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# Climate effects on the flight period of Lycaenid butterflies in Massachusetts

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ABSTRACT

The effect of climate change on the phenology of plants and birds of eastern North America has been well studied in recent years, but insects have received less attention. In this study we investigated whether the response to climate warming of 10 short-lived butterfly species from the Lycaenidae family in Massachusetts is similar to responses seen in other taxonomic groups. We also determined the relative value of museum and citizen science data in ecological and conservation research, and how best to analyze these data. We obtained over 5000 records of butterflies in flight using museum collections (1893–1985) and citizen science data (1986–2009). We analyzed the data using linear regression models with sighting date as the response variable and temperature, precipitation, geographic location, and year as predictors. Temperature in the months during and prior to flight explained more variation in sighting date than the other predictors, with the average advance of flight date being 3.6 days/°C. Statistical tests using the first 20% of observations of flight in a year explained much more variation than tests using all observations. The response of these butterfly species to temperature is similar to plant flowering and bee flight times and is significantly greater than bird arrival times, suggesting the possibility of trophic mismatches. Citizen science data were more abundant and useful than museum data for studying climate change effects on butterflies. Conservation biologists and ecologists will need to develop innovative statistical techniques to deal with the sampling issues associated with citizen science data.

## 1. Introduction

Shifts in range, abundance, and phenology resulting from climate change have recently been documented at multiple trophic levels in ecosystems around the world (Ahas et al., 2002; Miller-Rushing et al., 2008a; Thackeray et al., 2010). The centuries-old practice of monitoring phenology has realized a renewed place in the tool kit of scientists as a way to measure these changes (Menzel, 2002; Pau et al., 2011). Long-term datasets maintained by individuals, institutions, and governments have been instrumental in allowing researchers to quantify such changes, which have important conservation implications. Evidence is mounting that those species that are able to track temperature changes by shifting their phenology will fare better than those species that are not as flexible (Cleland et al., 2012; Willis et al., 2010).

Despite the prominent role that insects play in ecological food webs, the scarcity of long term datasets on insect phenology, and reduced awareness of those that do exist, compared to those available for birds and plants has led to their being largely underrepresented in phenological research. This missing link has limited the understanding of the community level effects caused by climate change. Here we examine the effect of climate change on butterfly phenology in Massachusetts and compare it to responses observed in plants, birds, and bees. For this study we selected 10 species of butterflies from the Lycaenidae family, including the rare frosted elfin (*Callophrys irus*) (Albanese et al., 2007), and examined the effect of temperature and other factors on the flight dates of these species in Massachusetts.

Butterflies are an ideal group of organisms for investigating insect phenology because they are relatively conspicuous and are of more interest to humans than most other insects because of their size and color, which leads to observations and collections (Sparks and Yates, 1997). Additionally, research has determined that butterflies and other insects respond more quickly to detrimental environmental changes than plants or birds, and there is concern over declines in butterfly populations worldwide (Ellwood et al.,

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2012; Thomas et al., 2004). The United Kingdom supports a well-organized butterfly monitoring scheme that has been in operation since 1976 recording the abundance and phenology of butterflies in the British Isles (Roy and Sparks, 2000). A similar network is in place in Spain and Japan as well (Ellwood et al., 2012; Stefanescu et al., 2003). There are no networks operating with that sort of precision for insect monitoring in the United States, but because people have long enjoyed studying and collecting butterflies, many butterfly specimens dating back to the 19th century are preserved in museums throughout the country. Museum specimens provide important insight into the past and have been useful in studies focusing on other taxonomic groups in determining changes in phenology over time (Bartomeus et al., 2011; Johnson et al., 2011; Primack and Miller-Rushing, 2009).

As collection of natural specimens has fallen out of favor over the past few decades, citizen science groups have picked up where museum collectors have left off (Breed et al., 2012; Scharlemann, 2001). Although some citizen science projects, such as the Christmas Bird Count run by the Audubon Society, go back more than a century, interest in citizen science has exploded over the past decade or so (Silvertown, 2009). Instead of taking physical specimens, many people now "collect" by taking pictures of insects in the field, a practice that has become more common with the advent of digital photography. As with birding, a large population of enthusiastic naturalists who is well educated about butterflies and spends a lot of time observing butterflies in the wild. Citizen science organizations of various sizes and level of professionalism have been founded by butterfly enthusiasts since the 1950s. The North American Butterfly Association (NABA) has chapters across the country and organizes events such as the annual Fourth of July Butterfly Counts. The Massachusetts Butterfly Club (MBC), a chapter of NABA but largely independent club, is an active group of butterfly enthusiasts who maintain records of the butterflies that club members see throughout the growing season.

To determine how butterfly flight times respond to variation in temperature and precipitation, we combined historic records from museums and contemporary observation records from the MBC. We hypothesized that butterflies would be responding to climatic variation in Massachusetts and that spring emerging species would show a stronger response than summer emergents, comparable to what is seen in plants (Miller-Rushing and Primack, 2008). To test this hypothesis we selected members of the Lycaenidae family from two genera, one of spring emergers (*Callophrys*, elfins) and one of summer emergers (*Satyrium*, hairstreaks). Species were also selected based on their recognizability by experienced observers. Their relatively short flight period (less than 2 months) and their univoltine habit make them ideal model species for ecological and conservation research investigating whether their time of emergence is affected by temperature or precipitation. An important secondary goal of this research was to determine the relative value of museum specimens and citizen science observations in phenological research, and any special sampling issues involved in analyzing these types of data.

## 2. Materials and methods

We investigated the effect of climate on the flight times of 10 butterfly species from the family Lycaenidae, five species in the genus *Callophrys* (elfins) and five in the genus *Satyrium* (hairstreaks; Table 1). Elfins, which overwinter as pupae, fly earlier in the spring while hairstreaks overwinter as eggs and emerge as adults to fly in the summer. Most of our study species are common, although the frosted elfin, which occupies sandplain habitats, is listed as being of special concern in Massachusetts (Albanese et al., 2007).

The sighting and collection records included in the study cover the period 1895–2009. Records were included only if they were collected in Massachusetts and if the labels specified both the location of collection at the town or county level and the collection date. Historic data (pre-1986) were obtained by visiting museum collections (see Acknowledgements for list of sources) and transcribing data from specimen labels, through online databases or emailed information of label data from museum collections and from records kept by individuals in field notebooks. Contemporary data (1986–2009) were obtained from the records of the Massachusetts Butterfly Atlas (http://www.massaudubon.org/butterfly-atlas/) and the Massachusetts Butterfly Club (http://www.massbutterflies.org). Records from the Massachusetts Butterfly Atlas are based on either voucher specimens or photographs, while MBC records are based on photographs or reported sightings from experienced club members. Throughout the rest of the paper data from the Massachusetts Butterfly Atlas and the MBC will be grouped together and all referred to as MBC data. Duplicate sightings or specimens reported or collected on the same day at the same location were removed from the database. In total we obtained 5096 sighting records, 86% of which were from the MBC.

The mean sighting date of elfins was May 11 (DOY 131), while the range of sighting dates of all elfins for all years was April 3–July 4. The mean sighting date of hairstreaks was July 14 (DOY 195), with a range of June 6–September 11 (Table 1).

Temperature and precipitation records were obtained from the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov). In order to get statewide averages of precipitation and temperature we combined records from three weather stations spaced across the state and located in Amherst, Plymouth, and Milton, Massachusetts. There is considerable variation in climate within Massachusetts related to elevation and proximity to the coast. To account for the geographical variation and resulting climatic differences in Massachusetts we used the six hardiness zones as designated by the United States Department of Agriculture (USDA; http://planthardiness.ars.usda.gov/PHZMWeb/). Each sighting or collection record was assigned to its corresponding hardiness zone. The hardiness zones are based on the average annual minimum temperature that an area experiences. For analysis the hardiness zones were numbered such that code numbers increased with increasing minimum temperatures. For example, hardiness zone 7a (minimum −15 to −17 °C), which was assigned a value of 7.0, has milder winters than zone 4b (minimum −32 to −29 °C), which was assigned the value 4.5.

For each species we used a linear regression model incorporating four continuous predictor variables with the date of sighting as the dependent variable. We included all of the records collected for each species in our analysis rather than using only the mean or median. It is possible that there may be a bias toward more collections and sightings at the beginning of a particular season, as people are eager to get their first collections and sightings early in the flight season. There may also be an opposing bias to collect individuals throughout the season, especially the last flying individuals late in the season. To account for these potential biases and to provide a more precise index of first flight times in the season, we repeated the analysis for each species using only the first 20% of the sightings recorded. Using a percentage of the records rather than a specific number of records for each species helps to avoid bias of different samples sizes. In these first sighting models we used data only from years in which there were at least five observations. Because the number of observations for pre-MBC years was generally small, we used only MBC data in our first 20% sighting models. We deliberately selected species with short flying times as adults to minimize the effects of sampling bias and to increase the chances of detecting the effects of climate change.

**Table 1**
The number of records found for each study species as well as the mean and range of sighting dates of the individual species in numbered day of year. Also listed is the percentage of records for each species from the MBC years (1986–2009).

| Scientific name | Common name | *N* | Mean sighting date | Range of sighting dates | % records from 1986 to 2009 |
|---|---|---|---|---|---|
| *Callophrys augustinus* | Brown elfin | 599 | 126 | 93–171 | 87 |
| *Callophrys henrici* | Henry's elfin | 271 | 129 | 96–185 | 78 |
| *Callophrys irus* | Frosted elfin | 313 | 140 | 102–180 | 83 |
| *Callophrys niphon* | Eastern pine elfin | 1053 | 134 | 88–183 | 88 |
| *Callophrys polios* | Hoary elfin | 146 | 128 | 103–163 | 79 |
| *Satyrium acadicum* | Acadian hairstreak | 211 | 194 | 172–227 | 93 |
| *Satyrium calanus* | Banded hairstreak | 875 | 192 | 163–233 | 93 |
| *Satyrium edwardsii* | Edward's hairstreak | 374 | 193 | 142–254 | 86 |
| *Satyrium liparops* | Striped hairstreak | 687 | 197 | 157–243 | 88 |
| *Satyrium titus* | Coral hairstreak | 567 | 199 | 177–236 | 84 |

The independent variables included in the analysis were year, mean air temperature of the 2 months before emergence (March and April for elfins and May and June for hairstreaks), precipitation (mean monthly totals for March and April were used for all species), and hardiness zone code. This model is subsequently referred to as the ALL model. We also ran the models for each species using only contemporary data (data collected after 1985); this model is referred to as the MBC model, as it uses data collected almost entirely by the Massachusetts Butterfly Club from the years 1986–2009. Finally, we have the First Twenty Percent (FTP) model in which we ran the same predictor variables as other models, but used only the earliest 20% of sightings from each of the MBC years. We ran the FTP model on all species with the exception of the hoary elfin for which there were not enough data (<20 observations).

We also combined data from all elfins and all hairstreaks, as the species in each group share common life history characteristics and flight times, and used simple regressions to determine changes over time and response to temperature for each group. We ran these regressions three times for each group, using the ALL data, the MBC data, and the FTP data.

We used these analyses because they give results in terms of changes with temperature, which are directly comparable to analyses of plants and other animals that have been studied in this region. There are certain advantages to other types of analyses, such as degree-day models, but the results are more difficult to compare with prior studies. In this paper, we compared the responses of these butterfly phenologies to temperature and precipitation to the responses of Massachusetts and Northeast bee sighting dates, plant flowering dates, and bird arrival dates to temperature using an ANOVA with a Tukey's Honestly Significant Difference (HSD) Test. Specifically, we used the slopes of the response of individual species to temperature as the response variable since this information was available for each of these groups (Bartomeus et al., 2011; Miller-Rushing et al., 2008a; Miller-Rushing and Primack, 2008).

## 3. Results

We obtained a combined total of 5096 individual records for all 10 species (Table 1). The species with the most records (1053) was the eastern pine elfin (*Callophrys niphon*) and that with the fewest (146) was the hoary elfin (*Callophrys polios*). Although we have data back to the late 19th century (1895), over 85% of the records were from after 1985.

### 3.1. Year

As a factor in the ALL models in which species were analyzed separately, year was a significant predictor of sighting date for only two species, frosted elfin ($p = 0.030$), which is flying later over time (0.05 ± 0.03SE days/year), and coral hairstreak (*Satyrium titus*; $p < 0.001$), which is flying earlier over time (0.1 ± 0.02SE days/year). In the MBC model (years since 1986), year was a significant predictor for five of the 10 species, all of which are flying significantly earlier in 2009 than in 1986 (Tables A1 and A2). In the FTP model year was significant predictor of sighting date only for the eastern pine and brown elfins, and the coral and Edward's hairstreaks (Table 2).

Using a simple regression to determine changes over time in all elfin species combined, we found no significant changes with the ALL model, but in the MBC years there was a significant advancement of 6.1 ± 0.05SE days over the study period ($R^2 = 0.013$; $F = 27.64$; $p < 0.001$). With the FTP model for all of the elfins there was a significant advancement in sighting dates over time and an average advancement of 7.6 ± 0.06SE days over the same 24 year study period ($R^2 = 0.0537$; $F = 22.2$; $p < 0.001$; Fig.1). The FTP model explained four times more of the variation than using all of the MBC data. Hairstreaks were sighted significantly earlier over time for both time periods, 7.2 ± 0.01SE days in the ALL model ($R^2 = 0.011$; $F = 29.9$; $p < 0.001$) and 2.8 ± 0.03SE days earlier during the MBC years ($R^2 = 0.005$; $F = 11.77$; $p = 0.001$). The first sightings of all hairstreaks together (FTP model) have advanced significantly over time, advancing an average of 3.2 ± 0.04SE days over the study period ($R^2 = 0.023$; $F = 12.33$; $p = 0.0005$); again the FTP model explained more of the variation than using all of the MBC data.

### 3.2. Temperature

Mean March and April temperature in Massachusetts increased by 1.4 °C between 1893 and 2009, a significant increase ($p = 0.001$). For the same time period mean May and June temperature increased by 0.97 °C ($p = 0.002$). Between 1986 and 2009 there has been an increase in mean March and April temperature of 0.46 °C and in mean May and June temperature of 0.22 °C, although neither of these increases are significant ($p = 0.549$ and $p = 0.707$ respectively).

In the ALL model, warmer mean temperatures for the 2 months before the flying period were significantly correlated to earlier sighting dates for all species with the exception of the frosted elfin, which did not show a significant relationship (Table A1). In this model the striped hairstreak (*Satyrium liparops*) showed the strongest response to temperature, with an advancement of 3.6 ± 0.62SE days/°C. The mean response to temperature of the five elfin species was 2.0 ± 0.41SE days/°C and the mean response of the five hairstreak species was 2.7 ± 0.24SE days/°C. In the MBC model, all species except the hoary elfin were seen significantly earlier with warmer temperatures (Table A2). Using this model, Henry's elfin (*Callophrys henrici*) responded most strongly to temperature, with an advancement of 4.2 ± 1.2SE days/°C. In the FTP model all species except the Edward's hairstreak responded to temperature with significantly advanced sighting dates. Although not significant, the Edward's hairstreak did show a trend toward responding to temperature ($p = 0.058$). In this model the eastern pine elfin responded most strongly with an advancement rate of 5.6 ± 0.61SE days/°C. The

**Table 2**
Significance values for each predictor variable, as well as the slope of the temperature response, from the FTP model, using the first 20% of observations from each year 1986–2009.

| Species | Temperature | Temperature response (days/°C) | Precipitation | Hardiness zone code | Year | Overall | *N* |
|---|---|---|---|---|---|---|---|
| *Callophrys augustinus* | <0.0001* | −5.35 | 0.135 | 0.0484* | <0.0001* | <0.0001* | 104 |
| *Callophrys henrici* | 0.0033* | −3.86 | 0.992 | 0.546 | 0.186 | 0.0169* | 39 |
| *Callophrys irus* | 0.0024* | −4.43 | 0.656 | 0.265 | 0.128 | 0.0076* | 46 |
| *Callophrys niphon* | <0.0001* | −5.64 | 0.1115 | 0.0704 | <0.0001* | <0.0001* | 185 |
| *Callophrys polios* | n/a | n/a | n/a | n/a | n/a | n/a | <20 |
| *Satyrium acadicum* | 0.0353* | −3.04 | 0.496 | 0.217 | 0.67 | 0.0553 | 37 |
| *Satyrium calanus* | <0.0001* | −3.54 | 0.226 | 0.278 | 0.185 | <0.0001* | 162 |
| *Satyrium edwardsii* | 0.0576 | −1.41 | 0.838 | 0.684 | 0.0055* | 0.0118* | 65 |
| *Satyrium liparops* | <0.0001* | −3.42 | 0.366 | 0.0002 | 0.643 | <0.0001* | 117 |
| *Satyrium titus* | 0.0026* | −1.63 | 0.789 | 0.501 | 0.0119* | 0.0025* | 95 |

* Designates significance at the 0.05 level.

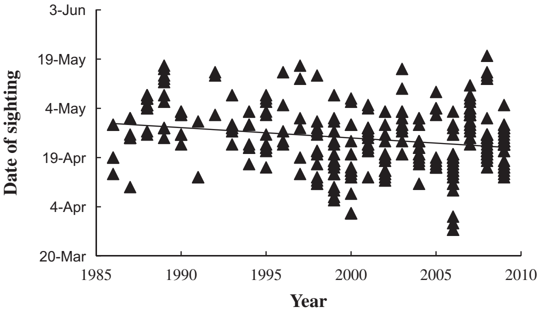

**Fig. 1.** The change in the first 20% of sighting dates (FTP model) over time for elfins for the years 1986–2009. Over this period the sighting date of elfins has advanced by 7.6 days ($R^2 = 0.0537$; $F = 22.2$; $p < 0.001$).

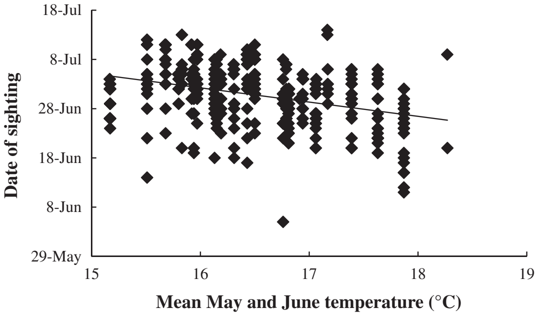

**Fig. 3.** First 20% of sighting dates for hairstreaks (FTP model) for 1986–2009 regressed against average May and June temperatures. Hairstreak sighting date advanced approximately 2.8 days for each 1 °C ($R^2 = 0.036$; $p < 0.001$).

mean advancement rate for elfin species in the FTP model was 4.8 ± 0.41SE days/°C, the mean response for hairstreak species was 2.6 ± 0.45SE days/°C and for all species combined was 3.6 ± 0.49SE days/°C (Table 2).

In a simple regression using all elfin sighting dates for ALL years, elfins responded to temperature at a rate of 1.8 ± 0.3SE days/°C ($R^2 = 0.014$; $F = 15.38$; $p = 0.0001$), while hairstreaks responded at a rate of 1.2 ± 0.1SE days/°C ($R^2 = 0.051$; $F = 146.7$; $p < 0.001$). In MBC years, the response of all elfins to the mean March and April temperature was 3.0 ± 0.50 days/°C ($R^2 = 0.028$; $F = 57.72$; $p < 0.001$) and the response of hairstreaks was 2.8 ± 0.10 days/°C ($R^2 = 0.036$; $F = 90.51$; $p < 0.001$) (Tables A1 and A2). In the FTP model the response of all elfins (except hoary) to mean March and April temperature was 5.5 ± 0.49 days/°C ($R^2 = 0.25$; $F = 123.94$; $p < 0.001$) (Fig. 2) and the response of hairstreaks to mean May and June temperature was 2.9 ± 0.34 days/°C ($R^2 = 0.13$; $F = 74.44$; $p < 0.001$) (Fig. 3). The models using just first sightings explained far more of the variation than using the MBC model; the FTP model increased the amount of variation explained by a factor of 18 for elfins and 3.6 for hairstreaks.

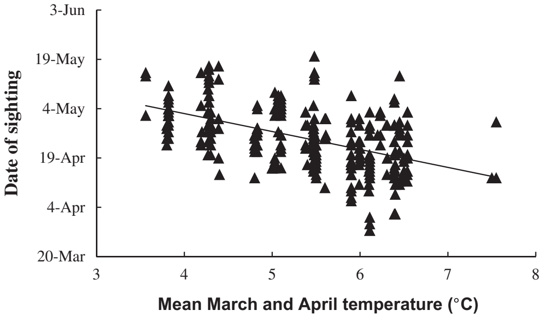

**Fig. 2.** Sighting dates for elfins for the first 20% of sightings (FTP model) in 1986–2009 regressed against mean March and April temperatures. Elfin sighting date advanced approximately 5.5 days for each 1 °C ($R^2 = 0.25$; $F = 123.94$; $p < 0.001$).

### *3.3. Precipitation*

Unlike temperature, precipitation was not significantly correlated with sighting dates in most of the study species. In the ALL model, the frosted elfin and the striped hairstreak were sighted significantly later with increased March and April precipitation ($p = 0.019$ and $p = 0.0058$ respectively), while the hoary elfin was sighted significantly earlier with increased precipitation ($p = 0.020$). In the MBC model only the striped hairstreak had a significant relationship between sighting date and precipitation, in which sighting date was delayed with increasing precipitation ($p = 0.0058$). Thus, higher spring precipitation may have accelerated the appearance of one species and delayed it in two others. In the FTP model mean March and April precipitation did not have a significant effect on the sighting dates of any of the study species (Table 2).

### *3.4. Hardiness zone*

In the ALL model 5 of 10 species showed a significant relationship between hardiness zone and sighting date. For the eastern pine elfin (*Callophrys niphon*) ($p = 0.0011$) and the brown elfin (*Callophrys augustinus*) ($p = 0.026$), this relationship was negative, with sighting date earlier in higher ranked hardiness zones (zones with higher minimum winter temperatures). Eastern pine elfins were seen an average of 2.4 ± 0.73SE days earlier for each increase in zone ranking, and the brown elfin seen 1.3 ± 0.79SE days earlier. On the other hand, for the frosted elfin and the coral and striped hairstreaks, an increase in zone ranking led to significantly later sightings. The frosted elfin had the most dramatic response to

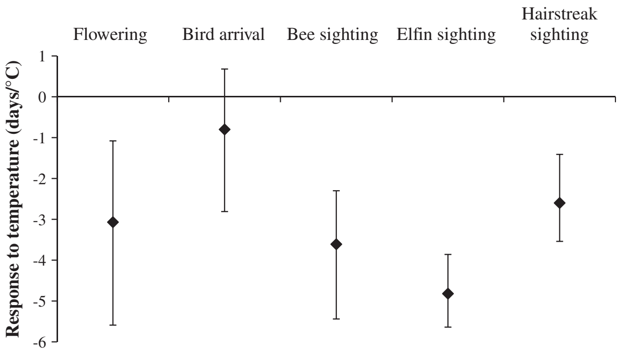

**Fig. 4.** The phenology advancement rate of several taxonomic groups in the northeastern United States. Each point represents the mean response to temperature of the species included in a particular study, while the error bars represent the minimum and maximum responses (Bartomeus et al., 2011; Miller-Rushing et al., 2008a; Miller-Rushing and Primack, 2008).

hardiness zone, with a delay in mean sighting of 6.5 ± 1.3SE days/zone ranking ($p < 0.001$). The striped hairstreak showed a delay in sighting date of 1.7 ± 1.7SE days/zone ($p < 0.001$) and the coral hairstreak 3.7 ± 0.58SE days/zone ($p = 0.034$). In the MBC model the same trends were shown, with response to zone ranking slightly stronger for each species (increases between 0.1 and 0.5 days/zone). Additionally, in this model Edward's hairstreak (*Satyrium edwardsii*) also showed a significant delay in sighting date in higher ranked zones (2.3 ± 1.2SE days/zone; $p = 0.0495$). In the FTP model hardiness zone was a significant predictor of sighting dates only in the brown elfin (1.6 ± 0.78SE days/zone) and the striped hairstreak (3.6 ± 0.94SE days/zone), both of which appeared earlier in higher ranked zones.

### 3.5. Comparisons to other taxonomic groups

The response of butterfly sighting date (using the FTP model) to temperature is not significantly different from the response of plant flowering ($p = 1.0$) or bee collection date ($p = 0.90$) to temperature. Butterfly response to temperature is significantly different from the response of bird arrival dates to temperature ($p < 0.001$). The response of bird arrival dates is also significantly different from responses of plant flowering and bee collection dates ($p < 0.001$ for both), but plant flowering and bee collection are not significantly different from one another ($p = 0.90$) (Fig. 4).

## 4. Discussion

Of our three models, the FTP model produced the most significant results. We found that this novel data analysis technique, the use of the first 20% of sightings for each year, provides a qualitatively better assessment than all observations, median observation, or single first observation. For example, in the FTP model temperature explains 25% of the variation in sighting date in elfins rather than the 2.8% explained by the MBC model. A tendency to collect and observe only early in a particular season can affect the ability to detect the effects of climate change on phenology (Miller-Rushing et al., 2008a). The FTP model is apparently better because the first flight dates are likely more sensitive to temperature than the entire range of flight dates for a season. The FTP model captures the beginning of a species flight period when observers most carefully look for and report sightings with greater awareness, minimizing collecting bias. The FTP model also excludes observations late in the season, particularly the last remaining individuals of the season, which greatly increase variation in flight times.

Temperature was the most important factor in determining sighting dates of elfins and hairstreaks in Massachusetts. The rate of advance in sighting date with warming temperatures, averaging between 1.3 and 5.6 days/°C for individual species across all three models, falls at the low half of the range of 2–10 days/°C advancement in first and peak appearance found in a study of 35 butterfly species in the United Kingdom (Roy and Sparks, 2000). As their study included a much larger and more diverse group of species it is not surprising that our range of responses to temperature is narrower than theirs. We found slightly greater advancement with higher temperatures in the spring-emergent elfins than in the summer-emergent hairstreaks, particularly at the front end of the flight period (in the FTP model).

Hairstreaks have been emerging significantly earlier over the whole study period (1895–2009), whereas elfins have been emerging significantly earlier only in the period 1986–2009. During the past 25 years, the first 20% of sighting dates of elfins, which are spring emergents, has advanced 4.4 days more than the advancement of the first sightings of the summer emerging hairstreaks. This result agrees with findings from studies in the United Kingdom and California that indicate that butterflies that emerge earlier in the year have advanced emergence dates in response to climate warming more than those emerging later in the year (Diamond et al., 2011; Forister and Shapiro, 2003). This may be partially explained by the fact that insect development is directly affected by temperature, and spring temperatures have risen more than summer temperatures in Massachusetts over this time period. Similar patterns have also been seen in eastern Massachusetts plants; those that flower in the spring have been found to be more responsive to temperature than summer flowering species (Miller-Rushing and Primack, 2008).

Half of the study species showed a significant response to geographic variation, which was represented by USDA hardiness zones. In this case the response was opposite for elfins and hairstreaks, with elfins being sighted earlier in coastal zones and hairstreaks showing the opposite trend. This may be a result of the inland zones, particularly those in Western Massachusetts, experiencing more severe winter temperatures, but warmer summers. Elfins, emerging in the spring, are more likely to be affected by the colder winter temperatures in these inland areas whereas by the time the hairstreaks are emerging these same inland areas are warmer than coastal regions.

An important, but difficult to document, conservation implication resulting from climate change is the possibility of trophic mismatches between associated species whose phenologies do not respond to warming or other climate factors at the same rate (Nakazawa and Doi, 2012). To begin to elucidate the multi-trophic level effects that climate change is having on Massachusetts' ecosystems, we can compare the results from this study with those of other studies examining bees, birds, and plants in the region (Fig. 4). The response to temperature of spring phenology seen in this study with our butterfly species is similar to the advancement rate of 3.1 days/°C reported for plant flowering in Concord, MA (Miller-Rushing and Primack, 2008) and the 3.6 days/°C reported for bees (Bartomeus et al., 2011). As in our study, Bartomeus et al. (2011) found a steeper slope for response to temperature in more recent years. Migratory birds tell a somewhat different story, as their response to temperature varies greatly among species and ranges from advancements in arrival date in Massachusetts of almost 4 days/°C to a delay of the same degree, but an average response of arriving earlier at a rate of only 1.1 days/°C (Miller-Rushing et al., 2008b). The discrepancy between birds and butterflies, plants, and bees is likely because, as migrants, these bird species are overwintering elsewhere and not experiencing the same meteorological conditions as are occurring in their summer habitat; instead it is likely that they are relying on a combination of factors, including photoperiod, as well as temperature, to time their migrations (Butler, 2003). Although this delayed response in arrival dates of migratory birds relative to plants and insects suggests the possibility of a trophic mismatch between birds and their food source is high, Jonzen et al. (2007) report that in fact, it may be advantageous for migratory birds to advance their arrival somewhat less than the advancement of the peak of their food source, as long as the distribution of food availability is wide enough.

There are many underutilized museum collections in the United States, often with specimens dating back to the 1800s. There has been increased interest in making use of these varied collections for exactly this type of research (Johnson et al., 2011; Robbirt et al., 2011; Suarez and Tsutsui, 2004). Unfortunately, museum collections are often somewhat limited, providing only several records for a given species in a given year, and specimen labels are often missing important data such as precise collection site or date. With museum data it is also usually impossible to communicate with collectors to determine what collection protocol, if any, they followed. Although there have been successful insect phenology studies performed using museum data (Bartomeus et al., 2011), in taxonomic groups where reliable citizen science data are available, this type of data can be far more powerful for scientific analysis than museum data.

In North America we lack the nation- or continent-wide highly organized monitoring scheme seen in the United Kingdom with the British Butterfly Monitoring Scheme (Sparks and Yates, 1997; Stefanescu et al., 2011). Despite this lack, we do have other valuable sources for contemporary insect phenology data. As collecting of natural specimens has fallen out of favor over the past few decades, citizen science groups, including the MBC, have picked up where museum collectors have left off (Breed et al., 2012; Scharlemann, 2001). Some citizen science projects, such as the Christmas Bird Count run by the Audubon Society, go back more than a century, and interest in citizen science has exploded over the past decade or so (Silvertown, 2009). Qualified and enthusiastic volunteers provide data that are valuable and can successfully be used in scientific research (Dickinson et al., 2012).

It is apparent from this study, and others (Breed et al., 2012; Lye et al., 2012), that citizen science data are highly valuable. By including the public in data collection, the scientific community has an exponentially increased amount of data (Bonney et al., 2009; Dickinson et al., 2012). While recognizing the potential for the use of citizen science data, it is important to recognize their limitations. Not all citizen science data are created equal, and it is important that the data be reliable and accurate, something that cannot always be validated with publicly collected data. With the Massachusetts Butterfly Club, a core group of highly involved and dedicated butterfly enthusiasts collect data. Club leaders who are familiar with local butterfly habitat and individual club members vet observations and individual observers for accuracy before the data is accepted into the MBC records. These data have been used successfully in other studies (Breed et al., 2012). These data are valuable not only for climate change research, but also as a management tool. Since many Lepidopteran species live in habitats dependent on disturbance, such as fire or mowing, understanding the phenology and range shifts, land managers can optimize management practices for protection of species of interest (Lawson et al., 2012).

In summary, Lycaenid butterflies in Massachusetts are responding to a warming climate by flying earlier in warmer years. The effect that temperature has on this group of butterflies is comparable to that of plants, bees and other species of butterflies (Bartomeus et al., 2011; Roy and Sparks, 2000) and is greater and more consistent than the response of migratory birds. Citizen science observations proved to be an effective way to investigate the potential impacts of climate change on butterflies in this study and can be used to inform conservation policies on these species and associated habitat. Museum data were also helpful, but less abundant and useful than our citizen science dataset.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.12.024.

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