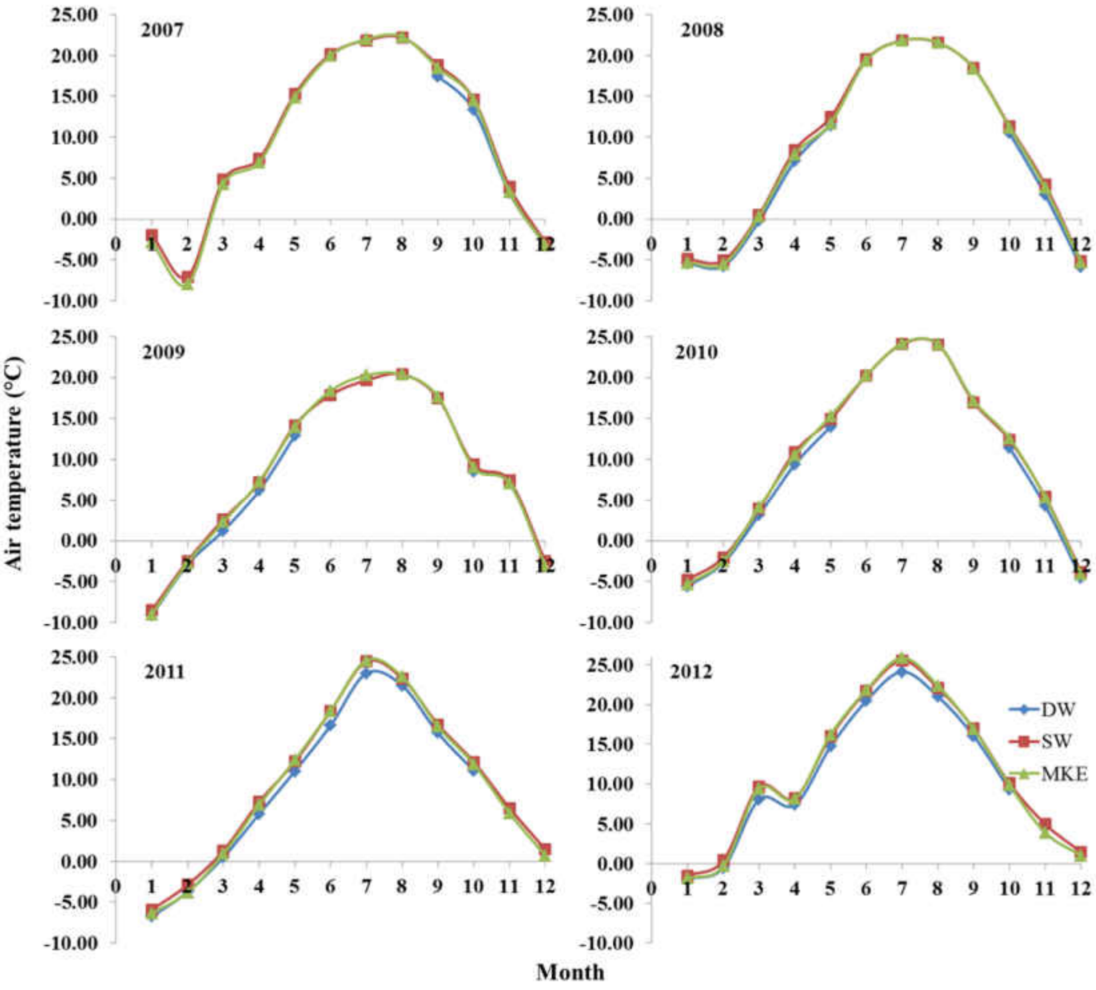


Figure 19: Mean monthly air temperatures at Downer Woods, Shorewood, and the Milwaukee airport weather station (DW: Downer Woods; SW: Shorewood; MKE: the Milwaukee airport weather station)

Figure 20 illustrates the departure of mean monthly air temperatures from the 1994-2006 mean temperatures at Shorewood. 2012 was the warmest year of these six years, except in 2012; the winters were consistently colder than the 13 year mean, especially in 2007. Summer temperatures were always above the 13 year mean, except in 2009, which was slightly cooler in summer and autumn.

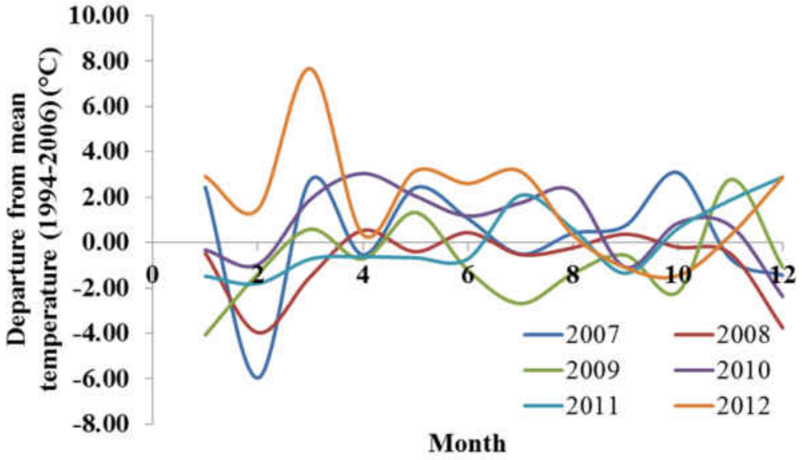


Figure 20: Temperature anomaly (°C), departure from 1994-2006 baseline

6.3.1.3 Growing degree-days and chilling degree-days

Figures 21-1 and 21-2 present accumulated growing degree days (AGDD, base temperature: 3°C) and accumulated chilling degree days (ACDD, base temperature: 20°C) by year, respectively. In spring, sensible heat accumulation started in the middle of March, and then gradually increased. 2012 was the warmest year in the time series and began to accumulate temperatures more rapidly after DOY~70. In autumn, temperatures below 20°C started at the beginning of September, after which the ACDD gradually increased. There were very few differences recorded between years, but 2009 tended to accumulate chilling more rapidly between DOYs 275 and 340 than the other years (Figure 21-2).

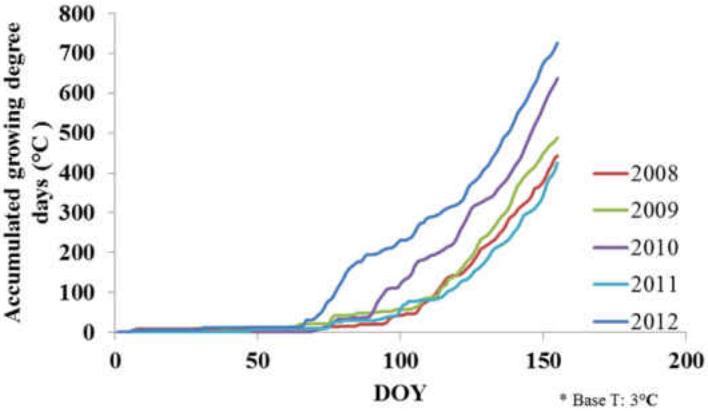


Figure 21-1: Comparison of accumulated growing degree days (AGDDs) by year

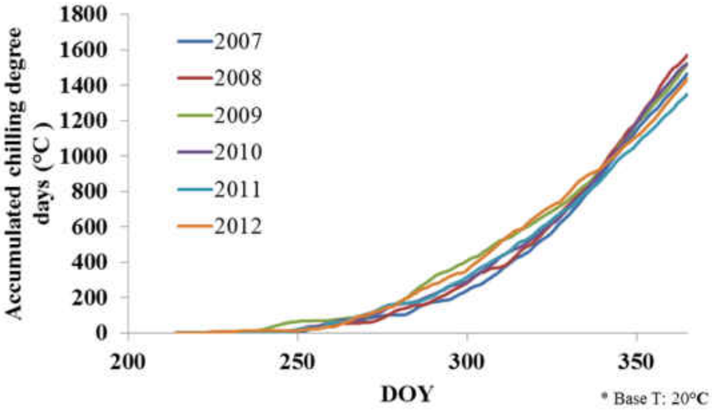


Figure 21-2: Comparison of accumulated chilling degree days (ACDDs) by year

6.3.1.4 Precipitation

Figure 22 illustrates the departure of the total monthly precipitation from 1994 to 2006 baseline. Rainfall peaked in early summer in 2008, mid-summer in 2010, late summer in 2011 and mid-autumn in 2009. Summer 2010 was the wettest with a peak during July of 330mm above the 1994-2006 baseline. Summer precipitation during 2009 and 2011 was less than the other years.

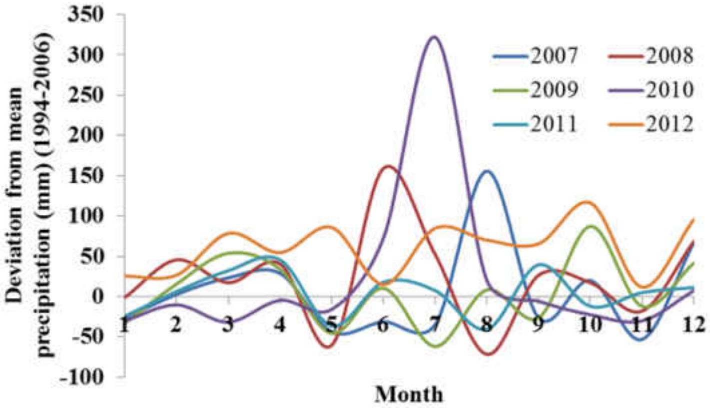


Figure 22: Precipitation anomaly (mm), departure 1994-2006 baseline

6.3.1.5 Water balance

Figure 23 illustrates the variation in monthly soil moisture by year. Here, we focused on the drought introduced by soil water deficits (Oliver, 2005). There were short-duration droughts during each year from 2007 to 2010, although the length and timing differed significantly. In 2007 there was a late spring and early summer drought, in 2008 a mid- and late summer drought, in 2009 a consistent drought throughout the whole summer and early autumn, and in 2010 a drought in spring as well as in mid- to late autumn.

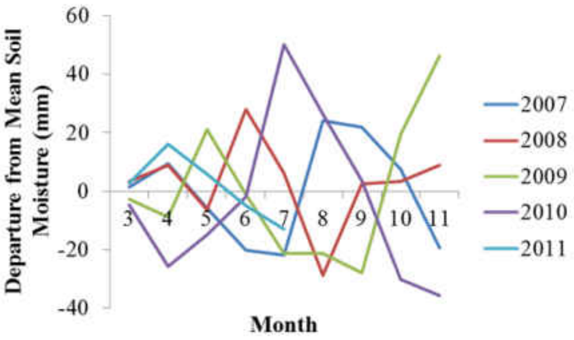


Figure 23: Departure from mean monthly water balance by year

6.3.1.6 Day length and light intensity

Although day length is essentially consistent over years, it was important to present this data for completeness. Figure 24 shows day length by minute in Downer Woods. Day length changes gradually by day and it reaches its peak value in late June. Since the study area is relatively small, it was not expected that any spatial difference would be observed and day length was constant among years.

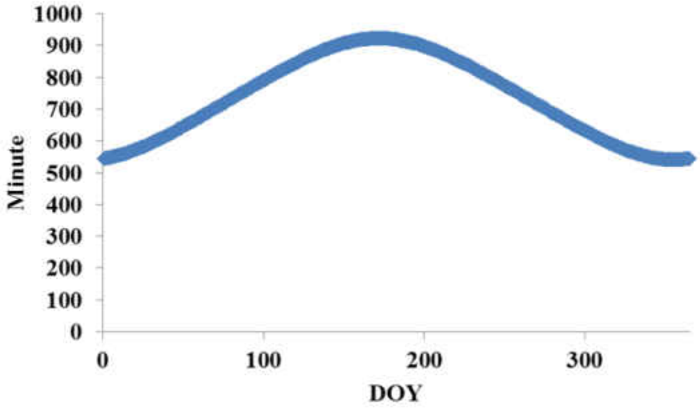


Figure 24: Day length at Downer Woods, by DOY

Figure 25 illustrates daily light intensity by year. In early October there was a steep drop in daily light intensity in both 2008 and 2009.

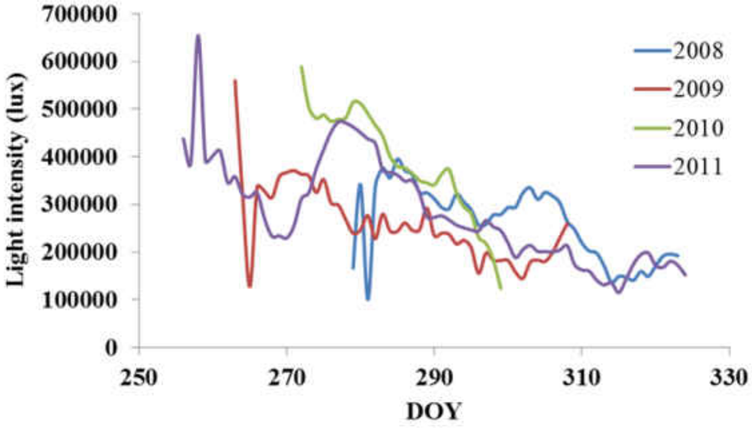


Figure 25: Daily light intensity by year

6.3.1.7 Wind

Figures 26 and 27 show the wind diagrams for Milwaukee. Figure 26 presents the 2007-2011 average wind speed and dominant wind directions. Figure 27 shows the 2007-2011 average seasonal wind speed. The mean monthly wind speed was normally higher than 3 m/s. The prevailing winds came from the southeast in spring and the southwest in autumn.

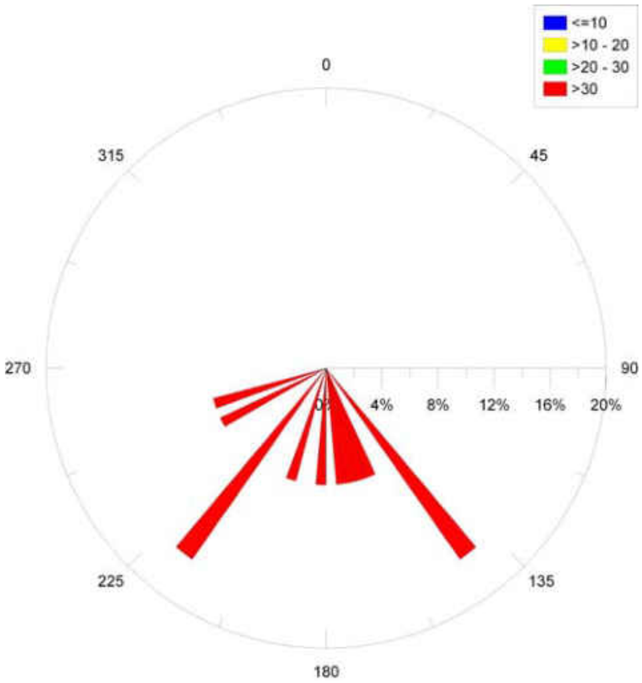
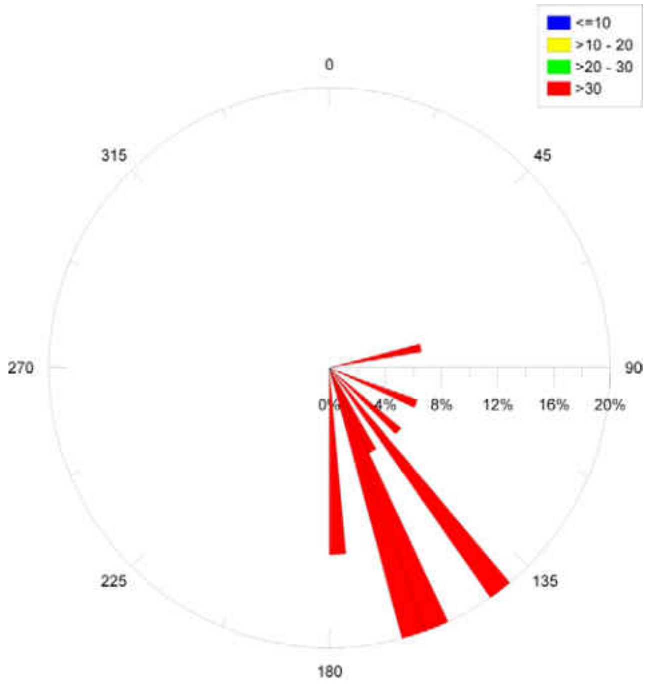
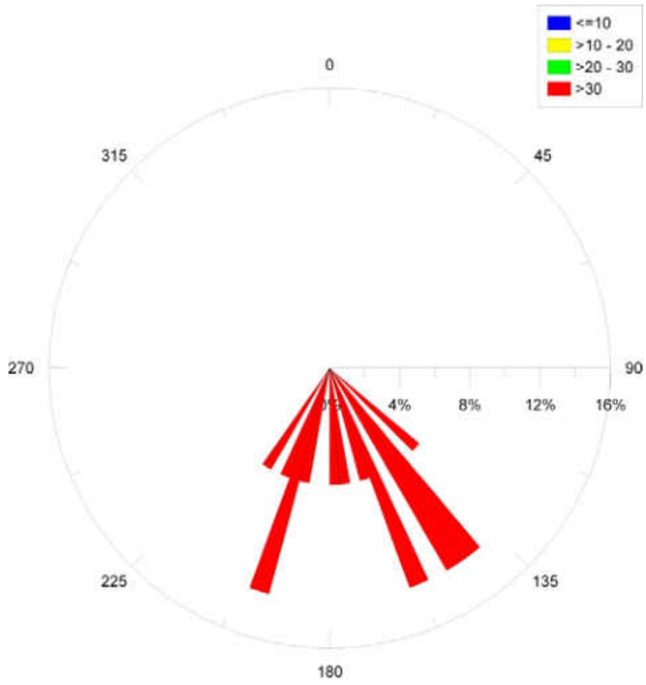


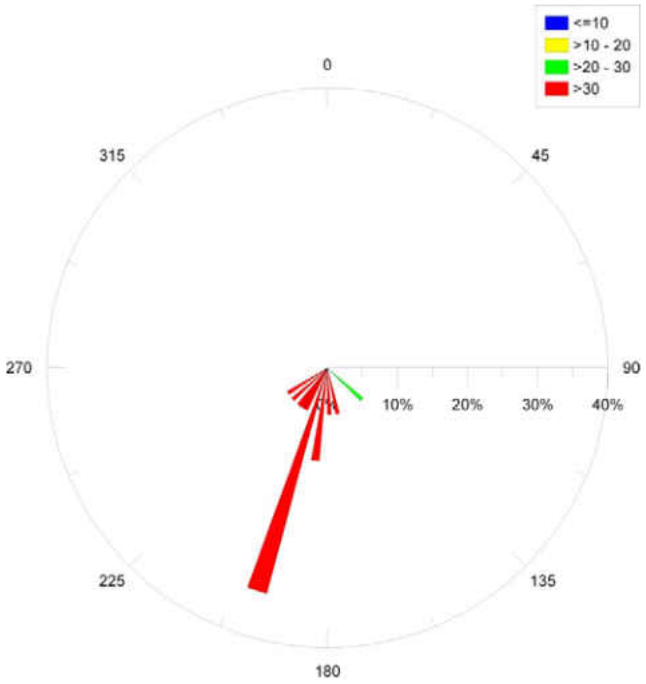
Figure 26: wind diagram for Milwaukee showing average direction and speed (2007-2011 average)



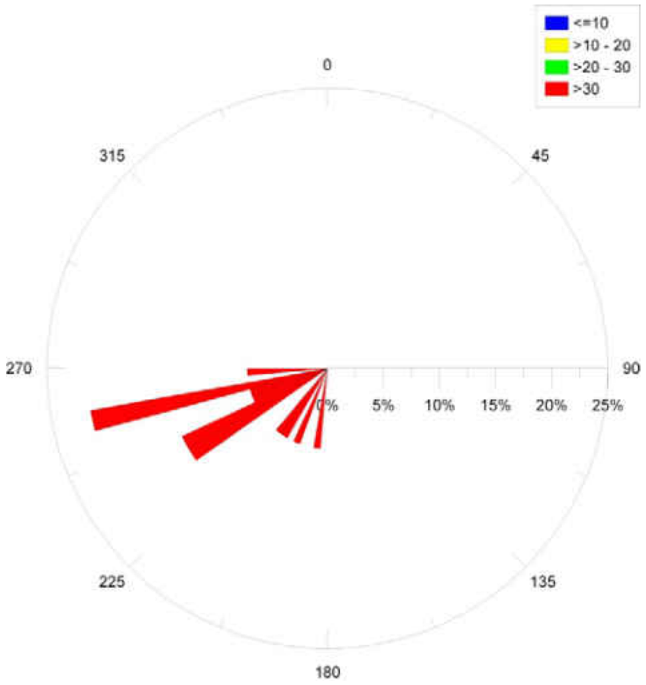
March-May



June-August



September-November



December-February

Figure 27: Wind diagrams for spring (March-May), summer (June-August), autumn (September-November), and winter (December-February)

6.3.2 Correlation between phenology and temperature

Tables 27-29 show the Pearson's *r* for spring phenology and temperature parameters. Temperature parameters include three groups: 1) maximum, minimum, and mean air temperatures; 2) maximum, minimum, and mean soil temperatures; and 3) the accumulated growing degree days calculated by air and soil temperatures. Tables 30-32 show the Pearson's *r* for the autumn phenophase of leaf coloration and temperature parameters. Tables 33-35 show the Pearson's *r* for the autumn phenophase of leaf fall and temperature parameters, which include the maximum, minimum, and mean air and soil temperatures, and the accumulated chilling degree days by air temperature.

Correlation between spring phenology and temperature parameters

At both the community and the species level, the three air temperature parameters (maximum, minimum, and mean) showed strong positive relationships with spring phenology (Table 27). This suggests that when air temperature is high, spring phenology develops earlier. Of the three air temperature parameters, minimum air temperature showed the highest correlations with spring phenology of each species and the community as a whole (0.604, $P \leq 0.001$). Among the five individual species, minimum temperature presented the highest correlation with spring phenology of white ash (0.631, $P \leq 0.001$) and the lowest correlation with spring phenology of boxelder (0.407, $P \leq 0.001$).

The three soil temperature parameters (maximum, minimum, and mean) showed very strong positive relationships with spring phenology (Table 28). Similar to air temperature, minimum soil temperature displays the highest correlations with spring phenology of each species and the community as a whole (0.870, $P \leq 0.001$). Again, spring phenology of white ash shows the strongest correlations with minimum soil temperature (0.879, $P \leq 0.001$), and red oak shows the weakest correlations (0.835, $P \leq 0.001$).

Among the three groups of temperature parameters, accumulated growing degree days (AGDD) showed the strongest relationships with spring phenology (Table 29). In contrast to the daily temperature parameters, AGDD by air temperature had a better relationship with spring phenology than AGDD by soil temperature. The correlation coefficient between AGDD by air temperature and spring phenology of the community as a whole was 0.964 at the 0.001 significance level. The correlation coefficients between AGDD by air temperature and spring phenology of individual species were as high as 0.971 (basswood and red oak, $P \leq 0.001$) and only as low as 0.951 (boxelder, $P \leq 0.001$).

Generally, spring phenology has a strong positive relation to temperature. Among these eight temperature parameters, AGDD by air temperature showed the strongest relationship with spring phenology, meaning that it can serve as a potential critical indictor to predict phenological progress in spring.

Table 27: Correlation between spring phenology and air temperature

		AT_MAX	AT_MIN	AT_MEAN
BASSWOOD	Pearson Correlation	.326**	.554**	.487**
	Sig. (2-tailed)	.000	.000	.000
	N	112	112	112
WHITE ASH	Pearson Correlation	.384**	.631**	.545**
	Sig. (2-tailed)	.000	.000	.000
	N	126	126	126
WHITE OAK	Pearson Correlation	.348**	.599**	.505**
	Sig. (2-tailed)	.000	.000	.000
	N	119	119	119
RED OAK	Pearson Correlation	.290**	.500**	.438**
	Sig. (2-tailed)	.003	.000	.000
	N	106	106	106
BOXELDER	Pearson Correlation	.261*	.407**	.375**
	Sig. (2-tailed)	.019	.000	.001
	N	80	80	80
COMMUNITY	Pearson Correlation	.358**	.604**	.519**
	Sig. (2-tailed)	.000	.000	.000
	N	123	123	123

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

(AT_MAX means maximum air temperature; AT_MIN means minimum air temperature; AT_MEAN means average air temperature)

Table 28: Correlation between spring phenology and soil temperature

		ST_MAX	ST_MIN	ST_MEAN
BASSWOOD	Pearson Correlation	.833**	.845**	.845**
	Sig. (2-tailed)	.000	.000	.000
	N	112	112	112
WHITE ASH	Pearson Correlation	.867**	.879**	.877**
	Sig. (2-tailed)	.000	.000	.000
	N	126	126	126
WHITE OAK	Pearson Correlation	.856**	.874**	.871**
	Sig. (2-tailed)	.000	.000	.000
	N	119	119	119
RED OAK	Pearson Correlation	.820**	.835**	.835**
	Sig. (2-tailed)	.000	.000	.000
	N	106	106	106
BOXELDER	Pearson Correlation	.821**	.837**	.840**
	Sig. (2-tailed)	.000	.000	.000

	N	80	80	80
COMMUNITY	Pearson Correlation	.857**	.870**	.869**
	Sig. (2-tailed)	.000	.000	.000
	N	123	123	123

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(ST_MAX means maximum soil temperature; ST_MIN means minimum soil temperature; ST_MEAN means average soil temperature)

Table 29: Correlation between spring phenology and accumulated growing degree days

		AGDD_AT	AGDD_ST
BASSWOOD	Pearson Correlation	.971**	.935**
	Sig. (2-tailed)	.000	.000
	N	119	119
WHITE ASH	Pearson Correlation	.952**	.953**
	Sig. (2-tailed)	.000	.000
	N	133	133
WHITE OAK	Pearson Correlation	.966**	.950**
	Sig. (2-tailed)	.000	.000
	N	126	126
RED OAK	Pearson Correlation	.971**	.942**
	Sig. (2-tailed)	.000	.000
	N	113	113
BOXELDER	Pearson Correlation	.951**	.897**
	Sig. (2-tailed)	.000	.000
	N	87	87
COMMUNITY	Pearson Correlation	.964**	.952**
	Sig. (2-tailed)	.000	.000
	N	130	130

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(AGDD_AT means accumulated growing degree days by air temperature; AGDD_ST means accumulated growing degree days by soil temperature)

Correlation between autumn phenology and temperature parameters

Both at the community and individual species level, three air temperature parameters also showed relatively strong negative relationships with autumn phenology (Tables 30 and 33). Similar to spring phenology, minimum air temperature presented the strongest correlations with leaf coloration and leaf fall of each species and the community as a whole (-0.401 and -0.577, respectively, $P \leq 0.001$). Among the five individual species, minimum temperature showed the strongest correlations with leaf coloration of basswood (-0.444, $P \leq 0.001$) and leaf fall of white oak (-0.576, $P \leq 0.001$), and the weakest correlations with leaf coloration of white ash (-0.228, $P \leq 0.05$) and leaf fall of white ash (-0.414, $P \leq 0.001$).

Three soil temperature parameters also showed strong negative relationships with autumn phenology (Tables 31 and 34). Differing from air temperature, maximum soil temperature displayed the strongest correlations with leaf coloration and leaf fall of each species and the community as a whole (-0.645 and -0.752, respectively, $P \leq 0.001$). Again, leaf coloration of basswood and leaf fall of white oak showed the strongest correlations with maximum soil temperature (-0.685 and -0.748, respectively, $P \leq 0.001$), and leaf coloration and leaf fall of white ash exhibited the weakest correlations with it (-0.476 and -0.560, respectively, $P \leq 0.001$).

Similar to spring phenology, among the three groups of temperature parameters, accumulated chilling degree days (ACDD) showed the strongest relationships with autumn phenology (Tables 32 and 35). The correlation coefficients between ACDD by air temperature and leaf coloration and leaf fall of the community as a whole were 0.869 and 0.877 ($P \leq 0.001$), respectively. The correlation coefficients between ACDD by air temperature and leaf coloration and leaf fall of individual species were as high as 0.892 (basswood, $P \leq 0.001$) and 0.935 (white oak, $P \leq 0.001$), respectively, and as low as 0.721 (white ash, $P \leq 0.001$) and 0.793 (white ash, $P \leq 0.001$), respectively.

Generally, the association between autumn phenology and temperature parameters was also strong, although not as strong as for spring phenology. ACDD by air temperature illustrated a very strong positive relationship with autumn phenology.

Table 30: Correlation between the phenophase of leaf coloration and air temperature

		AT_MAX	AT_MIN	AT_MEAN
BASSWOOD	Pearson Correlation	-.276**	-.444**	-.420**
	Sig. (2-tailed)	.005	.000	.000
	N	103	103	103
WHITE ASH	Pearson Correlation	-.174	-.228*	-.250*
	Sig. (2-tailed)	.116	.038	.023
	N	83	83	83
WHITE OAK	Pearson Correlation	-.197*	-.407**	-.349**
	Sig. (2-tailed)	.044	.000	.000
	N	105	105	105
RED OAK	Pearson Correlation	-.195*	-.362**	-.316**
	Sig. (2-tailed)	.046	.000	.001
	N	105	105	105
BOXELDER	Pearson Correlation	-.220*	-.389**	-.361**
	Sig. (2-tailed)	.028	.000	.000
	N	100	100	100
COMMUNITY	Pearson Correlation	-.242*	-.401**	-.382**
	Sig. (2-tailed)	.013	.000	.000
	N	104	104	104

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(AT_MAX means maximum air temperature; AT_MIN means minimum air temperature; AT_MEAN means average air temperature)

Table 31: Correlation between the phenophase of leaf coloration and soil temperature

		ST_MAX	ST_MIN	ST_MEAN
BASSWOOD	Pearson Correlation	-.685**	-.633**	-.655**
	Sig. (2-tailed)	.000	.000	.000
	N	103	103	103
WHITE ASH	Pearson Correlation	-.476**	-.422**	-.447**
	Sig. (2-tailed)	.000	.000	.000
	N	83	83	83
WHITE OAK	Pearson Correlation	-.637**	-.601**	-.616**
	Sig. (2-tailed)	.000	.000	.000

	N	105	105	105
RED OAK	Pearson Correlation	-.585**	-.550**	-.565**
	Sig. (2-tailed)	.000	.000	.000
	N	105	105	105
BOXELDER	Pearson Correlation	-.614**	-.580**	-.594**
	Sig. (2-tailed)	.000	.000	.000
	N	100	100	100
COMMUNITY	Pearson Correlation	-.645**	-.594**	-.616**
	Sig. (2-tailed)	.000	.000	.000
	N	104	104	104

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(ST_MAX means maximum soil temperature; ST_MIN means minimum soil temperature; ST_MEAN means average soil temperature)

Table 32: Correlation between the phenophase of leaf coloration and accumulated chilling degree days

		ACDD_AT
BASSWOOD	Pearson Correlation	.892**
	Sig. (2-tailed)	.000
	N	111
WHITE ASH	Pearson Correlation	.721**
	Sig. (2-tailed)	.000
	N	91
WHITE OAK	Pearson Correlation	.861**
	Sig. (2-tailed)	.000
	N	113
RED OAK	Pearson Correlation	.852**
	Sig. (2-tailed)	.000
	N	113
BOXELDER	Pearson Correlation	.855**
	Sig. (2-tailed)	.000
	N	108
COMMUNITY	Pearson Correlation	.869**
	Sig. (2-tailed)	.000
	N	112

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(ACDD_AT means accumulated growing degree days by air temperature)

Table 33: Correlation between the phenophase of leaf fall and air temperature

		AT_MAX	AT_MIN	AT_MEAN
BASSWOOD	Pearson Correlation	-.355**	-.533**	-.491**
	Sig. (2-tailed)	.000	.000	.000
	N	113	113	113
WHITE ASH	Pearson Correlation	-.251*	-.414**	-.380**
	Sig. (2-tailed)	.017	.000	.000
	N	90	90	90
WHITE OAK	Pearson Correlation	-.467**	-.576**	-.551**
	Sig. (2-tailed)	.000	.000	.000
	N	134	134	134
RED OAK	Pearson Correlation	-.492**	-.564**	-.556**
	Sig. (2-tailed)	.000	.000	.000
	N	132	132	132
BOXELDER	Pearson Correlation	-.313**	-.484**	-.431**
	Sig. (2-tailed)	.001	.000	.000
	N	113	113	113
COMMUNITY	Pearson Correlation	-.426**	-.577**	-.541**
	Sig. (2-tailed)	.000	.000	.000
	N	131	131	131

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

(AT_MAX means maximum air temperature; AT_MIN means minimum air temperature; AT_MEAN means average air temperature)

Table 34: Correlation between the phenophase of leaf fall and soil temperature

		ST_MAX	ST_MIN	ST_MEAN
BASSWOOD	Pearson Correlation	-.736**	-.711**	-.721**
	Sig. (2-tailed)	.000	.000	.000
	N	113	113	113
WHITE ASH	Pearson Correlation	-.560**	-.526**	-.539**
	Sig. (2-tailed)	.000	.000	.000
	N	90	90	90
WHITE OAK	Pearson Correlation	-.748**	-.747**	-.747**
	Sig. (2-tailed)	.000	.000	.000
	N	134	134	134
RED OAK	Pearson Correlation	-.715**	-.715**	-.714**
	Sig. (2-tailed)	.000	.000	.000
	N	132	132	132
BOXELDER	Pearson Correlation	-.663**	-.643**	-.650**
	Sig. (2-tailed)	.000	.000	.000

	N	113	113	113
COMMUNITY	Pearson Correlation	-.752**	-.733**	-.741**
	Sig. (2-tailed)	.000	.000	.000
	N	131	131	131

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(ST_MAX means maximum soil temperature; ST_MIN means minimum soil temperature; ST_MEAN means average soil temperature)

Table 35: Correlation between the phenophase of leaf fall and accumulated chilling degree days

		ACDD_AT
BASSWOOD	Pearson Correlation	.899**
	Sig. (2-tailed)	.000
	N	121
WHITE ASH	Pearson Correlation	.793**
	Sig. (2-tailed)	.000
	N	98
WHITE OAK	Pearson Correlation	.935**
	Sig. (2-tailed)	.000
	N	149
RED OAK	Pearson Correlation	.914**
	Sig. (2-tailed)	.000
	N	149
BOXELDER	Pearson Correlation	.874**
	Sig. (2-tailed)	.000
	N	121
COMMUNITY	Pearson Correlation	.877**
	Sig. (2-tailed)	.000
	N	145

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(ACDD_AT means accumulated growing degree days by air temperature)

6.3.3 Correlation between phenology and moisture

Table 36 shows the Pearson's *r* for spring phenology, daily water balance, and accumulated precipitation. Tables 37 and 38 show the Pearson's *r* for autumn phenology, daily water balance, and accumulated precipitation.

In spring, water balance showed significant negative relationships with phenology at both the community and individual species levels (Table 36). The Pearson's *r* for water balance and spring phenology of the community as a whole was -0.609 ($P \leq 0.001$). At the individual species level, correlations were negative with Pearson's *r* ranging from -0.665 (red oak, $P \leq 0.001$) to -0.429 (boxelder, $P \leq 0.001$). Accumulated precipitation presented significant positive relationships with phenology at both levels. The Pearson's *r* for the accumulated precipitation and spring phenology of the community as a whole was 0.554 ($P \leq 0.001$). At the individual species level, the Pearson's *r* was as high as 0.608 (white ash, $P \leq 0.001$) and as low as 0.349 (boxelder, $P \leq 0.001$).

In autumn, water balance shows significant negative relationships with leaf coloration of the community as a whole (-0.345, $P \leq 0.001$), and with basswood (-0.403, $P \leq 0.001$), white ash (-0.446, $P \leq 0.001$), and boxelder (-0.324, $P \leq 0.001$). This suggests that when water is limiting leaf coloration occurs early. There were no significant correlations between water balance and leaf coloration of white oak or red oak. Differing from water balance, accumulated precipitation showed positive relationships with leaf coloration of the community as whole (0.224, $P \leq 0.05$), and with white ash (0.225, $P \leq 0.05$), white oak (0.404, $P \leq 0.001$), red oak (0.213, $P \leq 0.05$), and boxelder (0.275, $P \leq 0.01$).

In contrast to leaf coloration, leaf fall showed weaker relationships with water balance and accumulated precipitation (Table 38). Water balance only showed a significant negative relationship with leaf fall of basswood (-0.219, $P \leq 0.05$), while there were no significant relationships with leaf fall of the community as whole and other individual species. The accumulated precipitation showed significant positive relationships with the community as whole (0.237, $P \leq 0.01$), white oak (0.320, $P \leq 0.001$), red oak (0.254, $P \leq 0.01$), and boxelder (0.187, $P \leq 0.05$), but no significant relationships with leaf fall of basswood and white ash.

Table 36: Correlation between spring phenology, water balance, and the accumulated precipitation

		WP	**Accu_PRECIPITATION**
BASSWOOD	Pearson Correlation	$-.625^{**}$	$.481^{**}$
	Sig. (2-tailed)	.000	.000
	N	119	119
WHITE ASH	Pearson Correlation	$-.586^{**}$	$.608^{**}$
	Sig. (2-tailed)	.000	.000
	N	136	136
WHITE OAK	Pearson Correlation	$-.593^{**}$	$.551^{**}$
	Sig. (2-tailed)	.000	.000
	N	126	126
RED OAK	Pearson Correlation	$-.665^{**}$	$.412^{**}$
	Sig. (2-tailed)	.000	.000
	N	113	113
BOXELDER	Pearson Correlation	$-.429^{**}$	$.349^{**}$
	Sig. (2-tailed)	.000	.001
	N	87	87
COMMUNITY	Pearson Correlation	$-.609^{**}$	$.554^{**}$
	Sig. (2-tailed)	.000	.000
	N	130	130

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(WB means water balance; Accu_PRECIPITATION means accumulated precipitation)

Table 37: Correlation between the phenophase of leaf coloration, water balance, and the accumulated precipitation

		WB	**Accu_PRECIPITATION**
BASSWOOD	Pearson Correlation	$-.403^{**}$	.170
	Sig. (2-tailed)	.000	.074
	N	86	111
WHITE ASH	Pearson Correlation	$-.446^{**}$	$.225^{*}$
	Sig. (2-tailed)	.000	.032

	N	74	91
WHITE OAK	Pearson Correlation	-.155	.404**
	Sig. (2-tailed)	.151	.000
	N	87	113
RED OAK	Pearson Correlation	-.081	.213*
	Sig. (2-tailed)	.453	.023
	N	88	113
BOXELDER	Pearson Correlation	-.324**	.275**
	Sig. (2-tailed)	.003	.004
	N	83	108
COMMUNITY	Pearson Correlation	-.345**	.224*
	Sig. (2-tailed)	.001	.018
	N	87	112

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(WB means water balance; Accu_PRECIPITATION means accumulated precipitation)

Table 38: Correlation between the phenophase of leaf fall, water balance, and the accumulated precipitation

		WB	**Accu_PRECIPITATION**
BASSWOOD	Pearson Correlation	-.219*	.157
	Sig. (2-tailed)	.034	.086
	N	94	121
WHITE ASH	Pearson Correlation	-.093	.174
	Sig. (2-tailed)	.414	.087
	N	80	98
WHITE OAK	Pearson Correlation	.024	.320**
	Sig. (2-tailed)	.801	.000
	N	117	149
RED OAK	Pearson Correlation	.053	.254**
	Sig. (2-tailed)	.570	.002
	N	119	149
BOXELDER	Pearson Correlation	-.036	.187*
	Sig. (2-tailed)	.729	.040
	N	94	121
COMMUNITY	Pearson Correlation	-.043	.237**
	Sig. (2-tailed)	.646	.004
	N	115	145

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
(WB means water balance; Accu_PRECIPITATION means accumulated precipitation)

Tables 39 and 40 illustrate the correlation between autumn phenology and accumulated precipitation by year. The correlation between autumn phenology and accumulated precipitation by year was significantly different from the correlation between them during the whole observation period from 2007 to 2011. There was a strong association between autumn phenology and accumulated precipitation during each year (Tables 39 and 40). The Pearson's *r* for the accumulated precipitation and leaf coloration was as high as 0.965 (white oak, the community as a whole 2008, $P \leq 0.001$) and as low as 0.567 (boxelder 2010, $P \leq 0.001$). The Pearson's *r* for accumulated precipitation and leaf fall was as high as 0.973 (the community as a whole 2007, $P \leq 0.001$) and as low as 0.612 (boxelder 2010, $P \leq 0.001$).

Table 39: Correlation between the autumn phenophase of leaf coloration and the accumulated precipitation, by year

		2007	2008	2009	2010	2011	2012
BASSWOOD	Pearson Correlation	.951**	.951**	.834**	.686**	.936**	.458
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.116
	N	30	17	17	22	25	13
WHITE ASH	Pearson Correlation	.889**	.921**	.849**	.872**	.954**	.904**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	21	17	18	18	17	9
WHITE OAK	Pearson Correlation	.902**	.965**	.910**	.752**	.922**	.673*
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.012
	N	29	17	19	22	26	13
RED OAK	Pearson Correlation	.848**	.918**	.940**	.609**	.875**	.807**
	Sig. (2-tailed)	.000	.000	.000	.003	.000	.000
	N	29	17	20	22	25	14
BOXELDER	Pearson Correlation	.937**	.955**	.740**	.567**	.721**	.834**
	Sig. (2-tailed)	.000	.000	.001	.007	.000	.000
	N	28	17	17	21	25	13
COMMUNITY	Pearson Correlation	.943**	.965**	.874**	.781**	.956**	.516
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.071
	N	30	17	18	22	25	13

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 40: Correlation between the autumn phenophase of leaf fall and the accumulated precipitation, by year

		2007	2008	2009	2010	2011	2012
BASSWOOD	Pearson Correlation	.934**	.913**	.846**	.648**	.910**	.739**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	32	19	18	25	27	24
WHITE ASH	Pearson Correlation	.956**	.899**	.904**	.697**	.900**	.759**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	21	17	20	22	18	24
WHITE OAK	Pearson Correlation	.841**	.923**	.975**	.919**	.893**	.971**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	35	25	25	32	32	24
RED OAK	Pearson Correlation	.835**	.910**	.950**	.935**	.869**	.926**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	38	25	25	31	30	24
BOXELDER	Pearson Correlation	.840**	.881**	.961**	.612**	.891**	.968**
	Sig. (2-tailed)	.000	.000	.000	.001	.000	.000
	N	29	20	21	24	27	24
COMMUNITY	Pearson Correlation	.973**	.924**	.924**	.762**	.930**	.814**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	35	24	25	31	30	24

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

6.3.4 Correlation between phenology and day length

Table 41 shows the correlation between spring phenology and day length and Tables 42 and 43 show the correlations between autumn phenology and day length. Both spring and autumn phenologies of individual species and the community as a whole showed strong associations with day length. The spring phenology of white ash was positively correlated with day length, with the highest Pearson's *r* (0.926, $P \leq 0.01$), and the spring phenology of boxelder was positively correlated with day length, with the lowest Pearson's *r* (0.716, $P \leq 0.01$). In contrast to the spring phenology, the autumn phenology of white oak was negatively correlated with day length, with the highest Pearson's r (leaf coloration: -0.880; leaf fall: -0.920, $P \leq 0.01$). Similar to spring phenology, the autumn phenology of boxelder was negatively correlated with day length, with the lowest Pearson's r (leaf coloration: -0.716; leaf fall: -0.869, P ≤ 0.01). Generally, the associations between leaf fall and day length were slightly stronger than the ones between leaf coloration and day length.

Table 41: Correlation between spring phenology and day length

		DAY LENGTH
BASSWOOD	Pearson Correlation	.870**
	Sig. (2-tailed)	.000
	N	137
WHITE ASH	Pearson Correlation	.926**
	Sig. (2-tailed)	.000
	N	157
WHITE OAK	Pearson Correlation	.870**
	Sig. (2-tailed)	.000
	N	145
RED OAK	Pearson Correlation	.857**
	Sig. (2-tailed)	.000
	N	131
BOXELDER	Pearson Correlation	.716**
	Sig. (2-tailed)	.000
	N	98
COMMUNITY	Pearson Correlation	.907**
	Sig. (2-tailed)	.000
	N	151

**. Correlation is significant at the 0.01 level (2-tailed).

Table 42: Correlation between the phenophase of leaf coloration and day length

		DAY LENGTH
BASSWOOD	Pearson Correlation	-.867**
	Sig. (2-tailed)	.000
	N	124
WHITE ASH	Pearson Correlation	-.868**
	Sig. (2-tailed)	.000

	N	97
WHITE OAK	Pearson Correlation	-.880**
	Sig. (2-tailed)	.000
	N	126
RED OAK	Pearson Correlation	-.865**
	Sig. (2-tailed)	.000
	N	127
BOXELDER	Pearson Correlation	-.848**
	Sig. (2-tailed)	.000
	N	120
COMMUNITY	Pearson Correlation	-.906**
	Sig. (2-tailed)	.000
	N	125

**. Correlation is significant at the 0.01 level (2-tailed).

Table 43: Correlation between the phenophase of leaf fall and day length

		DAY LENGTH
BASSWOOD	Pearson Correlation	-.882**
	Sig. (2-tailed)	.000
	N	145
WHITE ASH	Pearson Correlation	-.888**
	Sig. (2-tailed)	.000
	N	122
WHITE OAK	Pearson Correlation	-.920**
	Sig. (2-tailed)	.000
	N	173
RED OAK	Pearson Correlation	-.907**
	Sig. (2-tailed)	.000
	N	173
BOXELDER	Pearson Correlation	-.869**
	Sig. (2-tailed)	.000
	N	145
COMMUNITY	Pearson Correlation	-.920**
	Sig. (2-tailed)	.000
	N	169

**. Correlation is significant at the 0.01 level (2-tailed).

6.3.5 Correlation between phenology and light intensity

Table 44 shows the correlation between spring phenology and light intensity, and Tables 44 and 45 show the correlations between autumn phenology and light intensity. Only the spring phenology of red oak showed a positive association with light intensity (0.215, $P \leq 0.05$). Similar to spring phenology, the leaf coloration of red oak and boxelder showed a slight negative relationship with light intensity (-0.252 and -0.236, $P \leq 0.05$, respectively). In contrast to spring phenology and the phenophase of leaf coloration, the phenophase of leaf fall showed a moderate relationship with light intensity. The Pearson's r values were -0.307 (basswood, $P \leq 0.01$), -0.508 (white oak, $P \leq 0.001$), -0.512 (red oak, $P \leq 0.001$), -0.396 (boxelder, $P \leq 0.001$), and -0.398 (the community as a whole, $P \leq 0.001$). Only the leaf fall of white ash shows no significant relationship with light intensity.

Table 44: Correlation between spring phenology and light intensity

		LIGHT INTENSITY
BASSWOOD	Pearson Correlation	.141
	Sig. (2-tailed)	.139
	N	111
WHITE ASH	Pearson Correlation	.151
	Sig. (2-tailed)	.094
	N	125
WHITE OAK	Pearson Correlation	.140
	Sig. (2-tailed)	.131
	N	118
RED OAK	Pearson Correlation	.215*
	Sig. (2-tailed)	.028
	N	105
BOXELDER	Pearson Correlation	.040
	Sig. (2-tailed)	.725
	N	79
COMMUNITY	Pearson Correlation	.143

	Sig. (2-tailed)	.117
	N	122

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 45: Correlation between the phenophase of leaf coloration and light intensity

		LIGHT INTENSITY
BASSWOOD	Pearson Correlation	-.176
	Sig. (2-tailed)	.142
	N	71
WHITE ASH	Pearson Correlation	.003
	Sig. (2-tailed)	.981
	N	60
WHITE OAK	Pearson Correlation	-.195
	Sig. (2-tailed)	.096
	N	74
RED OAK	Pearson Correlation	-.252*
	Sig. (2-tailed)	.031
	N	74
BOXELDER	Pearson Correlation	-.236*
	Sig. (2-tailed)	.049
	N	70
COMMUNITY	Pearson Correlation	-.125
	Sig. (2-tailed)	.295
	N	72

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 46: Correlation between the phenophase of leaf fall and light intensity

		LIGHT INTENSITY
BASSWOOD	Pearson Correlation	-.307**
	Sig. (2-tailed)	.006
	N	78
WHITE ASH	Pearson Correlation	-.156
	Sig. (2-tailed)	.206
	N	67
WHITE OAK	Pearson Correlation	-.508**
	Sig. (2-tailed)	.000
	N	95
RED OAK	Pearson Correlation	-.512**

	Sig. (2-tailed)	.000
	N	93
BOXELDER	Pearson Correlation	-.396**
	Sig. (2-tailed)	.000
	N	82
COMMUNITY	Pearson Correlation	-.398**
	Sig. (2-tailed)	.000
	N	92

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

6.3.6 Correlation between phenology and wind

Table 47 illustrates the correlation between spring phenology and daily wind speed and direction, and Tables 48 and 49 show the correlations between autumn phenology and daily wind speed and direction. There was no significant relationship between phenology and daily wind speed and direction except for the leaf fall of red oak, which showed a weak positive correlation with daily wind speed (0.195, $P \leq 0.05$).

Table 47: Correlation between spring phenology and wind

		WIND SPEED	**WIND DIRECTION**
BASSWOOD	Pearson Correlation	-.021	-.021
	Sig. (2-tailed)	.818	.822
	N	119	119
WHITE ASH	Pearson Correlation	-.070	-.052
	Sig. (2-tailed)	.421	.549
	N	136	136
WHITE OAK	Pearson Correlation	-.085	-.092
	Sig. (2-tailed)	.344	.306
	N	126	126
RED OAK	Pearson Correlation	-.024	-.039
	Sig. (2-tailed)	.800	.683
	N	113	113
BOXELDER	Pearson Correlation	-.030	.115
	Sig. (2-tailed)	.786	.290
	N	87	87
COMMUNITY	Pearson Correlation	-.054	-.088

	Sig. (2-tailed)	.542	.319
	N	130	130

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 48: Correlation between the phenophase of leaf coloration and wind

		WIND SPEED	WIND DIRECTION
BASSWOOD	Pearson Correlation	.024	.134
	Sig. (2-tailed)	.805	.161
	N	111	111
WHITE ASH	Pearson Correlation	-.067	.036
	Sig. (2-tailed)	.526	.736
	N	91	91
WHITE OAK	Pearson Correlation	.042	.061
	Sig. (2-tailed)	.661	.522
	N	113	113
RED OAK	Pearson Correlation	.042	.110
	Sig. (2-tailed)	.655	.245
	N	113	113
BOXELDER	Pearson Correlation	.050	.145
	Sig. (2-tailed)	.606	.135
	N	108	108
COMMUNITY	Pearson Correlation	.017	.107
	Sig. (2-tailed)	.862	.259
	N	112	112

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 49: Correlation between the phenophase of leaf fall and wind

		WIND SPEED	WIND DIRECTION
BASSWOOD	Pearson Correlation	.098	.120
	Sig. (2-tailed)	.286	.189
	N	121	121
WHITE ASH	Pearson Correlation	.062	.134
	Sig. (2-tailed)	.545	.189
	N	98	98
WHITE OAK	Pearson Correlation	.124	.139
	Sig. (2-tailed)	.133	.090
	N	149	149
RED OAK	Pearson Correlation	.195*	.113

	Sig. (2-tailed)	.017	.170
	N	149	149
BOXELDER	Pearson Correlation	.085	.076
	Sig. (2-tailed)	.355	.405
	N	121	121
COMMUNITY	Pearson Correlation	.107	.146
	Sig. (2-tailed)	.199	.080
	N	145	145

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

6.3.7 Regression models for phenology and microclimatic factors

6.3.7.1 Downer Woods

Spring phenological progression models

Table 50 lists spring phenological progression models for each individual species as well as for the community as a whole. The models were built to summarize and predict how the leading climatic factors influence phenological progress. In spring models, accumulated growing degree days (AGDD) and day length served as explanatory variables.

According to the spring phenological progression model, when day length is held constant and AGDD increases 100 degree-days, the spring phenology of the community as a whole develops through nearly one phenophase. When AGDD is held constant and day length increases 100 minutes, the spring phenology of the community as a whole develops through nearly two phenophases. The model explains 92.6% of the development of spring phenology of the community as a whole. The standard error of the estimate is approximately half a phenophase. RMSE and MAE by day are 5.5 days and 4.5 days. (Note: RMSE (root mean squared error) and MAE (mean absolute error) were calculated not only by phenophase level unit, but also by day. Here, I will focus on RMSE and MAE by day, because these results can be easily compared with the results from other studies.)

When day length is held constant and AGDD increases 100 degree-days, the spring phenology of individual species develops through nearly 0.867(±0.561) (basswood), 0.634(±0.570) (white ash), 0.841(±0.586) (red oak), 0.868 (±0.415) (white oak), and 1.445(±0.504) (boxelder) phenophases. When AGDD is held constant and day length increases 100 minutes, the spring phenology of individual species develops through nearly 1.620(±0.561) (basswood), 2.608(±0.570) (white ash), 1.733(±0.586) (red oak), 1.088(±0.415) (white oak), and 0.851(±0.504) (boxelder) phenophases. The models explain as much as 93.4% (white oak) and as little as 87.9% (red oak) of the progression of spring phenology for individual species.

Table 50: Spring phenological progression models

Species	Model	R^2	Std. error of the estimate	Sig.	RMSE by phenophase	MAE by phenophase	RMSE by day	MAE by day
Basswood	$Y_{BW,SP} = .867 * AGDD + 1.620 * DL - 1154.442$	.899	56.104	.000	55.489	46.370	5.5	4.5
White ash	$Y_{WA,SP} = 0.634 * AGDD + 2.608 * DL - 1998.870$	.922	56.951	.000	56.393	45.650	5.2	4.1
Red Oak	$Y_{RO,SP} = .841 * AGDD + 1.733 * DL + 126.084$	.879	58.603	.000	57.930	48.074	5.9	4.8
White Oak	$Y_{WO,SP} = .868 * AGDD + 1.088 * DL - 715.651$	.934	41.520	.000	41.091	32.505	5.4	4.0
Boxelder	$Y_{BX,SP} = 1.445 * AGDD + .851 * DL - 449.806$	.892	50.398	.000	49.622	40.776	4.5	3.5
Community	$Y_{CM,SP} = .720 * AGDD + 1.996 * DL - 1458.872$	.926	50.574	.000	42.070	50.069	5.1	4.3

*RMSE: root mean squared error; MAE: mean absolute error; AGDD: accumulated growing degree days; DL: day length

Autumn phenological progression models

Tables 51 and 52 list autumn phenology of leaf coloration and fall progression models for each individual species, as well as for the community as a whole. In the autumn models, accumulated chilling degree-days (ACDD) and day length served as an explanatory variable.

The predictive power of the autumn model is not as good as that for spring with 75.8% (boxelder, leaf coloration) to 89.1% (white oak, leaf fall) of the progression explained. According to the autumn phenological progression models (Tables 51 and 52), when day length is held constant and ACDD increases 100 degree-days, leaf coloration and fall of the community as a whole develops approximately 0.1 phenophase and 0.14 phenophase, respectively. The two models explain 82.8% of the development of leaf coloration and 84.7% of the development of leaf fall. The standard errors of the estimate are approximately 0.12 and 0.14 phenophases, respectively. RMSE and MAE are 4.7 days and 3.6 days, 6.3 days and 4.8 days, respectively.

The models for boxelder had the lowest goodness of fit for leaf coloration, 75.8%, and basswood for leaf fall, 79.0%, respectively. The models for white oak had the highest goodness of fit, 79.6% (leaf coloration) and 89.1% (leaf fall). The influence of ACDD on the autumn phenology of individual species varies. In general, the ACDD influenced red oak least and boxelder most. When day length is held constant and ACDD increases 100 degree-days, the leaf coloration of white oak and red oak advances a little more than 0.1 phenophase, basswood and boxelder advance nearly 0.2 phenophase; the leaf fall of basswood advances less than 0.1 phenophase, red oak, white oak, and boxelder advance nearly 0.15 phenophase.

Table 51: Progression models for autumn phenology of leaf coloration

Species	Model	R^2	Std. error of the estimate	Sig.	RMSE by phenophase	MAE by phenophase	RMSE by day	MAE by day
Basswood	$Y_{BW,LC} = .189 * ACDD - .346 * DL + 1065.304$	.791	14.664	.000	14.489	11.067	5.4	4.3
White ash	$Y_{WA,LC} = -.103 * ACDD - .982 * DL + 1567.235$	.764	13.697	.000	13.484	10.3526	4.5	3.5
Red oak	$Y_{RO,LC} = .132 * ACDD - .372 * DL + 1070.148$	779	13.544	.000	13.384	10.072	5.2	4.0
White oak	$Y_{WO,LC} = .118 * ACDD - .440 * DL + 1128.329$	.796	13.466	.000	13.307	10.400	5.2	4.1
Boxelder	$Y_{BX,LC} = .179 * ACDD - .345 * DL + 1047.530$	.758	15.101	.000	14.915	11.810	5.2	4.3
Community	$Y_{CM,LC} = .069 * ACDD - .543 * DL + 1222.586$	.828	11.825	.000	11.684	8.844	4.7	3.6

*RMSE: root mean squared error; MAE: mean absolute error; ACDD: accumulated chilling degree days; DL: day length

Table 52: Progression models for autumn phenology of leaf fall

Species	Model	R^2	Std. error of the estimate	Sig.	RMSE by phenophase	MAE by phenophase	RMSE by day	MAE by day
Basswood	$Y_{BW,LF} = .092 * ACDD - .572 * DL + 1316.904$	.790	17.453	.000	17.272	13.400	6.7	5.2
White ash	$Y_{WA,LF} = -.071 * ACDD - 1.067 * DL + 1693.827$	.797	16.285	.000	16.085	11.782	5.1	3.8
Red oak	$Y_{RO,LF} = .127 * ACDD - .253 * DL + 1066.964$	.862	11.968	.000	11.871	9.050	5.6	4.5
White oak	$Y_{WO,LF} = .151 * ACDD - .265 * DL + 1075.775$	.891	11.522	.000	11.423	8.533	4.9	3.9
Boxelder	$Y_{BX,LF} = .165 * ACDD - .311 * DL + 1108.487$	.806	15.514	.000	15.353	11.994	5.8	4.8
Community	$Y_{CM,LF} = .018 * ACDD - .678 * DL + 1401.672$	.847	13.859	.000	13.736	10.463	6.3	4.8

*RMSE: root mean squared error; MAE: mean absolute error; ACDD: accumulated chilling degree days; DL: day length

6.3.7.2 Park Falls Range District

Table 53 lists spring and autumn phenological progression models for basswood at the Park Falls study site. In contrast to Downer Woods, AGDD and day length still served as explanatory variables in spring models, whereas only day length served as an explanatory variable in autumn models. When day length is held constant and AGDD increases 100 degree-days, spring phenology of basswood at Park Falls develops 1.078(±0.413) phenophases, compared to 0.867(±0.561) phenophases for basswood in Downer Woods. When day length declines 100 minutes, the leaf coloration of basswood at Park Falls develops 1.462(±0.133) phenophases. When day length declines 100 minutes, the leaf fall of basswood at Park Falls develops 1.036(±0.152) phenophases.

Table 53: Progression models for spring and autumn phenology of basswood in Park Falls

Season	Model	R^2	Std. error of the estimate	Sig.
Spring	$Y = 1.078 * AGDD + 3.826 * DL - 3250.492$	.943	41.322	.000
Leaves coloration	$Y = -1.462 * DL + 1911.084$	.853	13.336	.000
Leaf fall	$Y = -1.036 * DL + 1688.138$	.820	15.161	.000

*AGDD is accumulated growing degree days; DL is day length.

6.4 Relationships between VI and ground visual phenology

The scatter plots of VI and ground visual phenology (spring, leaf coloration, and leaf fall) in Downer Woods for 2007-2012 period are shown in Figure 28. All of the plots can be divided into two parts: a steep lower part and a gentle upper part. According to the shape of the plots, the logistic function was employed to acquire the breakpoints, which are important to bridge the gap between VI and ground visual phenology.

Table 54 summarized the corresponding VI value and phenophase level at each breakpoint for both EVI and NDVI and for spring, leaf coloration, and leaf fall. For EVI, leaf expansion at phenophase level 627 in spring corresponded to EVI value 0.291; leaf full coloration at phenophase level 892 corresponded to EVI value 0.219; and leaf full fall at phenophase level 991corresponded to EVI value 0.197. For NDVI, leaf expansion at phenophase level 609 in spring corresponded to a NDVI value of 0.513; leaf full coloration at phenophase level 888 corresponded to a NDVI value of 0.472; and leaf full fall at phenophase level 988 corresponded to a NDVI value of 0.43.

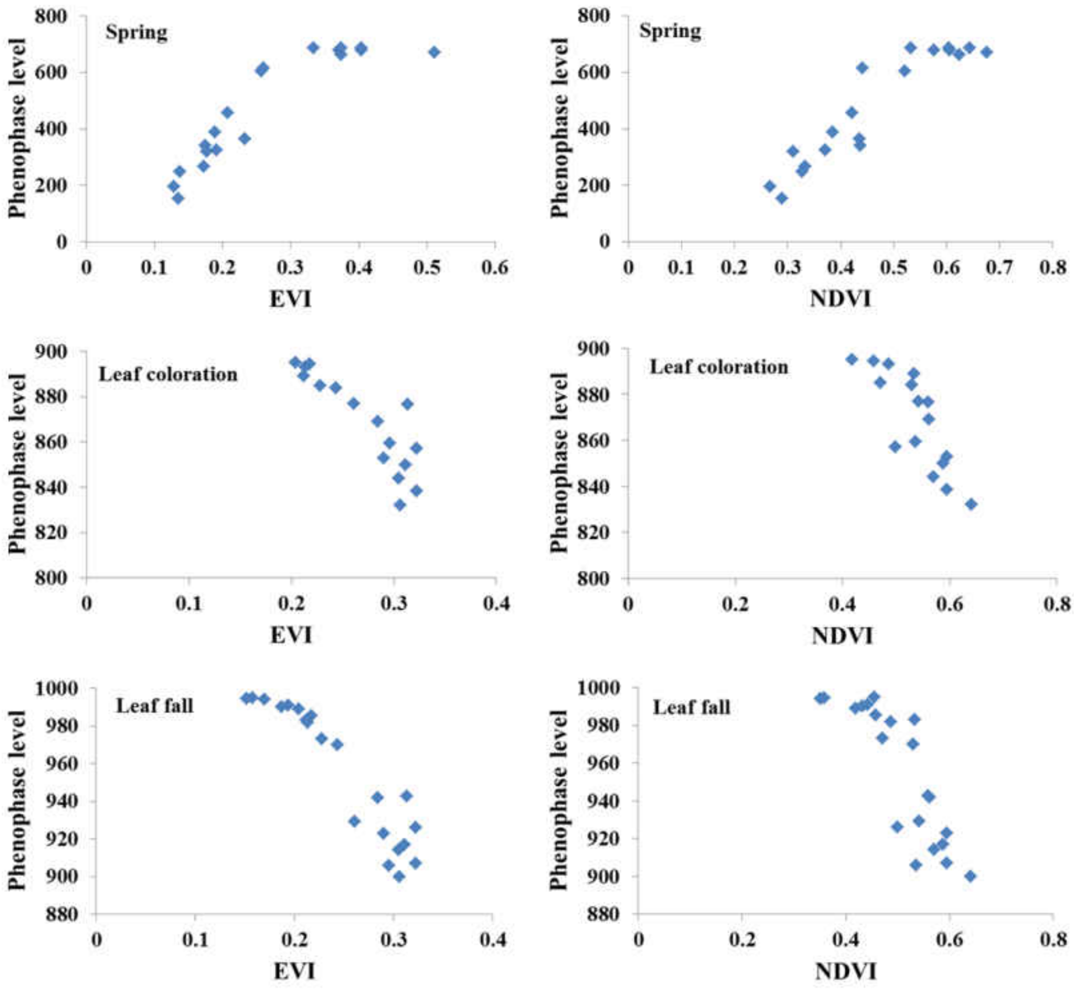


Figure 28: Scatter plots between VI and ground visual phenology

Table 54: Summary for the breakpoints on VI and ground visual phenology curve

VI	Season	VI value	Phenophase level	R^2
EVI	Spring	0.291	627	0.951
	Leaf coloration	0.219	892	0.777
	Leaf fall	0.197	991	0.922
NDVI	Spring	0.513	609	0.908
	Leaf coloration	0.472	888	0.721
	Leaf fall	0.43	988	0.764

The SOS is assigned to the date at which buds are fully open (phenophase level 390) and the EOS is assigned to the date at which leaves have reached full coloration (phenophase level 890). Here, the corresponding VI values to ground visual EOS and SOS were extracted (Table 55). Therefore, the corresponding EVI and NDVI for the SOS in Downer Woods were 0.201 and 0.403, respectively; and for the EOS were 0.227 and 0.458.

Table 55: The corresponding VI to SOS and EOS

VI values	SOS	EOS
EVI	0.201	0.227
NDVI	0.403	0.458

7. Discussion

This discussion begins with the spring and autumn phenological observations taken during this 6-year study (2007-2012) and puts the results into the context of the current literature. A detailed discussion of the spring and autumn phenological progression and the spatial models developed during this study follows, also in light of current research.

7.1 Spatially and temporally intensive phenological observations

Compared to most traditional direct observations, this dissertation contributes a unique phenological dataset with three exclusive characteristics: 1) high density observations both over time and space; 2) intensive spring and autumn phenological observations; and 3) an urban woodlot study site. This phenological dataset employs direct phenological observations with very high spatial and temporal resolutions at both the community and species level. Thus, this dataset provides a level of detail relating to phenological development throughout the season that is greater than the more commonly reported date-specific phenophases (Donnelly *et al.*, 2006; Estrella & Menzel, 2006; Schwartz *et al.*, 2006; Xu & Chen, 2013). In addition, the intensive autumn phenological observations and research are in contrast to many phenological studies focusing primarily on spring phenological observations (Badeck *et al.*, 2004; Donnelly *et al.*, 2006; Schwartz *et al.*, 2006; Caffarra *et al.*, 2011). Finally, the observations were conducted in an urban woodlot, so they are distinct from the observations in rural forests, botanical gardens, or agricultural fields.

This phenological dataset covers the entire durations of both spring and autumn leaf phenology from autumn 2007 to autumn 2012. Traditionally, direct observations usually record the date or dates on which one or a few specific phenophases occur. For example, phenological data from the European International Phenological Network included the dates of leaf unfolding, flowering, leaf coloring, etc. (Menzel & Fabian, 1999). Similarly, first leaf unfolding data were employed from the China Meteorological Administration phenological network (Xu & Chen, 2013). The first leaf and first bloom of cloned lilac and honeysuckle were used to build spring indices models (Schwartz, 1997). The phenophases used in most phenological studies are recorded on specific dates and are discrete from each other, whereas in this study I used a detailed observation protocol consisting of 24 spring phenophase levels and 8 autumn phenophase levels. These phenophase levels represent the progression of development from buds visible through to leaves fully expanded in spring and from leaf coloration through to leaf fall in autumn, thus providing a spring and autumn phenological profile for each season.

Phenological studies traditionally reported single dates for each phenophase. For example, Matsumoto *et al.* (2003) used the date of budding (20% buds open) and leaf-fall (80% leaves fall) for *Ginkgo biloba* L. in Japan from 1953 to 2000, and Gordo and Sanz (2009) employed a plant and animal phenological dataset in Spain for the period 1943-2003, which also reported the date of individual phenophases, such as flowering, leaf unfolding, fruit ripening. Both studies reported a single calendar date at which each phenophase occurred. In contrast to this date-specific record for a particular phenophase, here I subdivided each of six spring phenophases (Liang *et al.*, 2011), and two autumn phenophases into four levels, thus achieving more accurate and detailed phenological information for each phenophase through the use of intensive observations and recordings. Such high resolution data are crucial for detecting relationships between phenological development and environmental factors, building phenological progression models, and bridging the gaps between ground visual phenological data and remote sensing data. Having a range of data representing each phenophase allows more of the variability around each phenophase to be captured and presented, which results in more accurate modeling and allows direct comparisons with remote sensing data, which is available in a similar timeframe.

In addition to the large number of phenophases observed in this study, the observation frequency was also more intensive than traditional methods. In general, direct observations usually only report the day of the year when critical phenophases occur, whereas in this study the progression of the entire season (spring and autumn) was recorded by taking bi-daily phenological observations. For example, in a study conducted on deciduous trees by Delpierre *et al.* (2009) in France, phenological observations were conducted weekly and only two leaf coloration phase levels (10% yellow leaves and 90% yellow leaves) were recorded. Similarly, Morin *et al.* (2009) employed the dates of leaf unfolding from 18 North American temperate tree species at three locations in the United States. Again, high resolution data collection permits greater accuracy for 1) subsequent phenological model building, by portraying the whole progress of phenology and 2) remote sensing data validating, by scaling up from individual tree phenology to community phenology.

Combined with temporally intensive observations, spatially intensive observations also were conducted, in line with other studies conducted by Prof. Schwartz’s group (Liang & Schwartz, 2009; Hanes & Schwartz, 2011; Liang *et al.*, 2011). Spatially intensive observations can be used to: 1) fully examine community level as well as individual level phenology; and 2) build ground observation metrics corresponding to satellite pixels to fill the gaps between ground visual observations and remote sensing phenology.

Although high resolution data collection was a main focus of this study, the length of the time series was limited due to the nature of a PhD dissertation. Long time series of 30+ years are more common in places like Europe and Asia, where phenological recording has been ongoing for many years (decades to centuries) (Sparks & Carey, 1995; Walther *et al.*, 2002; Menzel *et al.*, 2005). For centuries, phenology has been observed and recorded by naturalists and widely used for managing agricultural activities, and for presenting the calendar of seasons in both Europe and Asia (Schnelle & Yang, 1965; Zhu & Wan, 1973). Since phenology has been recognized as a useful indicator of recent climate change (Schwartz, 2003; Rosenzweig *et al.*, 2008), the need to identify and establish suitable data sets has become a priority. However, in order to draw meaningful conclusions relating to climate change from phenological observations, the length of the data set is important. The longer the data series, the more confident one can be regarding the relationship between climate and phenology.

European countries and China established nationwide phenological networks in the mid-20th century (Chen, 2003; Menzel *et al.*, 2006) and most phenological studies employed spatially extensive observations (Schwartz & Hanes, 2010; Caffarra *et al.*, 2011; Xu & Chen, 2013) and across study areas, much larger than the ones in this study. There are tradeoffs between observation intensity/density and length/scale in phenological research. Here, spatially and temporally intensive observations were conducted to further understand the relationship between phenological progression throughout the season (especially autumn phenological development) and environmental factors, thus providing more detailed information than one date per phenophase.

7.2 Spring and autumn phenology

A discussion of spring phenology at both Wisconsin sites, Downer Woods (urban woodlot) (2008-2012) and Park Falls (rural forest) (2008-2010) is followed by a discussion of autumn phenology at both study sites. The growing season (start, end, and length) in Downer Woods is then examined.

7.2.1 Spring phenology

In any temperate deciduous woodland, some species leaf out before others (Lopez *et al.*, 2008) and not all trees of the same species leaf out at the same time (Seiwa, 1999), which could ultimately influence the distribution, structure, and function of woodlands. The current data suggests that considerable variation exists both within individual species (intraspecific variation) and also between different species (interspecific variation). Here, I focus on interspecific variation, with intraspecific variation discussed in the section on phenological spatial models (section 7.4).

In Downer Woods, boxelder was the first species to green up and (approximately two weeks later) advance to full leaf development. In early spring, basswood and oaks also started to leaf out early whereas white ash was the last species greening up. White oak was the latest species to reach full leaf expansion in late spring, whereas basswood, red oak, and white ash reached full leaf expansion at very similar times. These results suggest that boxelder, which is a shrubby species of the middle canopy layer, leaves out before the upper canopy closes and reduces light levels lower in the canopy, whereas oaks, which are the tallest species with the largest canopies in the woods, receive more light and are the last ones reaching canopy closure. Basswood and white ash, which are also tall tree species, reach full leaf development much later than boxelder. These results agree with the findings of Lopez *et al.* (2008) in southern Appalachian forests, which indicated that on average, bud burst of early leafing species (e.g., *Acer rubrum, Carpinus caroliniana*) was 24 days earlier than late leafing species (e.g., *Quercus rubra, Tilia Americana*). In addition, before canopy closure was reached, early leafing species had received 45-80% of their growing season light requirements in contrast to 8-15% for late leafing species. Thus, the timing of leaf-out is influenced by position in the overall canopy.

At Park Falls, spring phenology of basswoods, which is the only species common to both study sites, reached phenophase level 290 (buds fully swollen) and phenophase level 490 (leaves fully out) 16 and 11 days later than basswoods in Downer Woods in the same period (2008-2010). The later start to the basswood growing season in Park Falls was expected as the site is further north and experiences cooler temperatures than Downer Woods.

The timing of tree phenology in Downer Woods is within the range of similar deciduous trees in other areas in the US. For example, Richardson *et al.* (2006) calculated sugar maple leaves reaching 50% of their final length in the Hubbard Brook Experimental Forest (43°56′N 71°45′W) during the period 1989-2002 on DOY 134, whereas the community in Downer Woods reached phenophase level 650 (leave expansion level between 50% and 75% of mature leaves) on DOY 143. Both sites are located in the humid continental climate zone of the eastern United States and both consist of temperate deciduous forest/woodlot. Differences in dominant species, regional climates (especially spring temperatures), and research durations between the two study sites may explain the differences in timing of leaf full expansion.

Morin *et al.* (2009) simulated white ash leaf unfolding in OH, 41º33′N 84º09′W during the 1901-2000 period for white ash on DOY 138, white oak on DOY 134 (MA, 42º53′N 72º09′W), and red oak on DOY 140(MA, 42º53′N 72º09′W). In Downer Woods, white ash reached phenophase level 550 (50-90% leaves fully unfolded) on DOY 136, white oak on DOY 139, and red oak on DOY 134. Although Downer Woods and other study sites are in different places in the eastern United States and the time series are different, the results are within a similar range, indicating that the phenology of similar species may occur within a limited range even under different locations, time spans, and climates.

7.2.2 Autumn phenology

The average duration (2007-2012) of the autumn season in Downer Woods was more or less one month, starting in mid-September and ending in mid-October. In contrast to the large variation in the start of green up, all six species started yellowing at a similar time: DOY 263 for basswood, hophornbeam, and white ash and DOY 264 for red oak and white oak. White ash was the first species to reach full leaf fall, followed by basswood, then by boxelder and hophornbeam, and finally by white oak and red oak. This was an interesting result given that all species began to color at approximately the same time.

At Park Falls, autumn phenology of basswoods reached phenophase level 810 (leaf coloration) and phenophase level 990 (full leaf fall) 4 and 8 days earlier than in Downer Woods in the same period (2010 and 2012). The early autumn phenology in Park Falls was expected as the site is further north and experiences cooler temperatures than Downer Woods. Richardson *et al.* (2006) examined average 50% leaves fall for sugar maple in the Hubbard Brook Experimental Forest (43º56′N 71º45′W) during the period 1989-2002 on DOY 291, whereas the community in Downer Woods reached phenophase level 950 (10-50% leaf fall) on DOY 286. The Hubbard Brook study site has a slightly longer growing season at least for sugar maple than Downer Woods, perhaps as a result of differences in species, time spans of study, and local climate.

7.2.3 Growing season

All of the species studied in Downer Woods showed a non-statistically significant trend towards an earlier start to the growing seasons at the end of the time period (2008-2012) than at the beginning. Even though the trend is not statistically significant, it should not be completely dismissed because the lack of significance is probably a function of the short length of the time series, in contrast to other data sets reported in the literature. To some extent, this result is in agreement with other studies documenting spring advancement (Root *et al.*, 2003; Menzel *et al.*, 2006; Parmesan, 2007), which are mainly attributed to rising air temperatures.

All of the studied species in Downer Woods showed a trend towards an earlier end to the growing seasons at the end of time period (2008-2012) than at the beginning. Among species, the trends for basswood, white ash, and the community were statistically significant at the 0.05 level and that for red oak was statistically significant at the 0.10

level. In general, the EOS is not as well documented as the SOS, and it typically shows more variation than SOS. Richardson *et al.* (2006) detected no significant autumn trend for any model and species combination during the 1957-2004 period. And Menzel *et al.* (2006) detected no significant leaf coloring trend across 21 European countries during 1971-2000. In contrast, Chen and Xu (2012) detected a significant delay at a rate of 2.2 days per decade of the end of the growing season (the end date of leaf fall) in the temperate zone of China during 1986-2005. However, possibly due to the hot summers in 2010-2012, which may introduce summer drought, the autumn phenology of basswood, white ash, and red oak in Downer Woods significantly advanced. This evidence reinforces notions of the inherent variability and complexity of autumn phenology.

The length of the growing season (LOS) in Downer Woods appears to be contracting for most of the studied species (basswood, red oak, white ash) and for the community as a whole, because the EOS is advancing more rapidly than the SOS. The trends in the LOS were not in agreement with other studies of LOS (Menzel *et al.*, 2006; Delpierre *et al.*, 2009; Jeong *et al.*, 2011; Chen & Xu, 2012), which suggests in the context of global warming, that phenological responses are sensitive to local climate and environmental change. There are three possible reasons for the differences in the EOS and LOS trends of this and other studies. First, regional heterogeneity can contribute to variety of climate and environment changes as well as different responses of vegetation to climate and environment. Second, autumn phenology is more variable than spring phenology and, as a consequence, the results are more diverse. Finally, it is difficult to infer long-term trends with five years’ data, so further observations and retrospective modeling are both needed to achieve more consistent results.

7.2.4 Implications of changing phenology

Both positive and negative consequences may be induced by the advancement of spring phenology. Early budburst means that photosynthesis of plants starts early, leading to greater carbon assimilation and greater primary production, which could lead to reduced carbon dioxide levels in the atmosphere and increased agricultural and forestry production. At the same time, early budburst may increase the risk of late frost damage, which can lead to a reduction in agricultural productivity and may be especially detrimental to fruit production.

Early spring phenology could introduce mismatches in phenology between interdependent species or between species and their abiotic environment (Stenseth & Mysterud, 2002; Donnelly *et al.*, 2011). For example, warm temperature may lead to early transformations from caterpillar to butterfly, which may reduce the availability of food for migratory birds. Many of these timing mismatches could be negative for already established relationships between plants and pollinators, predators and prey. In Europe, scientists reported that rising winter temperature may result in chilling requirements not being fulfilled (Caffarra & Donnelly, 2011),but this is probably not the case in Wisconsin due to the long cold winters (Schwartz & Hanes, 2010). Negative consequences may also be induced by the advancement of autumn phenology. Early leaf coloration and early leaf fall means that photosynthesis of plants ends early, possibly leading to less carbon sequestration and less primary production.

Two possible applications could be related to the intensive observations conducted in this study. Two types of ground visual phenological data are absent in the United States: 1) Long-term visual ground observation phenological data, which can be valuable in tracking the long-term impacts of climate change on phenology, and 2) spatially and temporally intensive observational phenological data in different biomes, climate regions, and land cover types, which can be: a) a valuable source of phenological information at the community and individual species level; and b) a valuable validation for remote sensing phenology due to its community level phenological information, which can be more easily combined with integrated remote sensing signals.

7.3 Phenological progression models

Based on the analysis of the relationships between spring and autumn phenology and four groups of environmental factors (temperature, moisture, light, and wind), spring and autumn phenological progression models for each individual species and the community as a whole were built. These are empirical models based on data which represents the complete profile of leaf phenology, in contrast to the more traditional date-specific approach to representing a particular phenophase (such as budburst, leaf coloration).

7.3.1 Spring phenological progression models

The results of the statistical analysis showed that spring phenological development for each species and the community as a whole was highly correlated with air temperature, soil temperature, accumulated growing degree days, water balance, day length, and accumulated precipitation. Of these four groups of environmental factors, spring phenological development showed the highest correlation with accumulated growing degree days. This suggests that accumulated growing degree days is the critical driving factor in phenological development, consistent with the results of other studies on date-specific spring phenophase(s) (Chuine, 2000; Schwartz *et al.*, 2006; Fu *et al.*, 2012;

Xu & Chen, 2013) . These results confirm that whether a date-specific or a more comprehensive development approach is used to represent spring phenophases, accumulated growing degree days is the most important driving factor. To date, most phenological models have been based on individual species and have been built only for one specific phenophase instead of for the entire duration of phenological development. For example, most spring phenological models are based on a single bud burst date (Chuine, 2000; Caffarra *et al.*, 2011; Fu *et al.*, 2012), or a single first leaf/leaf unfolding date (Schwartz *et al.*, 2006; Vitasse *et al.*, 2011; Xu & Chen, 2013), whereas in reality these phenophases last longer than a specific date and the entire phenological development is a consecutive process.

In order to address these two issues, I used a more sophisticated approach, which took into account the full duration of phenological development. The major advantage of the spring/autumn phenological progression models used in this study is that, instead of using a single point for the start/end of the growing season, these models depict a whole profile for spring development and give a more accurate and detailed representation of phenology, which in turn can be used to set up more accurate phenological parameters for carbon simulation models and climate models. The main drawback of phenological progression models may be the amount of time required to make phenological observations.

Among phenological models, only those constructed by Richardson *et al.* (2006) for three hardwood species in the Hubbard Brook Experimental Forest considered the development of both spring and autumn phenology. Richardson *et al.* (2006) used 14 years' data (1989-2002) whereas this study used 6 years' data (2007-2012). The length of the data set is the main limitation of the current study, which was constrained by the annual cycle attribute of phenological observations and the length of the PhD program. This study is an initial effort to set up Downer Woods as a long-term phenological observation site, which has advantages due to its accessibility. It can be anticipated that with a longer time series, more meaningful trends and pheno-climatic information can be detected and achieved.

Richardson *et al.* (2006) analyzed three hardwood species (sugar maple, American beech, and yellow birch) whereas I sampled seven tree species according to the woodlot profile, presenting a more representative picture of phenology for the community and individual species. Richardson *et al.* (2006) used an observation index ranging from 0 (dormant, no leaves) to 4 (full, green canopy) whereas I use a detailed observation protocol with a total of 32 phenophase levels. Richardson *et al.* (2006)'s data was recorded weekly, whereas I recorded observations every other day. These detailed observations depict phenological processes more accurately since the major phenological transitions take place in a few weeks; weekly observations may not be frequent enough to capture the rapid changes of phenology. Richardson *et al.* (2006) used nine sample plots across the Hubbard Brook valley with elevations ranging from ~250 to 825 m ASL and at each plot there were three sample trees for each study species. This study used 27 evenly distributed plots without significant elevation difference, and at each site there are four sample trees. This data has greater spatial and temporal resolution and can more accurately describe the overall development of phenology, potentially scaling up to community level for direct comparison with satellite data.

Richardson *et al.* (2006) built and compared four types of logistic growth models of spring and autumn phenology respectively. Model 1 used day of year (DOY), model 2 used accumulated degree-days (HDD for spring phenology; CDD for autumn phenology), model 3 used both DOY and accumulated degree-days, and model 4 used HDD and CDD as input parameters. According to the correlation analysis and the regression performance among phenology and the four groups of climatic factors, this study built general linear models of spring and autumn phenology, respectively. Accumulated growing degree-days (AGDD) and day length was used as the explanatory variable in the spring models.

The spring phenological progression models developed here, which portrayed the complete duration of spring phenology in Downer Woods, performed well as indicated by the R^2 values, which ranged from 0.879 (red oak) to 0.934 (white oak). These values are similar to those reported by Richardson *et al.* (2006), describing the progress of spring phenology at Hubbard Brook (R^2 values ranging from 0.92 to 0.93). Accumulated growing degree days combined with day length showed a strong ability to simulate spring phenological development for both individual species and the community as a whole.

7.3.2 Autumn phenological progression models

The results of the correlation analysis for autumn phenology showed that the progression of both leaf coloration and leaf fall for each species and for the community as a whole were strongly correlated with air temperature, soil temperature, accumulated chilling degree days, and day length. Of these four groups of environmental factors, autumn phenological development showed the highest correlations with accumulated chilling degree days and day length. This suggests that accumulated chilling degree days and day length are the critical driving factor in phenological development in autumn, indicating that, phenologically, chilling is as important in autumn as heat is in spring. Because of the well-documented variability in autumn phenology, usually linked to photoperiod length, studies of autumn phenology reflect different opinions about the driving factor/factors, and so few models have been built previously to simulate autumn phenology.

Nearly all previously created autumn phenological models concentrated on autumn phenological events. For example, in their autumn phenological model, Doi and Takahashi (2008) used the date when most of the leaves were colored and 80% of the phase leaf fall was reached for *Ginkgo biloba* (Ginkgo) and *Acer palmatum* (Japanese maple). Similarly, Estrella and Menzel (2006) used the date when 50% of all leaf coloring for horse chestnut, beech, birch, and oak was reached, and Delpierre *et al.* (2009) used the date when 90% of European beech and oak showed yellow leaves over 20-50% of their crowns. Similar to the spring phenological progression models, the autumn phenological progression models built in this study simulated the development of the entire duration of autumn phenology for each species as well as for the community as a whole. Accumulated chilling degree-days (ACDD) and day length was the main explanatory variable in these models.

The autumn phenological models developed in this study did not perform as well as the spring models, as indicated by R^2 values, which ranged from 0.764 (white ash) to 0.891 (white oak). The performance of the autumn model for white ash was possibly enhanced by the potential influence of photoperiod. Models 2, 3, and 4 of Richardson *et al.* (2006) generally performed better than my models with R^2 values ranging from 0.87

to 0.90. However, accumulated chilling degree days may still be considered a strong parameter for simulating autumn phenological development for individual species, except perhaps for white ash and the community as a whole.

Generally speaking, my models performed well for spring phenology, whether for individual species or the community as a whole, and they performed best for oaks and moderately well for other species in autumn. The models can serve to 1) examine the interactions between spring and autumn phenology and environmental factors; 2) predict the impact of future climate change on ecosystems; and 3) establish more concise start and end points of growing seasons for carbon simulation models and climate models.

7.4 Spatial regression models

Usually, spatial patterns of phenology are examined at global, continental, or regional scales. Schwartz *et al.* (2006) employed spring index models to reconstruct spring phenology in the temperate Northern Hemisphere during 1955-2002 and confirmed that although a universal earlier onset of spring was detected, different regions (such as North America, Western Europe, and East Asia) showed different spatial patterns of changes in the timing of the onset of spring. At a regional level, Xu and Chen (2013) employed unified forcing and chilling phenology models, using first leaf unfolding data of four tree species (*Salix matsudana, Populus simonii, Ulmus pumila,*and *Prunus armeniaca*) combined with daily mean temperature to rebuild spatial patterns of spring phenology across northern China over 1960-2009.

In the current study, spatial regression models for all phenophase levels of two dominant species (basswood and white ash) in Downer Woods were built to examine spatial patterns in phenology at a site scale. No similar studies have been published to 1) permit detection of spatial patterns of phenology at the site scale, and/or 2) examine spatial patterns for each phenophase level in a consecutive sequence. The advantages of these spatial regression models are that 1) they facilitate detection of phenological variations of dominant trees at a site scale and provide an opportunity to examine the influence of local climate and local environmental factors, and 2) they allow examination of the influence of local climate and environmental factors on different stages of phenology progression.

7.4.1 Spring spatial regression models

Spring spatial regression models for basswood and white ash were built for a total of 21 phenophase levels in spring (190: buds fully visible – 675: full leaf expansion). Differences in the spatial patterns of spring phenology have been revealed between these two dominant tree species in Downer Woods. Three of the phenophase levels of basswood (210: buds swollen; 650 and 675: leaf expansion levels) and 20 of the phenophase levels of white ash showed significant spatial patterns. The analysis revealed that the timing of basswood spring phenology responded most to latitude (a proxy for temperature), whereas white ash showed a strong response to distance from each site to the edge of the study area (another proxy for temperature). However, white ash responded to the edge effect temperature gradient during early to mid-spring and to the north-south temperature gradient during late spring. The rates of phenological advance of white ash imposed by a latitudinally-driven change in temperature and by edge-effect temperature change are both greater than those of basswood. These results are surprising, and it was not anticipated that there would be such strong responses to temperature gradients imposed by latitude and edge effects in such a small area.

In general, the models explained 30.2%, 28.6%, and 25.6%, respectively of the variation in the spatial pattern of the three spring phenophase levels for basswood. By comparison, the models explained from 30.4% (200: buds swollen) to 61.1% (310: buds open) of the variation of spatial pattern of the 20 spring phenophase levels of white ash, which are generally higher than those of basswood. Latitude, longitude, and edge distance are possible proxies for temperature and shelter. A possible future addition to this study could be to use land surface temperature from high resolution remote sensing data to detect temperature variations within the study area.

7.4.2 Autumn spatial regression models

Autumn spatial regression models for basswood and white ash were built for a total of eight phenophase levels in autumn (800: leaf coloration – 990: full leaf fall). Similar to spring, there were major differences in autumn phenological spatial patterns between the two dominant tree species. In contrast to the spring phenophase levels, none of the autumn regression models for white ash were significant.

Two phenophase levels for basswood (890: full leaf coloration; 990: full leaf fall) showed significant spatial patterns. The two regression models showed that, in contrast to spring phenology, the timing of autumn phenology responded most to longitude (probably a proxy for temperature in autumn). The rates of phenological advance from west to east were -0.940 and -0.886 days/second, respectively. The models explained

29.4% and 33.4%, respectively of the variation in the spatial pattern of the two autumn phenophase levels of basswood.

The north-south temperature gradient and the edge effect temperature gradient were more critical in spring, whereas the west-east temperature gradient was more important in autumn. An interesting future study would be to compare temperature variations over the study area between spring and autumn aided by satellite data, since there is no high resolution ground micrometeorological data available.

7.5 Relationships between remote sensing phenology and ground visual phenology

The relationships between VI from MODIS and community phenology from ground observations confirmed that both EVI and NDVI can directly detect the change in vegetation phenology from one phenophase to the next, as has been reported by previous studies on remote sensing phenology (Reed *et al.*, 1994; Zhang *et al.*, 2003; Pettorelli *et al.*, 2005; Delbart *et al.*, 2006; White *et al.*, 2009). Bridging the gap between remote sensing data and ground visual phenological data, and determining the biological meaning of remote sensing data have always been important issues in phenological research (Morisette *et al.*, 2009; Liang *et al.*, 2011). How to scale up ground visual phenololgy to comply with satellite matrix data and how to acquire real ground phenological information of VI instead of a synoptic view are critical questions in this field (Schwartz *et al.*, 2002).

In order to resolve these issues, and based on Liang *et al.* (2011)'s research in northern Wisconsin, this study scaled ground individual phenology up to community phenology and compared it with MODIS VI for both spring and autumn seasons.

Generally, the logistic function fitting of the scatter plots of EVI and phenophase level were better than that of NDVI and phenophase level; and the fitting for spring was always better than the fitting for autumn (leaf coloration and leaf fall). The results showed that EVI can represent spring phenology well until early leaf expansion, and that NDVI can also represent spring phenology well until very early leaf expansion. In addition, both EVI and NDVI can represent autumn phenology well until the very end of leaf coloration and leaf fall. In general, EVI, which was enhanced from NDVI by correcting aerosol scattering and adjusting soil influences (Jensen, 2000), does achieve better representation of vegetation phenology than NDVI.

This study filled gaps between remote sensing phenology and ground visual phenology in a temperate woodlot and acquired the ground phenological meaning for the corresponding VI, which not only affirmed that both EVI and NDVI contain useful information for detecting vegetation dynamics, but also determined the potential VI values for the ground SOS and EOS as well as the breakpoint VI values, which correspond to the end of spring or autumn seasons. The results can be applied to temperate forests with similar community compositions or maybe similar spectral combinations. Moreover, this approach can be widely used over a variety of taxa and to compare VI value differences on breakpoints and SOS and EOS.

8. Conclusions

8.1 Major conclusions

This study set out to build a set of unique phenological progression models for individual tree species as well as for the community as a whole using a range of parameters pertaining to temperature, moisture, light, and wind conditions. The results of the statistical analysis showed that, of all the meteorological and environmental parameters tested, temperature was consistently the most influential factor driving both spring and autumn phenological progression. These models have the potential to be adapted to examine future phenological changes by incorporating temperature projections for a range of climate scenarios, as well as to be applied to other study areas at local, regional, and continental scales. In addition, there is also the possibility for phenological progression models to be integrated into carbon cycle models and climate models, to help establish not only the start and end of growing seasons but also define the critical phenophases in between.

Autumn phenology is equally as important as spring phenology in determining the length of the growing season, which is a critical parameter in global and regional carbon cycle modeling and climate simulation. However, autumn phenology is generally much less observed and studied. This study is the first of its kind to conduct an intensive autumn phenological observation campaign in a temperate deciduous woodlot, over six consecutive years. The results of statistical analysis show that accumulated chilling degree days (ACDD) and day length are crucial factors influencing autumn phenology, so it was used to build phenological progression models for each observed tree species and the plant community as a whole to predict the occurrence of future autumn phenological phases.

Similarly, the relationship between spring phenology and its possible driving climate drivers was also examined. The results are to some extent consistent with past studies, showing that temperature is the critical factor affecting the timing of some specific spring phenophases (such as first leafing, first flowering); this study showed that temperature (especially the accumulated growing degree-days) is the most important factor driving the development of plant phenology. The spring phenological progression models simulate spring phenological development very well, always having better predictability than the autumn models.

Two dominant species (basswood and white ash) showed significant spatial patterns. In spring, temperature gradients represented by latitude and the edge distance controlled spatial variations of phenology. In comparison, during autumn, temperature gradients represented by longitude dominated the spatial variations of phenology. These spatial patterns may be a consequence of air temperature gradients produced by the uneven distribution of features in the urban surroundings, especially buildings of different heights and types, indicating that local urban settings can significantly affect phenology.

By comparing ground visual community phenology with composite MODIS VI matrices, the results confirmed that both EVI and NDVI can detect vegetation dynamics from satellite, but showed that EVI can provide better ground phenological information than NDVI for both the spring and autumn seasons. From this initial analysis, it appears that the gaps between remote sensing data and ground visual phenology can be narrowed and the biological meaning of satellite data can be better determined. Moreover, ground validation over taxa should be done step by step to achieve more accurate information for paired VI /ground visual phenology in different biomes.

8.2 Remaining issues and recommendations

Limitations and challenges cannot be avoided in any scientific study, but these remaining issues often can inspire additional opportunities and lead to future discoveries.

8.2.1 Field observations

Although much observational effort (six years' observations) has been put into this initial study, phenology has an annual cycle, and long-term (ideally more than ten years) data series are needed to more fully understand the responses of vegetation to climate change. This study employed spring and autumn phenological observation protocols, which are effective for tracking the complete development of phenology throughout these seasons, but it is a relatively time consuming process. Spatially intensive observations can provide more detailed phenological profiles for individual species as well as the community as a whole, but again this process is quite time consuming, so the areas observed directly must be limited.

This study site has many advantages, including its potential to be a long-term intensive US phenological observation site. In addition, its easily accessible location on-campus makes for low resource input costs in terms of travel and accommodation. Since the phenological observations can be combined with undergraduate student education, undergraduates with an interest can be recruited to conduct observations. A near-ground camera was deployed in spring 2013, as part of the PhenoCam network, to take hourly daytime RGB and near infrared images of the entire site, which can provide a whole canopy phenological profile with high temporal resolution. Continued ground observations with these camera images will provide a long-term data set for future phenologists to work with, and will contribute to the growing number of data sets in the USA.

8.2.2 Model validation

Accurate phenological models representative of one site are not always transferrable to other sites (Richardson *et al.*, 2006), so, model validation should be used to verify the model performance retrospectively or predictively at the same site or in different sites. Six years of phenological data were employed to build the phenological progression models in this study. These models examine how accumulated growing degree days and accumulated chilling degree days influence the development of spring and autumn phenology, respectively. After a longer data set is achieved, it would be useful to divide the data set into two parts with one part being used to build the model and the second part being used to validate the model.

8.2.3 Retrospective modeling

In this study there are only six years of observational data for autumn and five years of observational data for spring. Phenological observation data alone are not enough to evaluate the possible impacts of climate change on spring and autumn phenology in Downer Woods. Since the comparison between temperatures in Downer Woods and at the Milwaukee airport weather station showed little differences, temperatures at Milwaukee airport, which go as far back as 1948, can be employed to retrospectively model spring and autumn phenology of dominant species and the community as a whole in Downer Woods. With such long-term data, potential impacts of climate change could be analyzed and compared with other studies.

8.2.4 Basswood modeling

Basswood is a common and widely distributed deciduous tree species throughout eastern and central North America. The USA National Phenology Network (USA-NPN) has collected nationwide phenological data of basswood acquired by citizen scientists since 2009. Combined with detailed basswood phenological data at Downer Woods and Park Falls, the current model could be extended to build a broader basswood phenological model to simulate phenology across the eastern and central USA.

References

Abu-Asab, M.S., Peterson, P.M., Shetler, S.G. & Orli, S.S. (2001) Earlier plant flowering in spring as a response to global warming in the Washington, DC, area. *Biodiversity and Conservation*, **10**, 597-612.

Ahas, R. & Aasa, A. (2006) The effects of climate change on the phenology of selected Estonian plant, bird and fish populations. *International Journal of Biometeorology*, **51**, 17-26.

Badeck, F.W., Bondeau, A., Bottcher, K., Doktor, D., Lucht, W., Schaber, J. & Sitch, S. (2004) Responses of spring phenology to climate change. *New Phytologist*, **162**, 295-309.

Bernstein, L.P.R.K.R.A.I.P.o.C.C. (2008) *Climate change 2007 : synthesis report*. IPCC, Geneva, Switzerland.

Bertin, R.I. (2008) Plant phenology and distribution in relation to recent climate change. *Journal of the Torrey Botanical Society*, **135**, 126-146.

Betancourt, J.L., Schwartz, M.D., Breshears, D.D., Brewer, C.A., Frazer, G., Gross, J.E., Mazer, S.J., Reed, B.C. & Wilson, B.E. (2007) Evolving Plans for the USA National Phenology Network. *Eos Trans. AGU Eos, Transactions American Geophysical Union*, **88**

Bradley, N.L., Leopold, A.C., Ross, J. & Huffaker, W. (1999) Phenological changes reflect climate change in Wisconsin. *Proceedings of the National Academy of Sciences of the United States of America*, **96**, 9701-9704.

Brown, M.E. & de Beurs, K.M. (2008) Evaluation of multi-sensor semi-arid crop season parameters based on NDVI and rainfall. *Remote Sensing of Environment*, **112**, 2261-2271.

Caffarra, A. & Donnelly, A. (2011) The ecological significance of phenology in four different tree species: effects of light and temperature on bud burst. *International Journal of Biometeorology*, **55**, 711-721.

Caffarra, A., Donnelly, A., Chuine, I. & Jones, M.B. (2011) Modelling the timing of Betula pubescens budburst. I. Temperature and photoperiod: a conceptual model. *Climate Research*, **46**, 147-157.

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M. & Peterson, D.H. (2001) Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, **82**, 399-415.

Chen, X.Q. (2003) East Asia. *Phenology: an integrative environmental science* (ed. by M.D. Schwartz), pp. 11-25. Kluwer Academic Publishers, Dordrecht; Boston.

Chen, X.Q. & Xu, L. (2012) Phenological responses of Ulmus pumila (Siberian Elm) to climate change in the temperate zone of China. *International Journal of Biometeorology*, **56**, 695-706.

Chen, X.Q., Hu, B. & Yu, R. (2005) Spatial and temporal variation of phenological growing season and climate change impacts in temperate eastern China. *Global Change Biology*, **11**, 1118-1130.

Chmielewski, F.M. & Rotzer, T. (2001) Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, **108**, 101-112.

Christidis, N., Stott, P.A., Brown, S., Karoly, D.J. & Caesar, J. (2007) Human contribution to the lengthening of the growing season during 1950-99. *Journal of Climate*, **20**, 5441-5454.

Chuine, I. (2000) A unified model for budburst of trees. *Journal of Theoretical Biology*, **207**, 337-347.

Chuine, I. & Beaubien, E.G. (2001) Phenology is a major determinant of tree species range. *Ecology Letters*, **4**, 500-510.

Chuine, I. & Belmonte, J. (2004) Improving prophylaxis for pollen allergies: Predicting the time course of the pollen load of the atmosphere of major allergenic plants in France and Spain. *Grana*, **43**, 65-80.

Chuine, I., Cambon, G. & Comtois, P. (2000) Scaling phenology from the local to the regional level: advances from species-specific phenological models. *Global Change Biology*, **6**, 943-952.

Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V. & Ladurie, E.L. (2004) Historical phenology: Grape ripening as a past climate indicator. *Nature*, **432**, 289-290.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A. & Schwartz, M.D. (2007) Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, **22**, 357-65.

Crimmins, M.A. & Crimmins, T.M. (2008) Monitoring plant phenology using digital repeat photography. *Environmental Management*, **41**, 949-958.

de Beurs, K.M. & Henebry, G.M. (2005) Land surface phenology and temperature variation in the International Geosphere-Biosphere Program high-latitude transects. *Global Change Biology*, **11**, 779-790.

Delbart, N., Le Toan, T., Kergoat, L. & Fedotova, V. (2006) Remote sensing of spring phenology in boreal regions: A free of snow-effect method using NOAA-AVHRR and SPOT-VGT data (1982-2004). *Remote Sensing of Environment*, **101**, 52-62.

Delpierre, N., Dufrene, E., Soudani, K., Ulrich, E., Cecchini, S., Boe, J. & Francois, C. (2009) Modelling interannual and spatial variability of leaf senescence for three deciduous tree species in France. *Agricultural and Forest Meteorology*, **149**, 938-948.

Doi, H. & Takahashi, M. (2008) Latitudinal patterns in the phenological responses of leaf colouring and leaf fall to climate change in Japan. *Global Ecology and Biogeography*, **17**, 556-561.

Donnelly, A., Salamin, N. & Jones, M.B. (2006) Changes in tree phenology: An indicator of spring warming in Ireland? *Biology and Environment*, **106B**, 49-56.

Donnelly, A., Caffarra, A. & O'Neill, B.F. (2011) A review of climate-driven mismatches between interdependent phenophases in terrestrial and aquatic ecosystems. *International Journal of Biometeorology*, **55**, 805-817.

Edwards, M. & Richardson, A.J. (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430**, 881-884.

Estrella, N. & Menzel, A. (2006) Responses of leaf colouring in four deciduous tree species to climate and weather in Germany. *Climate Research*, **32**, 253-267.

Fisher, J.I., Mustard, J.F. & Vadeboncoeur, M.A. (2006) Green leaf phenology at Landsat resolution: Scaling from the field to the satellite. *Remote Sensing of Environment*, **100**, 265-279.

Fitter, A.H. & Fitter, R.S.R. (2002) Rapid changes in flowering time in British plants. *Science*, **296**, 1689-1691.

Fitzjarrald, D.R., Acevedo, O.C. & Moore, K.E. (2001) Climatic consequences of leaf presence in the eastern United States. *Journal of Climate*, **14**, 598-614.

Forchhammer, M.C., Post, E. & Stenseth, N.C. (1998) Breeding phenology and climate ... *Nature*, **391**, 29-30.

Friedl, M., Henebry, G.M., Reed, B.C., Huete, A., White, M.A., Morisette, J., Nemani, R., Zhang, X.Y. & Myneni, R. (2006) *Land surface phenology NASA white paper*. Available at: http://landportal.gsfc.nasa.gov/Documents/ESDR/Phenology_Friedl_whitepaper.pdf (accessed

Fu, Y.S.H., Campioli, M., Van Oijen, M., Deckmyn, G. & Janssens, I.A. (2012) Bayesian comparison of six different temperature-based budburst models for four temperate tree species. *Ecological Modelling*, **230**, 92-100.

Gallo, K.P., Easterling, D.R. & Peterson, T.C. (1996) The influence of land use land cover on climatological values of the diurnal temperature range. *Journal of Climate*, **9**, 2941-2944.

Ganguly, S., Friedl, M.A., Tan, B., Zhang, X.Y. & Verma, M. (2010) Land surface phenology from MODIS: Characterization of the Collection 5 global land cover dynamics product. *Remote Sensing of Environment*, **114**, 1805-1816.

Gazal, R., White, M.A., Gillies, R., Rodemaker, E., Sparrow, E. & Gordon, L. (2008) GLOBE students, teachers, and scientists demonstrate variable differences between urban and rural leaf phenology. *Global Change Biology*, **14**, 1568-1580.

Gordo, O. & Sanz, J.J. (2009) Long-term temporal changes of plant phenology in the Western Mediterranean. *Global Change Biology*, **15**, 1930-1948.

Gordo, O. & Sanz, J.J. (2010) Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology*, **16**, 1082-1106.

Graham, E.A., Yuen, E.M., Robertson, G.F., Kaiser, W.J., Hamilton, M.P. & Rundel, P.W. (2009) Budburst and leaf area expansion measured with a novel mobile camera system and simple color thresholding. *Environmental and experimental botany*, **65**, 238-244.

Hamilton, M.P., Graham, E.A., Rundel, P.W., Allen, M.F., Kaiser, W., Hansen, M.H. & Estrin, D.L. (2007) New approaches in embedded networked sensing for terrestrial ecological observatories. *Environmental Engineering Science*, **24**, 192-204.

Hanes, J.M. & Schwartz, M.D. (2011) Modeling land surface phenology in a mixed temperate forest using MODIS measurements of leaf area index and land surface temperature. *Theoretical and Applied Climatology*, **105**, 37-50.

Hansen, J., Ruedy, R., Sato, M. & Lo, K. (2010) Global Surface Temperature Change. *Reviews of Geophysics*, **48**

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X. & Ferreira, L.G. (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, **83**, 195-213.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. &

Roughgarden, J. (2003) Climate change, human impacts, and the resilience of coral reefs. *Science*, **301**, 929-933.

Ibanez, I., Primack, R.B., Miller-Rushing, A.J., Ellwood, E., Higuchi, H., Lee, S.D., Kobori, H. & Silander, J.A. (2010) Forecasting phenology under global warming. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365**, 3247-3260.

Intergovernmental Panel on Climate Change. Working Group I. (2007) *Climate change 2007 : the physical science basis : summary for policymakers*. IPCC Secretariat, Paris.

Jensen, J.R. (2000) *Remote sensing of the environment : an earth resource perspective*. Prentice Hall, Upper Saddle River, N.J.

Jensen, J.R. (2007) *Remote sensing of the environment : an earth resource perspective*. Pearson Prentice Hall, Upper Saddle River, NJ.

Jeong, S.J., Ho, C.H., Gim, H.J. & Brown, M.E. (2011) Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology*, **17**, 2385-2399.

Jin, M.L., Dickinson, R.E. & Zhang, D.L. (2005) The footprint of urban areas on global climate as characterized by MODIS. *Journal of Climate*, **18**, 1551-1565.

Jonsson, P. & Eklundh, L. (2004) TIMESAT - a program for analyzing time-series of satellite sensor data. *Computers & Geosciences*, **30**, 833-845.

Kalnay, E. & Cai, M. (2003) Impact of urbanization and land-use change on climate. *Nature*, **423**, 528-531.

Keeling, C.D., Chin, J.F.S. & Whorf, T.P. (1996) Increased activity of northern vegetation inferred from atmospheric CO2 measurements. *Nature*, **382**, 146-149.

Lechowicz, M.J. (1984) Why Do Temperate Deciduous Trees Leaf Out at Different Times? Adaptation and Ecology of Forest Communities. *American Naturalist*, **124**, 821-842.

Liang, L. (2009) *Landscape phenology of wisconsin's temperate mixed forest: An initial study integrating high-resolution in situ and remote sensing observations (dissertation)*.

Liang, L. & Schwartz, M. (2009) Landscape phenology: an integrative approach to seasonal vegetation dynamics. *Landscape Ecology*, **24**, 465-472.

Liang, L.A., Schwartz, M.D. & Fei, S.L. (2011) Validating satellite phenology through intensive ground observation and landscape scaling in a mixed seasonal forest. *Remote Sensing of Environment*, **115**, 143-157.

Lieth, H. (1974) *Phenology and seasonality modeling*. Springer, Berlin, Heidelberg, New York.

Linderholm, H.W. (2006) Growing season changes in the last century. *Agricultural and Forest Meteorology*, **137**, 1-14.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B. & Ackerly, D.D. (2009) The velocity of climate change. *Nature*, **462**, 1052-5.

Lopez, O.R., Farris-Lopez, K., Montgomery, R.A. & Givnish, T.J. (2008) Leaf phenology in relation to canopy closure in southern Appalachian trees. *American Journal of Botany*, **95**, 1395-1407.

Lu, P.L., Yu, Q., Liu, J.D. & Lee, X.H. (2006) Advance of tree-flowering dates in response to urban climate change. *Agricultural and Forest Meteorology*, **138**, 120-131.

Luo, Z.K., Sun, O.J., Ge, Q.S., Xu, W.T. & Zheng, J.Y. (2007) Phenological responses of plants to climate change in an urban environment. *Ecological Research*, **22**, 507-514.

Matsumoto, K., Ohta, T., Irasawa, M. & Nakamura, T. (2003) Climate change and extension of the Ginkgo biloba L. growing season in Japan. *Global Change Biology*, **9**, 1634-1642.

McCarty, J.P. (2001) Ecological consequences of recent climate change. *Conservation Biology*, **15**, 320-331.

Menzel, A. (2003) Plant phenological anomalies in Germany and their relation to air temperature and NAO. *Climatic Change*, **57**, 243-263.

Menzel, A. & Fabian, P. (1999) Growing season extended in Europe. *Nature*, **397** 659-659.

Menzel, A., Estrella, N. & Fabian, P. (2001) Spatial and temporal variability of the phenological seasons in Germany from 1951 to 1996. *Global Change Biology*, **7**, 657-666.

Menzel, A., Estrella, N. & Testka, A. (2005) Temperature response rates from long-term phenological records. *Climate Research*, **30**, 21-28.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavska, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Filella, Y., Jatcza, K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.E., Zach, S. & Zust, A. (2006) European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**, 1969-1976.

Miller-Rushing, A.J. & Primack, R.B. (2008) Global warming and flowering times in Thoreau's concord: A community perspective. *Ecology*, **89**, 332-341.

Morin, X., Lechowicz, M.J., Augspurger, C., O' Keefe, J., Viner, D. & Chuine, I. (2009) Leaf phenology in 22 North American tree species during the 21st century. *Global Change Biology*, **15**, 961-975.

Morisette, J.T., Richardson, A.D., Knapp, A.K., Fisher, J.I., Graham, E.A., Abatzoglou, J., Wilson, B.E., Breshears, D.D., Henebry, G.M., Hanes, J.M. & Liang, L. (2009) Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. *Frontiers in Ecology and the Environment*, **7**, 253-260.

Moulin, S., Kergoat, L., Viovy, N. & Dedieu, G. (1997) Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. *Journal of Climate*, **10**, 1154-1170.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G. & Nemani, R.R. (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, **386**, 698-702.

Norby, R.J., Hartz-Rubin, J.S. & Verbrugge, M.J. (2003) Phenological responses in maple to experimental atmospheric warming and CO^2 enrichment. *Global Change Biology*, **9**, 1792-1801.

Oliver, J.E. (2005) *Encyclopedia of world climatology*. Springer, Dordrecht, Netherlands; New York.

Oliver, J.E.H.J.J. (2002) *Climatology : an atmospheric science*. Prentice Hall, Upper Saddle River, NJ.

Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics*, **37**, 637-669.

Parmesan, C. (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology*, **13**, 1860-1872.

Parmesan, C. & Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37-42.

Parry, M.L.I.P.o.C.C.W.G., II (2007) *Climate change 2007 : impacts, adaptation and vulnerability : contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K.; New York.

Penuelas, J. & Filella, I. (2001) Phenology - Responses to a warming world. *Science*, **294**, 793-+.

Penuelas, J., Rutishauser, T. & Filella, I. (2009) Phenology Feedbacks on Climate Change. *Science*, **324**, 887-888.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J. & Stenseth, N.C. (2005) Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, **20**, 503-510.

Piao, S.L., Fang, J.Y., Zhou, L.M., Ciais, P. & Zhu, B. (2006) Variations in satellite-derived phenology in China's temperate vegetation. *Global Change Biology*, **12**, 672-685.

Piao, S.L., Friedlingstein, P., Ciais, P., Viovy, N. & Demarty, J. (2007) Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. *Global Biogeochemical Cycles*, **21**, -.

Reed, B.C., Brown, J.F., Vanderzee, D., Loveland, T.R., Merchant, J.W. & Ohlen, D.O. (1994) Measuring Phenological Variability from Satellite Imagery. *Journal of Vegetation Science*, **5**, 703-714.

Rich, P.M., Breshears, D.D. & White, A.B. (2008) Phenology of mixed woody-herbaceous ecosystems following extreme events: Net and differential responses. *Ecology*, **89**, 342-352.

Richardson, A.D., Bailey, A.S., Denny, E.G., Martin, C.W. & O'Keefe, J. (2006) Phenology of a northern hardwood forest canopy. *Global Change Biology*, **12**, 1174-1188.

Richardson, A.D., Braswell, B.H., Hollinger, D.Y., Jenkins, J.P. & Ollinger, S.V. (2009) Near-surface remote sensing of spatial and temporal variation in canopy phenology. *Ecological Applications*, **19**, 1417-1428.

Richardson, A.D., Jenkins, J.P., Braswell, B.H., Hollinger, D.Y., Ollinger, S.V. & Smith, M.L. (2007) Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia*, **152**, 323-334.

Richardson, A.D., Black, T.A., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., Hollinger, D.Y., Kutsch, W.L., Longdoz, B., Luyssaert, S., Migliavacca, M., Montagnani, L., Munger, J.W., Moors, E., Piao, S.L., Rebmann, C., Reichstein, M., Saigusa, N., Tomelleri, E., Vargas, R. & Varlagin, A. (2010) Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365**, 3227-3246.

Richardson, A.D., Anderson, R.S., Arain, M.A., Barr, A.G., Bohrer, G., Chen, G.S., Chen, J.M., Ciais, P., Davis, K.J., Desai, A.R., Dietze, M.C., Dragoni, D., Garrity, S.R., Gough, C.M., Grant, R., Hollinger, D.Y., Margolis, H.A., McCaughey, H., Migliavacca, M., Monson, R.K., Munger, J.W., Poulter, B., Raczka, B.M., Ricciuto, D.M., Sahoo, A.K., Schaefer, K., Tian, H.Q., Vargas, R., Verbeeck, H., Xiao, J.F. & Xue, Y.K. (2012) Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. *Global Change Biology*, **18**, 566-584.

Rogerson, P. (2006) *Statistical methods for geography*. SAGE, London.

Root, T.L., MacMynowski, D.P., Mastrandrea, M.D. & Schneider, S.H. (2005) Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 7465-7469.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C. & Pounds, J.A. (2003) Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57-60.

Rosenberg, N.J., Blad, B.L. & Verma, S.B. (1983) *Microclimate : the biological environment*. Wiley, New York.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S. & Imeson, A. (2008) Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453**, 353-7.

Salamun, P.J. (1972) A Botanical History of Downer Woods. *Field Station Bulletin*, **5**, 1-9.

Saxe, H., Cannell, M.G.R., Johnsen, B., Ryan, M.G. & Vourlitis, G. (2001) Tree and forest functioning in response to global warming. *New Phytologist*, **149**, 369-399.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. & Walker, B. (2001) Catastrophic shifts in ecosystems. *Nature*, **413**, 591-596.

Schnelle, F. & Yang, Y.t. (1965) *Zhi wu wu hou xue (Plant Phenology)*. Ke xue chu ban she (Science Press), Beijing.

Schwartz, M.D. (1992) Phenology and Springtime Surface-Layer Change. *Monthly Weather Review*, **120**, 2570-2578.

Schwartz, M.D. (1996) Examining the spring discontinuity in daily temperature ranges. *Journal of Climate*, **9**, 803-808.

Schwartz, M.D. (1997) spring index models: an approach to connecting satellite and surface phenology.

Schwartz, M.D. (1998) Green-wave phenology. *Nature*, **394**, 839-840.

Schwartz, M.D. (1999) Advancing to full bloom: planning phenological research for the 21st century. *International Journal of Biometeorology*, **42**, 113-118.

Schwartz, M.D. (2003) *Phenology : an integrative environmental science*. Kluwer Academic Publishers, Dordrecht; Boston.

Schwartz, M.D. & Karl, T.R. (1990) Spring Phenology - Natures Experiment to Detect the Effect of Green-up on Surface Maximum Temperatures. *Monthly Weather Review*, **118**, 883-890.

Schwartz, M.D. & Reed, B.C. (1999) Surface phenology and satellite sensor-derived onset of greenness: an initial comparison. *International Journal of Remote Sensing*, **20**, 3451-3457.

Schwartz, M.D. & Reiter, B.E. (2000) Changes in North American spring. *International Journal of Climatology*, **20**, 929-932.

Schwartz, M.D. & Crawford, T.M. (2001) Detecting energy balance modifications at the onset of spring. *Physical Geography*, **22**, 394-409.

Schwartz, M.D. & Beaubien, E.G. (2003) North America. *Phenology : an integrative environmental science* (ed. by M.D. Schwartz), pp. 57-73. Kluwer Academic Publishers, Dordrecht; Boston.

Schwartz, M.D. & Hanes, J.M. (2010) Continental-scale phenology: warming and chilling. *International Journal of Climatology*, **30**, 1595-1598.

Schwartz, M.D., Reed, B.C. & White, M.A. (2002) Assessing satellite-derived start-of-season measures in the conterminous USA. *International Journal of Climatology*, **22**, 1793-1805.

Schwartz, M.D., Ahas, R. & Aasa, A. (2006) Onset of spring starting earlier across the Northern Hemisphere. *Global Change Biology*, **12**, 343-351.

Schwartz, M.D., Betancourt, J.L. & Weltzin, J.F. (2012) From Caprio's lilacs to the USA National Phenology Network. *Frontiers in Ecology and the Environment*, **10**, 324-327.

Seiwa, K. (1999) Changes in leaf phenology are dependent on tree height in Acer mono, a deciduous broad-leaved tree. *Annals Of Botany*, **83**, 355-361.

Sparks, T.H. & Carey, P.D. (1995) The Responses of Species to Climate over 2 Centuries - an Analysis of the Marsham Phenological Record, 1736-1947. *Journal of Ecology*, **83**, 321-329.

Sparks, T.H. & Menzel, A. (2002) Observed changes in seasons: An overview. *International Journal of Climatology*, **22**, 1715-1725.

Stenseth, N.C. & Mysterud, A. (2002) Climate, changing phenology, and other life history and traits: Nonlinearity and match-mismatch to the environment. *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 13379-13381.

Taylor, G., Tallis, M.J., Giardina, C.P., Percy, K.E., Miglietta, F., Gupta, P.S., Gioli, B., Calfapietra, C., Gielen, B., Kubiske, M.E., Scarascia-Mugnozza, G.E., Kets, K., Long, S.P. & Karnosky, D.F. (2008) Future atmospheric CO2 leads to delayed autumnal senescence. *Global Change Biology*, **14**, 264-275.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F., De Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., Van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L. & Williams, S.E. (2004) Extinction risk from climate change. *Nature*, **427**, 145-8.

Thomas, D.S.G. & Goudie, A.J. (2000) *The dictionary of physical geography*. Blackwell, Malden, Mass.

Thomas, M., Richardson, J.A. & Ranson, S.L. (1973) *Plant physiology*. Longman, [London.

Thompson, R. & Clark, R.M. (2008) Is spring starting earlier? *Holocene*, **18**, 95-104.

Thuiller, W., Lavorel, S., Araujo, M.B., Sykes, M.T. & Prentice, I.C. (2005) Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 8245-8250.

Thuiller, W., Albert, C., Araujo, M.B., Berry, P.M., Cabeza, M., Guisan, A., Hickler, T., Midgely, G.F., Paterson, J., Schurr, F.M., Sykes, M.T. & Zimmermann, N.E. (2008) Predicting global change impacts on plant species' distributions: Future challenges. *Perspectives in Plant Ecology Evolution and Systematics*, **9**, 137-152.

Tobler, W.R. (1970) A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography*, **46**, 234-240.

Tylianakis, J.M., Didham, R.K., Bascompte, J. & Wardle, D.A. (2008) Global change and species interactions in terrestrial ecosystems. *Ecology Letters*, **11**, 1351-1363.

Visser, M.E. (2008) Keeping up with a warming world; assessing the rate of adaptation to climate change. *Proceedings of the Royal Society B-Biological Sciences*, **275**, 649-659.

Visser, M.E. & Both, C. (2005) Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society B-Biological Sciences*, **272**, 2561-2569.

Vitasse, Y., Francois, C., Delpierre, N., Dufrene, E., Kremer, A., Chuine, I. & Delzon, S. (2011) Assessing the effects of climate change on the phenology of European temperate trees. *Agricultural and Forest Meteorology*, **151**, 969-980.

Walther, G.R. (2004) Plants in a warmer world. *Perspectives in Plant Ecology Evolution and Systematics*, **6**, 169-185.

Walther, G.R. (2010) Community and ecosystem responses to recent climate change. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365**, 2019-2024.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O. & Bairlein, F. (2002) Ecological responses to recent climate change. *Nature*, **416**, 389-395.

White, M.A. & Nemani, R.R. (2006) Real-time monitoring and short-term forecasting of land surface phenology. *Remote Sensing of Environment*, **104**, 43-49.

White, M.A., Nemani, R.R., Thornton, P.E. & Running, S.W. (2002) Satellite evidence of phenological differences between urbanized and rural areas of the eastern United States deciduous broadleaf forest. *Ecosystems*, **5**, 260-273.

White, M.A., de Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G., Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X.M., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T. & Lauenroth, W.K. (2009) Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology*, **15**, 2335-2359.

Witze, A. (2008) Climate change: Losing greenland. *Nature*, **452**, 798-802.

Wolfe, D.W., Schwartz, M.D., Lakso, A.N., Otsuki, Y., Pool, R.M. & Shaulis, N.J. (2005) Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Biometeorology*, **49**, 303-309.

Wood, R. (2008) Climate change - Natural ups and downs. *Nature*, **453**, 43-+.

Xu, H., Yang, X., Huang, Q., Fang, W. & Shi, P. (2008) Study of impact of urbanization on phenology using multisource satellite data. *Dig Int Geosci Remote Sens Symp (IGARSS) International Geoscience and Remote Sensing Symposium (IGARSS)*, **3**, III804-III807.

Xu, L. & Chen, X.Q. (2012) Spatial modeling of the Ulmus pumila growing season in China's temperate zone. *Science China-Earth Sciences*, **55**, 656-664.

Xu, L. & Chen, X.Q. (2013) Regional unified model-based leaf unfolding prediction from 1960 to 2009 across northern China. *Global Change Biology*, **19**, 1275-1284.

Xu, X.R. (2005) *Physics of remote sensing*. Peking University Press, Beijing.

Zalamea, M. & Gonzalez, G. (2008) Leaffall phenology in a subtropical wet forest in Puerto Rico: From species to community patterns. *Biotropica*, **40**, 295-304.

Zhang, P., Anderson, B. & Barlow, M. (2004a) Climate-related vegetation characteristics derived from Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index and normalized difference vegetation index. *Journal of Geophysical Research-Atmospheres*, **109**, -.

Zhang, X.Y., Friedl, M.A., Schaaf, C.B. & Strahler, A.H. (2004b) Climate controls on vegetation phenological patterns in northern mid- and high latitudes inferred from MODIS data. *Global Change Biology*, **10**, 1133-1145.

Zhang, X.Y., Friedl, M.A., Schaaf, C.B., Strahler, A.H. & Schneider, A. (2004c) The footprint of urban climates on vegetation phenology. *Geophysical Research Letters*, **31**, -.

Zhang, X.Y., Friedl, M.A., Schaaf, C.B., Strahler, A.H., Hodges, J.C.F., Gao, F., Reed, B.C. & Huete, A. (2003) Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment*, **84**, 471-475.

Zhao, M.S. & Running, S.W. (2010) Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009. *Science*, **329**, 940-943.

Zhao, T.T. & Schwartz, M.D. (2003) Examining the onset of spring in Wisconsin. *Climate Research*, **24**, 59-70.

Zhou, L.M., Dickinson, R.E., Tian, Y.H., Fang, J.Y., Li, Q.X., Kaufmann, R.K., Tucker, C.J. & Myneni, R.B. (2004) Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences of the United States of America*, **101**, 9540-9544.

Zhu, K. & Wan, M. (1973) *Wu hou xue*. Ke xue chu ban she : Xin hua shu dian Beijing fa xing suo fa xing, Beijing.

Appendix

Appendix 1: The list for observed trees in Downer Woods

Site #	Observed Tree #	Observed Species	Comments
1	1	White Ash	
1	2	Hophornbeam	
1	3	Basswood	
1	4	Boxelder	
3	1	White Oak	
3	2	Basswood	
3	3	Basswood	
3	4	Boxelder	
5	1	White Ash	
5	2	Basswood	
5	3	White Ash	
5	4	White Ash	
7	1	White Oak	
7	2	Basswood	
7	3	White Ash	
7	4	Basswood	
9	1	Basswood	
9	2	White Ash	
9	3	Basswood	
9	4	White Ash	
11	1	Basswood	HOBO 774E
11	2	Basswood	
11	3	White Ash	
11	4	Red Oak	
13	1	Hawthorn	
13	2	White Ash	
13	3	Basswood	
13	4	White Ash	
15	1	White Ash	
15	2	White Ash	
15	3	Basswood	
15	4	Basswood	
17	1	White Ash	
17	2	White Ash	
17	3	White Ash	
17	4	Basswood	

19	1	White Oak	
19	2	Basswood	
19	3	Basswood	
19	4	White Ash	
21	1	Basswood	
21	2	Basswood	
21	3	White Ash	
21	4	Basswood	
23	1	White Oak	HOBO 773E
23	2	Red Oak	
23	3	Basswood	
23	4	Basswood	
25	1	Basswood	
25	2	Basswood	
25	3	White Oak	
25	4	White Oak	
27	1	White Ash	
27	2	Boxelder	
27	3	White Ash	
27	4	Boxelder	
29	1	White Ash	
29	2	Basswood	
29	3	Basswood	
29	4	White Ash	
31	1	Basswood	
31	2	Basswood	
31	3	White Ash	
31	4	White Ash	
33	1	Red Oak	
33	2	White Ash	
33	3	Basswood	
33	4	White Ash	
35	1	Basswood	HOBO 701
35	2	White Ash	
35	3	White Ash	
35	4	Basswood	
38	1	White Ash	
38	2	Red Oak	
38	3	White Ash	
38	4	White Ash	
40	1	White Ash	

40	2	White Ash	
40	3	White Ash	
40	4	White Ash	
42	1	Basswood	
42	2	White Ash	
42	3	White Ash	
42	4	Basswood	
43	1	White Oak	
43	2	Basswood	
43	3	White Ash	
43	4	Hawthorn	
45	1	Basswood	HOBO 700
45	2	White Ash	
45	3	Basswood	
45	4	Basswood	
47	1	Basswood	
47	2	White Ash	
47	3	Basswood	
47	4	White Ash	
49	1	White Ash	
49	2	White Ash	
49	3	Boxelder	
49	4	White Ash	
51	1	Basswood	
51	2	Basswood	
51	3	Basswood	
51	4	White Ash	
56	1	White Ash	
56	2	Basswood	
56	3	White Oak	
56	4	Basswood	

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Woods and provided me with a working knowledge of the vegetation and ecosystem of the woods.

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Curriculum Vitae

EDUCATION

Ph.D. in Geography, University of Wisconsin-Milwaukee, 2013
Dissertation: Examining Spring and Autumn Phenology in a Temperate Deciduous Urban Woodlot
Advisor: Professor Mark D. Schwartz

M.S. in Geography, Peking University, P. R. China, 2005
Thesis: Spatial and Temporal Variation of Phenological Seasons in Deciduous Broad-leaved Forest Region of the Warm Temperate Zone in China
Advisor: Professor Xiaoqiu Chen

B.S. in Geography, Lanzhou University, P. R. China, 2001

RESEARCH INTERESTS

Ecosystem modeling, climate change, and human impacts on the environment
Ecological applications of remote sensing and GIS
Spring and autumn vegetation phenology, and remote sensing phenology
Urban ecology and urban phenology

PROFESSIONAL EXPERIENCE

GIS ASSISTANT

American Geographical Society Library, University of Wisconsin-Milwaukee 09/2012- current

- Processed digital data requests, including GIS data, aerial photos and remote sensing data, and census data

PROJECT ASSISTANT

Department of Geography, University of Wisconsin-Milwaukee 08/2007-05/2012

- Conducted intensive phenological monitoring in a temperate deciduous urban woodlot
- Validated Spring Index for a total of 646 meteorological sites across the contiguous United States
- Collected climatic and phenological data
- Served for the USA National Phenological Network
- Worked at the American Geographical Society Library (01/2011-05/2011, 09/2011-12/2011)
- Served as the Public Relations assistant in the Department of Geography (09/2010-12/2010)
- Edited the 2011 and 2012 Newsletters of the Climate Specialty Group in the Association of American Geographers, and the 2011 and 2012 Wisconsin Phenological Society Newsletters

RESEARCH ASSISTANT

College of Environmental Sciences, Peking University 02/2003-07/2006

- Analyzed the phenological seasons and growing seasons in deciduous broad-leaved forest region of the warm temperate zone in China
- Assisted in analyzing the growing season and climatic driving forces in temperate Eastern China (National Natural Science Foundation of China)
- Participated in the field study on phenological growing season and net primary production (NPP) of Nei Mongol Steppe in China (National Natural Science Foundation of China)
- Accomplished one section of The Ecological Planning of Nan'ao Town, Shenzhen, Guangdong Province and one section of The Ecological Planning of Bao'an District, Shenzhen, Guangdong Province

PEER-REVIEWED PUBLICATIONS

Chen XQ, **Yu R** (2007). Spatial and Temporal Variations of the Vegetation Growing Season in Warm-temperate Eastern China during 1982 to 1999. *Acta Geographica Sinica (in Chinese)*, 62: 41-51.
Chen XQ, Hu B, **Yu R** (2007). Spatial Extrapolation of the Vegetation Growing Season in Temperate Eastern China. *Acta Ecologica Sinica (in Chinese)*, 27: 0065-0074.
Chen XQ, Li HM, Hu B, **Yu R** (2007). Boden- und Satellitengestuetzte Erkennung der Phaenologischen Vegetationsperiode in der Gemaessigten Klimaregion Ostchinas. *Promet (in German)*, 33(1/2): 46-51.
Chen XQ, Hu B, **Yu R** (2005). Spatial and Temporal Variation of Phenological Growing Season and Climate Change Impacts in Temperate Eastern China. *Global Change Biology*, 11: 1118-1130.

Yu R, Schwartz MD (in preparation). Tracking Spring and Autumn Phenological Responses to Urban Microclimate Variations.

COMPUTER SKILLS

Proficient: ArcGIS, ERDAS IMAGINE, MATLAB, ENVI & IDL
Familiar: SPSS, Photoshop, SAS (Certified Base Programmer for SAS 9), IDRISI
Basic: R, Python, C++, CorelDRAW

FIELD WORK EXPERIENCE

- Spring and autumn phenological observations (4 days/week) (09/2007-05/2012)
- Deployment of temperature HOBOs and Light Sensors (09/2007-05/2012)
- Conducted the general survey and the measurement of photosynthetic rates in Nei Mongol Steppe in China (06/2005-07/2005)
- Conducted the general survey and the interview for The Ecological Planning of Nan'ao Town and Bao'an District (11/2003-12/2003)

REMOTE SENSING DATA WORK EXPERIENCE

MODIS NDVI and EVI, AVHRR NDVI, Landsat TM/ETM, SPOT

WORKSHOPS

2010 3rd USA National Phenology Network Annual Research Coordination Network Meeting (invited participant)
2008 2nd USA National Phenology Network Annual Research Coordination Network Meeting (invited participant)
2007 1st USA National Phenology Network Annual Research Coordination Network Meeting (invited participant)

CONFERENCE PRESENTATIONS

2013 **Yu R** and Schwartz MD. "Examining spring and autumn phenological in a temperate deciduous urban woodlot". 109th Annual Meeting of Association of American Geographers, Los Angeles.
2012 **Yu R** and Schwartz MD. "Spring and autumn phenological study in an urban woodlot – Part 2". 108th Annual Meeting of Association of American Geographers, New York.
2011 **Yu R** and Schwartz MD. "Tracking Spring and Autumn Phenological Responses to Microclimate Variations in an Urban Setting". 107th Annual Meeting of Association of American Geographers, Seattle, WA.

2008 **Yu R** and Schwartz MD. "Intensive Phenological Monitoring in an Urban Woodlot". 104th Annual Meeting of Association of American Geographers, Boston, MA.
2008 **Yu R** and Schwartz MD. "A Preliminary Phenology Study in an Urban Woodlot" (poster). 93rd Ecological Society of America Annual Meeting, Milwaukee, WI.

FELLOWSHIP, AWARDS, AND HONORS

2013 **Mary Jo Read Travel Scholarship**, Dept. of Geography, University of Wisconsin – Milwaukee
2012 **Mary Jo Read Travel Scholarship**, Dept. of Geography, University of Wisconsin – Milwaukee
2011 **Mary Jo Read Travel Scholarship**, Dept. of Geography, University of Wisconsin – Milwaukee
2008 **Mary Jo Read Travel Scholarship**, Dept. of Geography, University of Wisconsin – Milwaukee
2006-2007 **Mary Jo Read Fellowship**, Dept. of Geography, University of Wisconsin – Milwaukee
1998-2000 **University Excellence Scholarship**, Lanzhou University, P. R. China
1997-1998 **The Freshman Scholarship**, Lanzhou University, P. R. China

PROFESSIONAL SOCIETIES

2008-present **Member**, Association of American Geographers
2008-present **Member**, USA National Phenology Network
2009-present **Member**, International Society of Biometeorology
2008 **Member**, Ecological Society of America