



Impacts of Climate Change on Commonly Encountered Forest Lepidoptera of Pennsylvania

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INTRODUCTION

Given highly divergent physiology and population dynamics, terrestrial invertebrates may exhibit responses to climate change that vary greatly from those predicted for many vertebrates. Additionally, variation in abiotic factors associated with climate change (temperature, moisture, ambient CO₂ levels) may inconsistently impact taxonomic groups of terrestrial invertebrates due to differences in physiological mechanisms to handle temperature and moisture fluctuations (Bradshaw and Holzapfel 2010, Bale et al. 2002). This report focuses on Lepidoptera (butterflies and moths) that feed on temperate forest trees, holometabolous insects that experience drastic anatomical and physiological change during metamorphosis. Because these insects have two physiologically distinct life stages, an assessment of climate change impacts must consider potential benefits or risks to both life stages. The larval stage is concerned primarily with growth--the acquisition of resources that will be used to produce gametes, mate, and migrate during the adult stage. The species considered here are phytophagous in the larval stage, primarily consuming leaf tissue of deciduous trees and shrubs. In temperate forests Lepidoptera also enter dormancy during the winter months, with species overwintering at different stages of development. Adults are either non-feeding or nectivorous, relying on herbaceous plants or shrubs as a food source.

The direct effect of higher temperature on insects largely leads to accelerated development and mobility, resulting in increased fecundity and decreased development time. Decreased exposure to severe cold during the winter months may also reduce insect mortality (Bale et al. 2002). However, risks posed by climate change are also attributable to the indirect impacts of temperature on habitat variables, predators, and pathogens. Temperature directly impacts diapause initiation and cessation, a direct impact whose outcome depends on indirect impacts of temperature on host plant growth and development; if temperature impacts diapause timing at a different rate than host plant development, hosts may not be available for feeding or oviposition when needed. An understanding of the physiological and habitat needs of all life stages is necessary to predict how a changing climate impacts the Lepidopteran composition of our forests in Pennsylvania.

While many insect species assessed in this report are not ranked for conservation concern, understanding potential changes in abundance and distribution of these insects due to climate change will improve our understanding of potential secondary consequences of climate change on rare, threatened, or endangered vertebrate species. Furthermore, a number of temperate forest Lepidoptera species exhibit outbreak cycles of population growth, acting inconsistently as localized or regional defoliators and fruit crop pests. And finally, Lepidopterists and naturalists are reporting tangible declines in moth species, especially members of the Saturniidae and Sphingidae families, in northeastern

forests over the past 50 years. While it is likely that these declines are the result of habitat loss or modification, pressure from native and introduced enemies, and climate change, a clear picture of the relative impacts of these factors on species of interest is lacking (Wagner 2012). Given this, there are three primary objectives to assessing the vulnerability of temperate forest Lepidoptera species to climate change, the first being to assess sensitivity from the perspective of insect conservation, the second to consider species that may exhibit decreased vulnerability due to climate change and therefore act as pest species, and third, to assess how trends in climate change vulnerability in temperate forest Lepidoptera species may impact vertebrate species relying on these insects as their primary food source.

Predicted Climate Change

Pennsylvania's climate is predicted to become warmer and, despite predicted increases in annual precipitation, show declining available moisture by midcentury. Extreme temperatures, a metric of drought, are also projected to increase during the summer months. Growing season could be lengthened by as many as 5 weeks in areas of the state, and frost days reduced by as many as 6 weeks. While winter precipitation is projected to increase, precipitation in the summer months is projected to change marginally, if at all. Models predict an increase in storm variability, with temperature islands and small-scale convective forces contributing to more localized precipitation events (Union of Concerned Scientists 2008). This could contribute to a patchwork of suitable areas for certain insects across the landscape, potentially acting to fragment contiguous habitat.

Phenology

Though both budbreak in temperate trees and diapause termination in Lepidoptera are advancing, rates of advancement are not necessarily consistent across trophic levels (Both et al. 2009). Caterpillars that emerge too early risk starving, while those that emerge too long after bud break may face lower quality food, as older leaves generally increase in toughness and secondary compounds (Feeny 1970, Hunter and Elkinson 2000). For many temperate forest trees, budburst date varies from year to year. Lepidoptera must respond to environmental cues that are triggering budburst in order to maintain synchrony (Visser and Holleman 2001). The earliest spring-feeding caterpillars are predicted to be most affected by phenological mis-timing because of their reliance on young leaves (Hunter and Elkinson 2000, Forkner et al. 2008).

Variation in the effects of phenological mistiming make it difficult to gain a generalized understanding of the impact on Lepidoptera survival or population size. Decreases in leaf quality are generally thought to increase the amount of time spent feeding, but the consequence of this increase in feeding time varies. In the whitemarked

tussock moth (*Orgyia leucostigma*) this increase in feeding time leads to an increase in pupal weight and corresponding fecundity (Kopper et. al. 2002). In gypsy moths (*Lymantria dispar*), a caterpillar from the same family as the whitemarked tussock, leaf age negatively affects fecundity (Hunter and Elkinton 2000). However, in this same species later-feeding populations showed greater survival due to behavioral responses to decreased plant quality. Despite observed negative impacts of climate change on specific aspects of temperate forest Lepidoptera physiology or population growth, it appears that many species have adapted means of handling variation in environmental conditions to maximize reproduction or survival.

Host Plant Distributions & Climate Change

Climate change can impact the larval stage of phytophagous insects directly through changes in temperature and moisture availability or indirectly through impacts on distributions and physiology of host plant species (Bale, et al. 2002, Schroeder 1986). The climatic release hypothesis, first articulated in the 1950's (Greenbank 1956), suggested that variation in climate may be the driver in forest defoliator outbreaks, with periods of favorable conditions “releasing” a species from climatic conditions that generally limited reproduction, growth, or survival. Tests of this theory are useful in assessing how predicted changes in temperature and moisture due to climate change may impact temperate forest insects.

Habitat specialists, specifically insects that rely on one or a limited number of host plants for growth and development, may be vulnerable to climate changes that impact the distribution or health of those host plants. The dominant host plants of Lepidoptera species analyzed in this report are expected to shift northward during the next century (Table 1). Additionally, all host plants relevant here are expected to decrease in importance value (a measure of dominance in density, frequency, and coverage) over the same period (McKenney et al. 2007, Prasad et al. 2007). On the scale of fifty years these shifts may have incremental impacts on host plant availability throughout Pennsylvania and attempts are made here to gauge the impact of such changes on Lepidoptera populations.

Some of the indirect impacts of climate change on phytophagous insects are site or system specific and therefore very difficult to predict without direct evidence from the area or ecosystem being assessed. For example, increased ambient levels of CO₂ may impact plant sugar content, toughness, or secondary metabolites, which certainly impact herbivory rates. We would expect an increase in secondary metabolites might decrease herbivory on a particular species, while a increase in C-N ratio might increase herbivory in response to the decrease in food quality (Bradshaw and Holzapfel 2010). Polyphagous insects may modify their host preferences based on these changes in C-N ratio. Plant species vary in their response to higher ambient levels of CO₂, so assuming a generalized response by a set of plants and insect herbivores is not possible. Instead, each plant-

insect system might have a predictable response to elevated levels of CO₂ which should be experimentally investigated in to more accurately predict response to climate change (Hunter 2001). Information on secondary impacts of elevated CO₂ on insect herbivory, when available, are incorporated into the vulnerability index through assessment of diet versatility and reliance on other species to generate habitat.

Pathogens and Disease

Our understanding of insect pathogens and disease hails primarily from research on control mechanisms. Four types of entomopathogens: bacteria, viruses, fungi, and nematodes are used as biological control agents in limiting agricultural or ornamental pest insects. This body of research indicates that environmental conditions of temperature and moisture play an integral role in the pathogenicity and mortality of these diseases (Lacey et al. 2001). Some non-target Lepidoptera may be negatively impacted by pathogens used for pest control, whereas others species may benefit (Rastall 1999, Rastall et al. 2003). Given the variation in the biology of these pathogens, it is unlikely increases in temperature and reductions in available moisture will consistently impact their transmission or virulence. Instead, physiological stress induced via climate changes may make temperate forest insects more susceptible to these pathogens (Donegan and Lighthart 1989).

Tritrophic Interactions

Phytophagous insects, caterpillars in particular, form a large component of the diet of breeding birds in temperate deciduous forests (Goodbred and Holmes 1996, Perrins 1991, Royama 1970). While caterpillar density can differ dramatically among host plant species (see e.g., Futuyma and Gould 1979, Wheatall et al. 2013), birds have a measured impact on caterpillar biomass and reductions in plant damage during the breeding season (Holmes et al. 1979). Reproduction in neotropical migrants is primarily food-limited (Nagy and Holmes 2005), which may reflect availability of prey or birds' ability to locate and capture prey. Certainly changes to prey populations, whether they be increases, decreases, or greater annual population variability will impact availability of prey to neotropical migrants.

Table 1. Predicted effect of climate change on size and location of tree species commonly utilized by Lepidoptera assessed in this report (adapted from McKenney et al. 2007).

Tree Species	Northward shift in latitude*
<i>Prunus pensylvanica</i>	7.1
<i>Prunus serotina</i>	8.5
<i>Fagus grandifolia</i>	7.4
<i>Betula alleghaniensis</i>	8.2
<i>Acer saccharum</i>	8.9
<i>Acer rubrum</i>	7.6

* 1 degree latitude is approximately 69 miles.

METHODS

Vulnerability Assessment

The Climate Change Vulnerability Index (CCVI) provides an assessment of a species' vulnerability to climactic changes predicted by 2050. The assessment is based on a species' sensitivity to climate factors and projected exposure to climate change in a specific area. Sensitivity is assessed in terms of physiological, habitat, dispersal, and genetic constraints. Exposure to climate change is determined both by direct impacts of temperature and moisture availability on a species, and the potential effects of indirect exposure via factors such as changes in sea level or human modifications of the landscape in response to climate change. The CCVI also allows integration of modeled response to climate change where such data are available (Young et al. 2010).

Each sensitivity factor is categorized as having an impact on species' vulnerability using the following scale:

- Greatly Increase Vulnerability*
- Increase Vulnerability*
- Somewhat Increase Vulnerability*
- Neutral*
- Somewhat Decrease Vulnerability*

The Nature Conservancy's Climate Wizard (www.climatewizard.org), using downscaled climate models from Mauerer et al. (2007), provided mid-century predictions for changes in climate and moisture across Pennsylvania (Figures 3, 4).

For a number of species assessed here sensitivity fell into more than one category and all applicable categories were used for those sensitivity factors. This method of ranking tends to decrease the confidence of the modeled response and was also used to indicate a potential range in sensitivity.

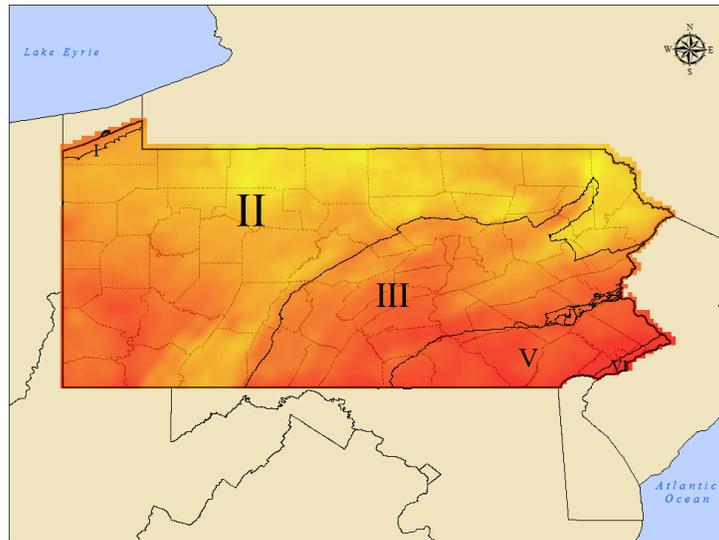


Figure 1. Map of mean annual temperature in Pennsylvania over the last 55 years (1951-2006). Average historic annual temperature ranges from approximately 43°F (yellow) to nearly 56°F (red). Grey lines represent county boundaries; solid lines symbolize physiographic providences within the state. Data provided by climatewizard.org.

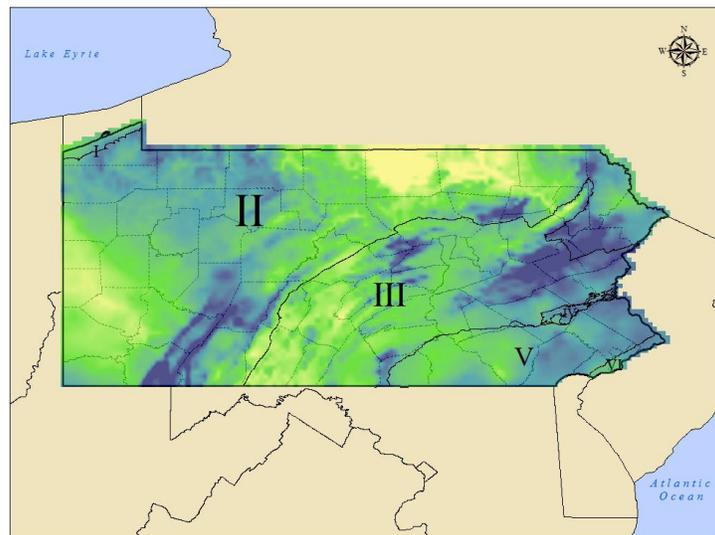


Figure 2. Map of mean annual precipitation in Pennsylvania over the last 55 years (1951-2006). Wetter areas are indicated by cooler colors (e.g.: dark blue) while drier areas are represented by warmer colors (e.g.: pale yellow). Grey lines represent county boundaries; solid lines symbolize physiographic providences within the state. Data provided by climatewizard.org.

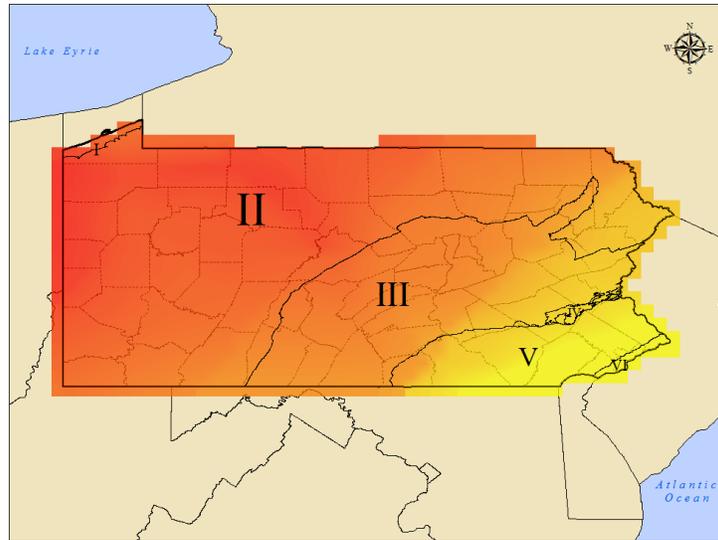


Figure 3. Projected changes in average annual temperature in Pennsylvania by 2050 according to MediumA1B emission scenario. The scenario estimates annual temperature changes will range from +5.26 °F (red) to +4.75°F (yellow).

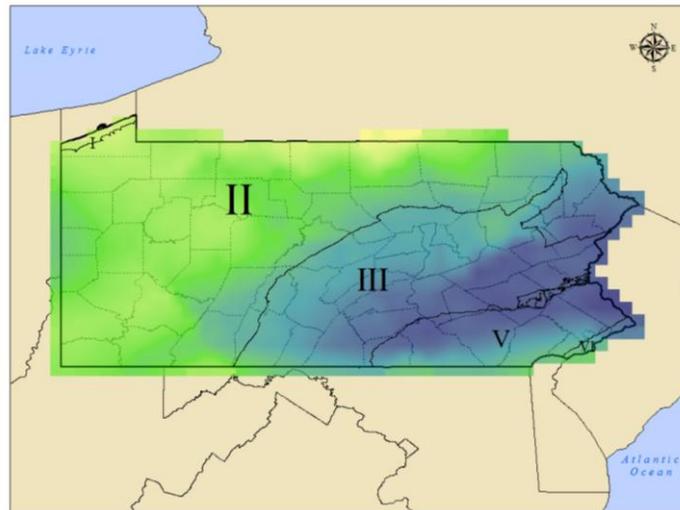


Figure 4. Projected changes in average annual precipitation in Pennsylvania by 2050 according to MediumA1B emission scenario. Areas with darker, cooler colors (e.g.: dark blue) are expected to experience the least amount of change (drying) while areas characterized with warmer colors (e.g.: pale yellow) are expected to experience the most change (drying).

Species selection

Climate change vulnerability assessments were conducted as part of a broader ongoing research project investigating tritrophic interactions among plants, ungulate herbivores, phytophagous insects, and insectivorous birds in the Allegheny National Forest of northwestern Pennsylvania. During 2010 we used the branch clipping method, where 50-centimeter branch tips are clipped from trees into bags and all caterpillar larva are collected, measured and identified (Wheatall et al. 2013). In 2011 we added experimental component to the study, sampling from paired branches with one branch protected from bird predation via protective netting (Keating 2012).

Lepidoptera species chosen for this study reflect a subset of the species encountered during larval collection during the 2010 and 2011 field seasons. Literature reviews on selected species were conducted and, in combination with analysis of data from Allegheny National Forest collections, used to provide assessment scores in the Climate Change Vulnerability Index calculator (Young et al. 2010). Where possible documented or modeled responses to climate change were integrated into assessments. Admittedly, there is a paucity of information on many of the commonly encountered temperate forest moth species.

Phenology

We sampled caterpillars from trees in the Allegheny National Forest and state lands in Warren, McKean, Elk, and Forest Counties, Pennsylvania (U.S.A.). The six tree species of interest, American beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), pin cherry (*Prunus pennsylvanica*), yellow or sweet birch (*Betula* spp.), red maple (*Acer rubrum*), and sugar maple (*Acer saccharum*) comprise over 90% of the forest cover in these areas. During the summer of 2011, 72 trees of each of six tree species were sampled once a month in May, June, and July for caterpillar and sawfly larvae. In August 48 of these 72 trees were sampled. In 2012 72 trees of these six species were sampled once every three weeks in May, June, and July. The distal ca. 50 cm of these branches were carefully checked for all Lepidoptera and Symphyta larvae greater than 5 millimeters in length. Larvae were reared individually in deli containers on the same host plant leaves until an identification could be determined. Because the primary objective of the research was to gauge the impact of bird predation on larval distributions, one of the two sampled branches of each tree was enclosed in a net to exclude bird predators. These results are also included here, as they provide information how changes in phenology may impact trophic interactions and vice versa.

RESULTS

Vulnerability Assessment

Analysis of climate change vulnerability in common, temperate forest Lepidoptera projects nearly half to be minimally impacted by climate change, and just over half to benefit from climate change (Table 1).

Table 2. Results of CCVI analysis for 14 temperate forest Lepidoptera in Pennsylvania.

Family	Species	Common Name	GRank	SRank	Υ Index	Conf. [†]
Tortricidae	<i>Choristoneura rosaceana</i>	Oblique banded leafroller	5	SNR	PS	Mod
Drepanidae	<i>Drepana arcuata</i>	Masked birch caterpillar	5	SNR	IL	Low
Saturniidae	<i>Dryocampa rubicunda</i>	Green-striped mapleworm	5	SNR	IL	VH
	<i>Automeris io</i>	Io moth	5	SNR	PS	Mod
	<i>Eacles imperialis</i>	Imperial Moth	5	SNR	PS	Mod
Notodontidae	<i>Heterocampa guttivitta</i>	Saddled prominent	5	SNR	PS	Mod
Arctiidae	<i>Hyphantria cunea</i>	Fall webworm	5	SNR	IL	VH
Eribidae	<i>Lymantria dispar</i>	Gypsy moth	5	SNR	IL	VH
	<i>Orgyia leucostigma</i>	Whitemarked tussock moth	5	SNR	IL	High
Lasiocampidae	<i>Malacosoma americanum</i>	Eastern tent caterpillar	5	SNR	PS	Mod
	<i>Malacosoma disstra</i>	Forest tent caterpillar	5	SNR	IL	Low
Geometridae	<i>Melanolophia spp.</i>	Melanolophia	5	SNR	IL	VH
Noctuidae	<i>Morrisonia confusa</i>	Confused woodgrain	5	SNR	PS	High
	<i>Morrisonia latex</i>	Fluid arches	5	SNR	PS	Mod
Papilionidae	<i>Papilio glaucus</i>	Eastern tiger swallowtail	5	SNR	IL	VH

^Y PS: Not Vulnerable/Presumed Stable: Available evidence does not suggest that abundance and/or range extent within the geographical area assessed will change (increase/decrease) substantially by 2050. Actual range boundaries may change. IL: Not Vulnerable/Increase Likely: Available evidence suggests that abundance and/or range extent within geographical area assessed is likely to increase by 2050.

[†] The Climate Change Vulnerability tool calculates a measure of confidence in species information that quantifies the uncertainty in information provided corresponding to low, moderate (Mod), high, and very high (VH).

Io moth (*Automeris io*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed stable

Confidence: Moderate

Life History & Habitat

Automeris io (Saturniidae: Hemileucinae) is polyphagous, recorded from a variety of unrelated herbaceous and woody plant species. In the northeast one generation is produced per year with diapause occurring in the pupal stage. Southern populations produce between two and four generations per year, usually with one diapausing generation. Gregarious while young, *io* moth caterpillars become solitary feeders in later instars. Adults live for only a few days, emerging during the afternoon, but remaining quiescent until dark and mating in the late evening or night (Manley 1993).

Current Threats

Though this species is a generalist feeder and occurs in a variety of habitats from contiguous forest to developed, suburban areas, declines have been reported at light traps in the northeastern United States where it appears this species is becoming highly localized (Wagner 2012). There is no current information on the mechanism for this localization, but speculation that it may be due to *Compsilura concinnata* parasitization or increased pressure from other natural enemies. *C. concinnata*, a tachinid fly introduced to control gypsy moth populations, disproportionately impacts gregarious feeders with longer development time (Wagner 2012), attributes of most *Automeris* species.

That adults have showy eyespot on their hind wings indicate that bird predation is an important source of mortality in this species. Larval *io* moths are covered in urticating spines which may protect them from vertebrate predation, but likely have little impact on parasitoid attack.



Factors Contributing to Vulnerability

According to rearing guidance, northern populations of Saturniid moths must experience historic winter temperatures in order to complete adult development, though *Automeris* species generally pupate in leaf litter and need some protection from direct exposure to freezing temperatures. While there is not experimental evidence on the impact of winter temperature variation on eclosion rates, Manley (1993) cites insulation from leaf litter, depth of snow, and duration of frost as factors influencing development responses in diapausing pupae. Directions provided by Tuskes et al. (1996) indicate that northern pupae must experience historic winter temperatures until spring, encouraging people rearing these populations in warmer climates to keep them at 0-5°C during pupal diapause. Evidence from rearing studies was used to rate *A. io* as have somewhat increased vulnerability via its physiological thermal niche. The underlying genetic component to these physiological or ecological adaptations is not well understood, but could result in the loss of northern populations to southern populations that are better adapted genetically to warmer temperatures.

Oblique banded leafroller (*Choristoneura rosaceana*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed Stable

Confidence: High

Life History & Habitat

Choristoneura rosaceana (Tortricidae: Tortricinae) is a native species found throughout Pennsylvania. It is considered oligophagous, though highly preferring species in Rosaceae. In Pennsylvania the species has two generations a year with the second brood larvae entering diapause as third instar to overwinter. The first generation generally feeds on developing flower buds and developing fruits, mating and producing the second generation which feeds primarily on leaves prior to entering diapause (Reissing 1980).

Current Threats

This species is considered a minor pest of farms and orchards throughout Pennsylvania and organophosphate insecticides are used to control populations in conventional orchards (Reissig 1980). Parasitoids may also play an important role in population regulation with parasitization rates near 25% during the summer (Wilkinson et al. 2004).

Factors Contributing to Vulnerability

The oblique-banded leafroller relies on photoperiod and temperature to enter diapause, but each appears able to trigger diapause independent of the other (ie: at a critical photo period of 14 hours regardless of temperature). Diapause is induced in first and second instar larvae, but expressed in third or fourth instar. This corresponds with larval feeding in mid- to late- summer such that diapause begins prior to colder fall temperatures. In laboratory studies fluctuating temperatures between 16°C and 32°C induce diapause independent of photoperiod for 67% individuals (Gangavalli and Aliniabee 1985). This indicates that severe temperature fluctuations may be able to



initiate diapause independent of photoperiod, especially those that reach above 25C. The range of this temperature fluctuation is consistent with those seen in June, July, and August throughout the state, and into October in southern and metropolitan areas of the state. Generally warmer temperatures are expected to increase the number of generations of temperate forest Lepidoptera. However, if diapause in the second brood of the oblique-banded leafroller is triggered earlier, individuals would enter diapause prior to the end of summer and a third generation would not be produced.

A related species, the spruce budworm (*Christoneura fumiferana*), shows increased overwintering mortality when exposed to higher temperatures for long periods during diapause prior to winter temperatures. This seems at least partially attributable to changes in glycerol production in these larvae (Han and Bauce 2002). Experimental evidence is needed to more rigorously test predictions about changes in physiology resulting from warming and impacts on population growth. Uncertainty is built into the assessment of this species' physiological response to climate change.

While this species accepts a broad range of hosts, changes to the quality or distribution of favored hosts may lead to population loss or increased occurrence on less preferred hosts. Apple production is projected to fall in southeastern areas of Pennsylvania if current emissions are not curbed, attributed primarily to warmer winters and decreasing chill hours required for proper flower development (Union of Concerned Scientists 2008). This could directly influence the second generation of oblique-banded leafroller larvae as they emerge in spring to feed, though the larva are often highly mobile as they search for appropriate food (Carriere 1992). Given their mobility and fairly wide host plant breadth, it is unlikely that even radical changes to a favored host will curb population growth on the scale of the next century.

Host plant quality appears to influence diapause initiation and voltinism (number of generations per year), with lower plant quality leading to early diapause initiation. Hunter and McNeil (1997) found that larvae feeding on chokecherry continued feeding while those feeding on red maple and black ash entered diapause, resulting in a greater proportion of chokecherry reared individuals producing a second generation. The effects of warming and decreased moisture availability vary by plant species, but increases in CO₂ generally decrease nitrogen content, rendering plants lower in nutrition (Ayers 1993).

Masked birch caterpillar / Arched hooktip (Drepana arcuata)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Increase Likely

Confidence: Very High

Life History & Habitat

Drepana arcuata (Drepanidae: Drepaninae) are distributed throughout Pennsylvania and feed exclusively on Birch (*Betula spp.*) and Alder (*Alnus spp.*). This species is bivoltine, with the first generation of caterpillars maturing in June or early July, and the second in late August or September (possibly October in warmer areas) (Wagner 2005). Though a great deal is known about communication in this species (Yack et al. 2001), there are no empirical studies of physiology or dispersal.



Current Threats

Drepana caterpillars are nocturnal, spending daylight in shelters they create using silk to curl a leaf edge. This may reduce pressure from bird predation. During field collections in Northwestern Pennsylvania double the number of individuals were collected from branches exposed to bird predation than those protected, indicating that birds play role in mortality in this species (Keating 2012).

Factors Contributing to Vulnerability

Being oligophagous, it is likely that the greatest threat of climate change to the masked birch caterpillar would be changes to host plant distributions. However, many Birch and Alder species are fast-growing, light demanding species that grow well in poor soils and withstand heat stress (Brand 2001). Generally these tree species are colonists of disturbed habitats and human activities that disturb established forest cover tend to abet these species. However,



nearly a dozen climate change models constructed by the Canadian Forest Service predict severe northward shifts in the core range of both sweet birch (*Betula lenta*) and black birch (*B. alleghaniensis*) by 2070, shifts that would remove large parts if not all of the core ranges of these species out of Pennsylvania (CFS 2013, Mckenney et al. 2007). Such reductions in potential host plants are predicted to increase the vulnerability of this species.

Green-striped mapleworm / Rosy maple moth (Dryocampa rubicunda)



Global Rank: G5 - secure
State Rank: SNR
State Wildlife Action Plan: None
Climate Change Vulnerability: Increase Likely
Confidence: Very High

Life History & Habitat

Dryocampa rubicunda (Saturniidae: Ceratocampinae) is univoltine in Pennsylvania, with egg laying beginning in May and extending as long as July. Pupal diapause begins in late August or September and pupae overwinter in leaf litter (Allen 1976). Larvae feed on Maple (*Acer*) and Oak (*Quercus*) species, and are also reported from America Beech (*Fagus grandifolia*).

Current Threats

Though groups of *D. rubicunda* may cause very localized defoliation to small stands of trees, it is generally not considered a serious pest species. An outbreak in Pennsylvania in the 1970's caused defoliation in nearly 27,000 acres, indicating the potential for significant impact on forests. It is susceptible to a number of parasitoids, the most abundant being a tachinid fly that develops during the pupal stage (Allen 1976).

Factors Contributing to Vulnerability

Changes in forest cover in Pennsylvania will not likely impact this species. Though *D. rubicunda* are prevalent in Northern Hardwoods, a forest type expected to decline with rising temperature and decreased moisture availability, red maple, a preferred host plant, is not expected to decline in the state (Mooney 2007). In fact, increases in anthropogenic disturbance for energy development, whether well pads for gas extraction or clearing for wind energy will tend to increase edge and early-successional forests, both of which are often comprised largely of red maple. Rises in temperature immediately increase adult *D. rubicunda* activity levels (Bailey and Horn 2007), indicating climate change may directly increase adult movement and dispersal. Additionally, the length of the warm season influences the number of broods produced, with longer warm seasons allowing for higher brood production.



Saddled Prominent (*Heterocampa guttivitta*)



Global Rank: G5
State Rank: SNR
State Wildlife Action Plan: None
Climate Change Vulnerability: Increase Likely
Confidence: Moderate

Life History & Habitat

Heterocampa guttivitta (Notodontidae) is found throughout hardwood forests in Pennsylvania, preferentially feeding on American beech, sugar maples, yellow birch, and paper birch, but found on nearly all temperate forest trees with the exception of conifers, red maple, striped maple, and white ash. The saddled prominent has one generation per year with pupae overwintering in leaf litter, generally emerging in May to mate. Females oviposit for an average of 10 days, laying between 200 and 250 eggs. The oviposition window lasts 4 to 5 weeks, resulting in many life stages occurring simultaneously (Rush and Allen 1987).

Current Threats

The saddled prominent is characterized as a native pest species because populations often reach outbreak proportions and contribute to local or regional defoliation (Rush and Allen 1987, Martinat and Allen 1988). However, a number of predators and parasites help regulate populations and may contribute to the prevention of outbreaks, with parasitoids contributing significantly to mortality (Allen 1972).

Factors Contributing to Vulnerability

Saddled prominent females reared on yellow birch show higher fecundity than those reared on other preferred tree species. Thus, yellow birch, an early-successional tree species that often dominates forest cover in areas after disturbance, may play a key role in outbreaks of the saddled prominent (Allen 1973). Increasing development for resource extraction or energy generation could create desirable habitat for the saddled prominent.

Current average temperatures in Pennsylvania during June – August range from 15.5° C to 21.1 in rural and northern areas of the state and 21.1 to 29.4 around larger cities and in the



southeastern corner of the state (Climate Wizard). Laboratory experiments indicate that egg and larval development rates increase with increasing temperature, and that survivorship is maximized at higher temperatures with greater relative humidity (Martinat and Allen 1987). However, eggs incubated at 21.1° C had greater survivorship at humidity extremes than those incubated at lower or higher temperatures. While an increase in temperature is predicted to increase development time, decreases in relative humidity consistent with predicted drying in Pennsylvania over the next 50 years may reduce survivorship of eggs at higher temperatures. The predicted average increase in temperatures for Pennsylvania (2.8° C to 3.1° C) would push temperatures in some areas of Pennsylvania far above 21.1° C. It is likely that in the warmer areas of the state—currently around the larger metropolitan areas and in the southeastern corner, saddled prominent populations may be reduced by climate change. Alternately, in rural and northern areas of the state, where the lower average temperatures will be pushed closer to 21.1 C, saddled prominent populations are expected to increase due to increasing survivorship.



Fall webworm (Hyphantria cunea)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Increase Likely

Confidence: Very High

Life History & Habitat

Hyphantria cunea (Erebidae: Arctiinae) is found throughout Pennsylvania and is considered a generalist recorded from nearly 90 species of deciduous trees and shrubs. In studies conducted in Northwestern Pennsylvania, the fall webworm was found almost exclusively on black cherry (*Prunus serotina*) (Keating 2012). Black cherry is also recorded as the preferred host in New York State (Allen 1993). The fall webworm prefers trees exposed to full sun and is therefore often found in early successional habitat, orchards, or along roadsides and disturbed areas. In the northeastern United States the fall webworm is univoltine, but may have up to four generations in southern states.

Current Threats

The fall webworm, rarely causing complete defoliation of host trees, is considered a mild pest species of temperate forests. It is primarily a concern for fruit and nut growers in Pennsylvania, as localized outbreaks may reduce fruit production. Small-scale eradication in Pennsylvania threatens populations in orchards, but likely does little to the overall stability of the species in the state.

Factors Contributing to Vulnerability

Though there are no direct tests of climate change on this species in North America, studies of fall webworm in Japan, where it is non-native, indicate that increasing temperature may decrease generation time. Introduced to Japan in 1945, populations across the country were immediately bivoltine. Within three decades, however, observers noticed that some southwestern populations were trivoltine, a shift that is thought to have occurred within one decade (Gomi 2007 and Takeda). Gomi et al. (2007) attribute this change in generation time to an interaction between the critical photoperiod for diapause induction and temperature, with both reduced in southwestern populations. The fall webworm appears to be able to rapidly adapt when exposed to changes in climate, with shifts towards shorter generation times and higher populations occurring in the course of a decade. Certainly an increase in the number of generations

per year in Pennsylvania would contribute to increased stress on temperate forests and orchards throughout the state.

Due to its affinity for high light environments, development that increases edge or early-successional habitat will increase desirable habitat for this species. In Pennsylvania the development of alternative energy sources such as wind power will tend to increase edge habitats.



Imperial moth (*Eacles imperialis*)

Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed Stable

Confidence: Moderate

Life History & Habitat

Eacles imperialis (Saturniidae: Ceratocampinae) is found throughout the United States from southern New England west to the great lakes basin and south to central Texas. In the northeast caterpillars feed from mid to late July through September, when they burrow into the ground, pupate, and enter diapause for winter (Opler et al. 2012).

There are two sub species of imperial moth, *Eacles imperialis imperialis* and *E.*

imperialis pini, the latter of which feeds exclusively on coniferous trees. *E. imperialis pini* relies on sandy, scrub habitats because pupae need to be protected from winter freezes, but emerge toward the surface in the spring for adults to eclose. Adults are non-feeding.



Photo courtesy of Liz Milica

The HOSTS database lists over three dozen genera of host plants, both broadleaved deciduous and coniferous trees. It is likely that polyphagy exists at the species-level with populations showing far more specialization than is indicted by recorded occurrence (Goldstein 2010). Selective forces attributable to habitat variables contribute greatly to variation in host plant use— individuals from dry forests in Costa Rica share greater sequence similarity with those from the Great Smokey Mountains than individuals living in Costa Rican rainforests (Janzen et al. 2005).

Current Threats

The parasitoid *Compsilura concinnata*, a tachinid fly released numerous times in the 20th century to target gypsy moth (*Lymantria dispar*) populations, appears to also attack *E. imperialis*. Increases in pesticide use and metal halide street lights are also shown to reduce population sizes (Goldstein 2010).

Factors Contributing to Vulnerability

The widespread distribution and localized abundance belies the potentially sensitive nature of this species to environmental change. *E. imperialis* was largely extirpated from New England by the middle of the 1900's, and despite a number of

hypotheses on cause, no one factor explains its rapid decline (Goldstein 2003). Given the wide host breadth of *E. imperialis imperialis*, changes in host plant distributions might be expected to have minimal impact on populations sizes. However, Goldstein (2010) found that host plant choice does not necessarily align with host plant suitability, that is caterpillars from specific populations will refuse host plants that are known to be sufficient food source for other populations. Given the limited range of coniferous forests in Pennsylvania (PA Wildlife Action Plan 2005), *E. imperialis pini* may be at a much greater risk with predicted reductions in coniferous forests and tree survival predicted with climate change (Solomon 1986). Wind energy development on ridgetops, if not coordinated to prevent it, will also reduce coniferous forests in the state (PA Wildlife Action Plan 2005). While the species as a whole is considered stable across its range, we may witness the loss of populations suited to particular ecosystems or host plants. That the adult males are strong fliers (Tuskes et al. 1996) also indicates that dispersal in this species would not be hindered and may actually increase with rising temperatures.

Gypsy Moth (*Lymantria dispar*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed Stable

Confidence: Moderate

Life History & Habitat

Lymantria dispar (Erebidae: Lymantriinae) the gypsy moth, is widespread in hardwood forests of Pennsylvania, inhabiting nearly every area with woody vegetation (NatureServe 2011). Gypsy moth larvae are polyphagous and are recorded from nearly 500 food plants including oaks, alder, apple, box elder, hawthorn, hemlock, hazelnut, birch, larch, mountain ash, poplars, bushes, sumac, willows, witch-hazel, pine and spruce trees. Food plant use changes throughout development, with a preference towards understory shrubs in early instars and beech, hickory and oak in later instars. Despite this apparently wide range of host species, Gypsy moth larvae do show a preference toward oak species (Liebhold 2003, Opler et al. 2013, Wagner 2005).

Current Threats

Rather than being a species of conservation risk, the gypsy moth is characterized as a pest species with local defoliation events occurring every few years with population growth and crashes. The primary threats to *Lymantria dispar* populations are human-induced suppression to prevent forest defoliation. *L. dispar* suppression and eradication programs by humans such as USDA's "Slow The Spread" program (Liebhold, 2003) is limiting their opportunities for expansion however not greatly enough to be considered a threat to their existence.



Factors Contributing to Vulnerability

Gypsy moths, being ectotherms, may be greatly influenced by changes in temperature. With increasing temperatures invertebrate pest species such as the gypsy moth are predicted to increase in number or expand their range. This species spends its winter in the egg stage and hatches from mid-April to mid-May when temperatures begin to reach about 15 degrees Celsius (Liebhold 2003). Gypsy moths produced one generation per year, a generation time unlikely to change with the predicted temperature changes in Pennsylvania. However, increases in temperatures may result in earlier hatching of gypsy moth larvae. It is difficult how this might influence populations, since if the larvae emerge prior to leaf-out they may struggle to survive until food is available. Alternately, if early hatching provides increases in feeding time, decreases in predation, or higher pupal weight, it could positively contribute to population growth.

Overwinter survival is critical for gypsy moth population growth and expansion, and with a predicted increase in temperature during the winter months, there will likely be less winter mortality seen in populations of *Lymantria dispar*, along with other insects. It has been observed from previous studies that this species will experience winter mortality if air temperatures reach below -20°C , and may experience mortality post-hatch if freezing temperatures occur early in May (Hoover 2000). With average lows (December – February) of -8.3° to -6.7°C in southwestern PA, -11.7° to -7.8°C in northwestern PA, and -7.8° to -4.4°C in northeastern PA, the predicted average increase in temperatures for these areas by midcentury (2.8° to 3.1°C) may increase overwintering egg survival, specifically in southwestern and northeastern areas of the state.

The female gypsy moth adults cannot fly and have been observed to move an average of only 1 to 2 meters between sites of eclosion and oviposition (Elkinson 1990). Male flight is not assumed to contribute to dispersal because it is limited by the location



of females. The major mode of long distance dispersal in this species is through “ballooning”, when newly hatched larvae release a long silk thread that catches the wind, supplemented with anthropogenic dispersal. Late-instar larvae are the most active and may crawl up to 100 meters from tree to tree in search of food and shelter, however they are incapable of long distance dispersal exhibited by the first instars (Lance and Barbosa 1982). Liebhold et al. (1992) reported slower rates of spread among populations of *L. dispar* in colder climates, potentially due to decreased activity at colder temperatures.

Other documented modes of long distance dispersal among gypsy moths include caterpillars becoming attached to boots and clothing of individuals carried to other sites. Egg masses travel well on various objects such as camping equipment, lawn furniture, containers and hulls of ships. The variety of dispersal tactics at various life stages indicate no significant natural barriers exist for this species in Pennsylvania. If there were to be an increase of human activity in gypsy moth habitat for various activities such as planting of trees or building wind turbines to offset climate change, this is expected to positively affect the gypsy moth populations as increased movement around the state would increase human-based dispersal.



Increase in moisture as a result of climate change may lead to an increase in the presence of the highly virulent fungal pathogen of gypsy moths, *Entomophaga maimaiga*. Moisture is very important in the pathogenicity of this fungus. Resting spores of *E. maimaiga* germinate best one to two days after precipitation. High humidity and rainfall is required for conidial (infectious spore) development and discharge (Buss et al. 2001). High gypsy moth larval mortality has been linked to the activities of this fungal pathogen under high humidity and wet spring weather in many recorded instances across the North Eastern United States (Liebhold 2003, Elkinson 1990).

Eastern Tent (*Malacosoma americanum*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed Stable

Confidence: Moderate

Life History & Habitat

Malacosoma americanum (Lasiocampidae: Lasiocampinae) is characterized as oligophagous, preferring *Prunus* species, specifically black cherry *Prunus serotina*, and found less often on oaks, maples, birches, and other shade trees of temperate forests. Adult moths show oviposition preference for trees that are the first to leaf out in spring, though after decimating their natal tree caterpillars may move on to another host species (Hodson 1941). The species is univoltine, overwintering in the egg stage.

Current Threats

The eastern tent caterpillar is characterized as a pest species with outbreaks causing local and at times regional defoliation. While trees generally recover from these outbreaks, their health and viability is often reduced. Additionally, eastern tent caterpillar populations are implicated in mare reproductive loss syndrome wherein females that have accidentally ingested caterpillars while eating their host plants experience spontaneous abortion (Potter et al. 2005).

Ants foraging at extrafloral nectaries on *P. serotina* may decimate local colonies. Tilman (1978) found that colonies within 5 meters of red-headed ant (*Formica obscuripes*) nests had survivorship close to zero. While weather, disease, and predators are shown to limit outbreaks in *M. americanum*, human actions directed at curbing outbreaks and spread of this species are the primary threats to populations.

Factors Contributing to Vulnerability

Though considered oligophagous, changes to the range or quality of the eastern tent caterpillar's preferred host, black cherry, may reduce populations sizes. Black cherry is currently found throughout eastern North America from Florida west into Texas and north



Photo courtesy of Cody Hough

to Nova Scotia. Despite the seemingly widespread distribution, black cherry is prevalent in the Northern hardwood forests in counties north of interstate 80, but is far less dominant in the oak-hickory forests in the southern areas of the state (Block and Rhoades 2005). Global warming is expected to drive the ranges of many temperate forest trees northward, with black cherry's range expected to move approximately 587 miles north during the next century (McKenney 2007), reducing the prevalence of black cherry dominated in forests in the state (Iverson and Prasad 1998). Nearly half of the climate change models conducted by McKenney (2007) show the central range of *P. serotina* shifting out of areas of Pennsylvania. Models vary in their predictions of specific geographic area of *P. serotina* presence, making a precise understanding of how *M. americanum* distributions may change across the state difficult, but it is likely that habitat



loss will marginally increase vulnerability of northern populations and increase vulnerability in southern populations.

Though direct evidence of potential or actual dispersal distance in this species is not available, genetic homogeneity among geographically distant populations implies mating is occurring among individuals of these populations (Costa and Ross 1994). It is

unlikely that climate change will negatively impact dispersal distances in this species. Instead, warmer temperature may increase flight activity and dispersal ability.

That eastern tent caterpillars are behavioral thermoregulators may decrease their vulnerability to climate changes, especially severe fluctuations in spring temperatures (Knapp and Casey 1986). Temperature regulation provides more rapid nutrient uptake and enhances growth rates as caterpillars are able to more efficiently process food at a variety of ambient temperatures. These processes are expected to be enhanced by warmer ambient temperatures. It is not known how warming trends may influence thermoregulation and social behaviors in this species, but it appears this species will benefit from increases in temperature over the next 50 years.

It is likely that eastern tent caterpillars, like their forest tent caterpillar relative, use glycerol production during the egg stage to survive winter. Because glycerol production is reduced during warm periods this species faces the potential for greater egg mortality during extreme winter temperature fluctuations (Cooke and Roland 2003). As with the forest tent caterpillar, egg mortality due to severe cold is thought to be an important factor in population regulation and in general warmer winters are expected to reduce egg mortality.



Forest Tent Caterpillar (Malacosoma disstra)

Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Increase Likely

Confidence: Very High



Life History & Habitat

Malacosoma disstra (Lasiocampidae: Lasiocampinae) is found throughout hardwood forests in Pennsylvania. Like all temperate forest *Malacosoma* species, *M. disstra* has a wide host range, including members from six or more plant families. While ovipositional studies indicate host preference, caterpillars often defoliate entire trees and therefore must disperse to new host trees, often attacking a species different than their natal host (Hodon 1941). Sugar maple (*Acer saccharum*) appears to be a preferred host of this species, whereas red maple (*A. rubrum*) is generally avoided. The species is univoltine, overwintering in the egg stage.

Current Threats

The forest tent caterpillar, rather than being a species of conservation risk, is characterized as a pest species with local defoliation events impacting the timber and sugaring industries (Dodds and Seybold 1996). Entomologist T. W. Harris called for eradication of *M. disstra* in 1841 and various eradication efforts have continued since (Fitzgerald 1995, p. 235). Population outbreaks appear to be limited primarily by low spring temperatures, parasitism, disease, and starvation (Fitzgerald 1995, p. 214).

Factors Contributing to Vulnerability

In 2010 and 2011 sampling in the Allegheny National Forest *M. disstra* were found on American Beech, Black Cherry, Pin Cherry, Red Maple, Sugar Maple, Sweet Birch, and Yellow Birch. They were found at highest densities on Sugar Maple and Pin Cherry (Wheatall et al. 2013), suggesting Forest Tent Caterpillar prefer these species. While they are generalists and feed on a number of species, changes in Sugar Maple distributions due to climate change would likely impact the availability of a highly preferred food source and therefore population growth rates. For the purpose of this study we characterize *M. disstra* as having a broad habitat host range, and given that this species exhibits some host preference, we expect a neutral response in terms of the dependence on other species to generate habitat, but somewhat increased sensitivity in terms of diet versatility.

Direct evidence shows that moths of the genus *Malacosoma* travel 2-3 miles from natal sites and under certain circumstances can travel up to 300 miles from their natal site (Hodson 1941). *M. disstria* adults are known to regularly disperse 1-10 kilometers from their natal area and may have increased dispersal ability with higher temperatures, especially increases in or extension of late summer temperatures when adults mate and disperse (Dodds and Seybold 1996). Therefore, this species is characterized as having somewhat decreased vulnerability in terms of dispersal ability due to climate change.

Forest tent caterpillars over winter in the egg stage with cold tolerance achieved through glycerol production, a physiological process regulated by ambient temperatures. Specifically, warmer winter temperatures reduce glycerol production and may put eggs at risk of reduced cold tolerance. Winters with extreme variation in temperature greatly increase egg mortality in this species (Cooke and Roland 2003). However, egg mortality due to severe cold is currently thought to be an important factor in population regulation, and it is hypothesized that warmer winter temperatures will generally reduce egg mortality rates.

Diapause termination in *M. disstria* is temperature-dependent; eggs must experience an overwintering phase (around 2° C) for at least three months or they will not eclose (Hanec 1966). With average lows (December – February) of -8.3° to -6.7° C in southwestern PA, -11.7° to -7.8° C in northwestern PA, and -7.8° to -4.4° C in northeastern PA, the predicted average increase in temperatures for these areas (2.8° to 3.1° C) is not expected to impact diapause by midcentury. Diapause is also not expected to be affected in the Southeastern part of the state where average lows (December – February) are -6.7° to -3.8° C and are expected to increase 2.5°-2.7° C degrees by midcentury.

Foraging larvae show higher growth rates, presumably due to faster digestion rates, at higher temperatures (Levesque et al. 2002, Mansingh 1974). This, combined with the fact that midcentury temperatures are not expected to rise in a way that impacts diapause, is expected to result in a somewhat decreased vulnerability due to climate change in this species' physiological thermal niche. Note, however, that continued monitoring of diapause conditions will be important in making future predictions for the impact of climate change on this species.

Forest Tent Caterpillars are expected to show increased egg production and growth rates, and decreased generation times (more generations per season in temperate climates) with warming temperatures, earlier onset of snowmelt and leaf out, and extended summers (Parry et al. 2001, Levesque et al. 2002). There may also be decreased risk of spring mortality with a rise in spring temperatures (Fitzgerald 1995). These factors, combined with predicted midcentury temperatures that are not expected to rise in a way that impacts diapause, is expected to result in a *M. disstria* exhibiting a decreased vulnerability due climate change.

Canadian and Signate Melanolophia (*Melanolophia canadaria*, *M. signataria*)



Global Rank: G5 - secure
State Rank: SNR
State Wildlife Action Plan: None
Climate Change Vulnerability: Increase Likely
Confidence: Very High



Life History & Habitat

Melanolophia canadaria and *M. signataria* (Geometridae: Ennominae) are difficult to distinguish as adults and impossible to discriminate using larval field characteristics or current DNA barcoding methods (Keating 2012). Though one of the most common caterpillars collected during inventories in the Northeastern United States (Butler and Strazanc 2000, Wheatall 2011, Keating 2012), very little is known about the ecology or physiology of these species. In Northwestern Pennsylvania *Prunus* species are a preferred host of these *Melanolophia* species, but caterpillars are reported from a variety of host genera including *Prunus*, *Acer*, *Betula*, *Ulma*, *Quercus*, and even *Pinus*.

Current Threats

Given the cryptic appearance and behavior of larval and adult stages (Sargent 1969), it is likely that highly visual predators such as birds are an important source of mortality for *Melanolophia* populations. *Melanolophia* occurred less frequently in the presence of birds on four of the most common tree species in the Allegheny National Forest of Northwestern Pennsylvania (Figure 5, Keating 2012).



Factors Contributing to Vulnerability

Despite differences in distribution across hosts in the Allegheny National Forest, caterpillars reached comparable sizes on all hosts (Figure 6, Keating 2012), implying that host quality is not the primary driver in distributions. This, combined with evidence that caterpillars occur across a wide variety of hosts, indicated flexibility in host plant use. It is unlikely that changes to distributions of temperate forest trees brought on by climate change will negatively impact *Melanolophia* populations.



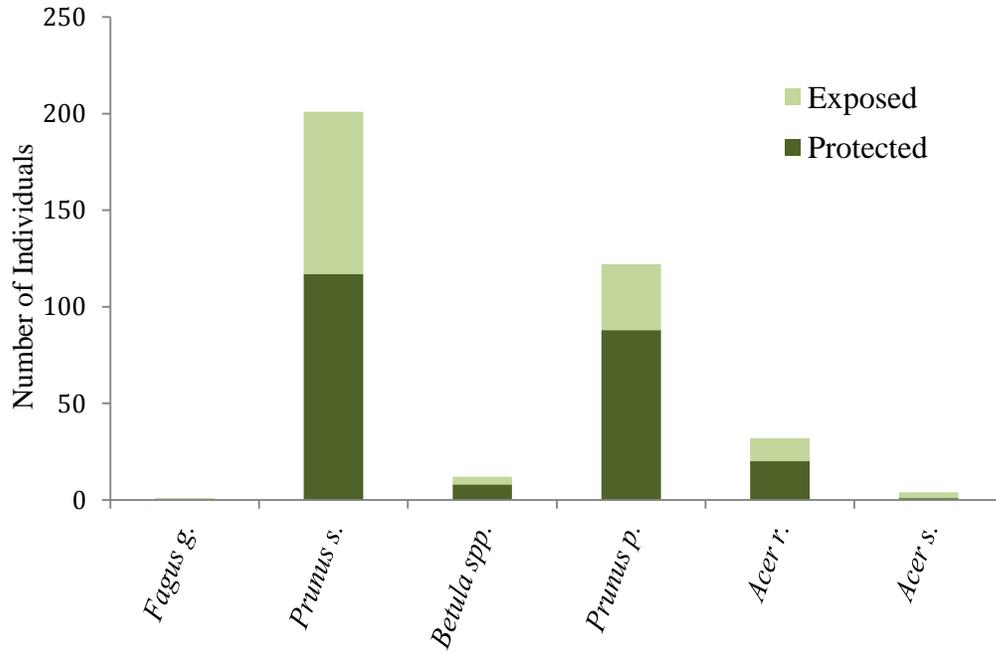


Figure 5. Number of *Melanolopia* collected from six tree species exposed to or protected from bird predators in the Allegheny National Forest June – August 2011.

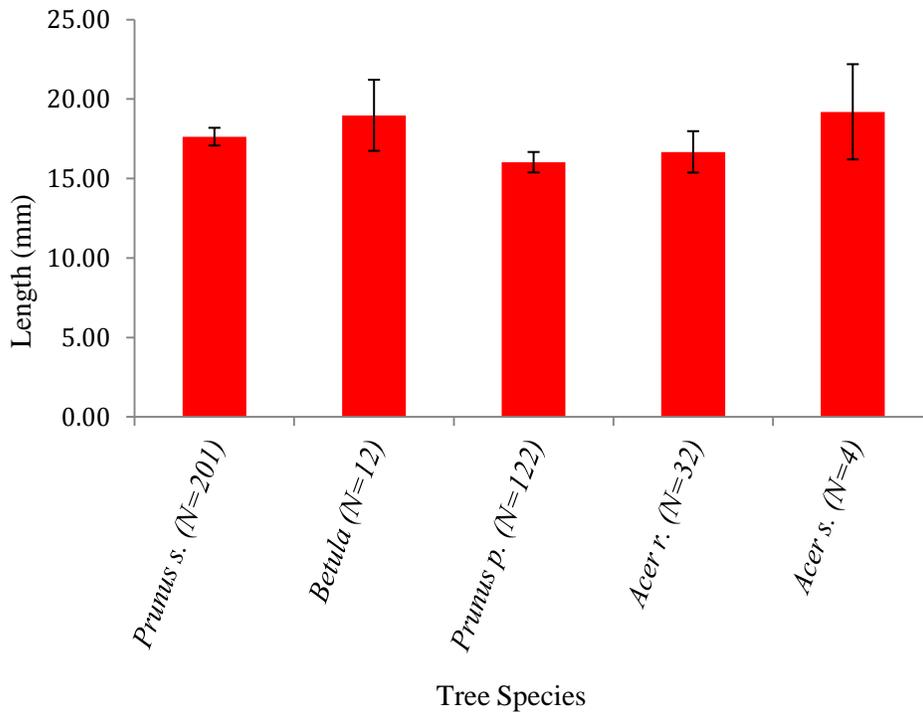


Figure 6. Mean length of *Melanolopia* individuals during June – August 2011. Error bars indicate standard error.

Confused woodgrain (*Morrisonia confusa*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Presumed Stable

Confidence: High

Life History & Habitat

Morrisonia confusa (Noctuidae: Hadeninae) is found throughout the northeastern United States and is assumed widespread in Pennsylvania. It is polyphagous with recorded host plants including maple (*Acer spp.*), birch (*Betula spp.*), oak (*Quercus spp.*), black cherry (*Prunus serotina*), flowering dogwood (*Cornus florida*), and American elm (*Ulmus americana*) (Wood and Butler 1991). In western Pennsylvania larvae appear to reach a larger size on American beech and sugar maple as compared with *Prunus* species, but there is a great deal of overlap in size among these species (Figure 7, Keating 2012).

The confused woodgrain has a flight period between mid-May and mid-June, peaking in late May in West Virginia. Dispersal distance for this species is not published. Larvae feed through the summer months with seven instars preceding pupation. Laboratory-reared specimens take an average of 71 days to reach pupation, potentially an overestimate of larval development due food replacement disturbance in the laboratory (Wood and Butler 1991).

Current Threats

While a commonly encountered species during field sampling in temperate forests, little is known about the biology of the *M. confusa*. Given what is known about bird prey selection and observations from the exclusion of bird predators, it is likely the birds remove a significant number of caterpillars during the summer months (Figure 8, Keating 2012).



Factors Contributing to Vulnerability

Similar to the related fluid arches (*Morrisonia latex*), there is much uncertainty worked into the ranking of this species in terms of impacts of climate change on vulnerability. Given its broad host range, this species has little risk of host loss under



climate change scenarios, but a lack of studies on its phenology and physiology make predictions about these factors difficult. As with many Lepidoptera, the direct impacts of temperature are expected to increase growth rates and potentially shorten generation time in this species.

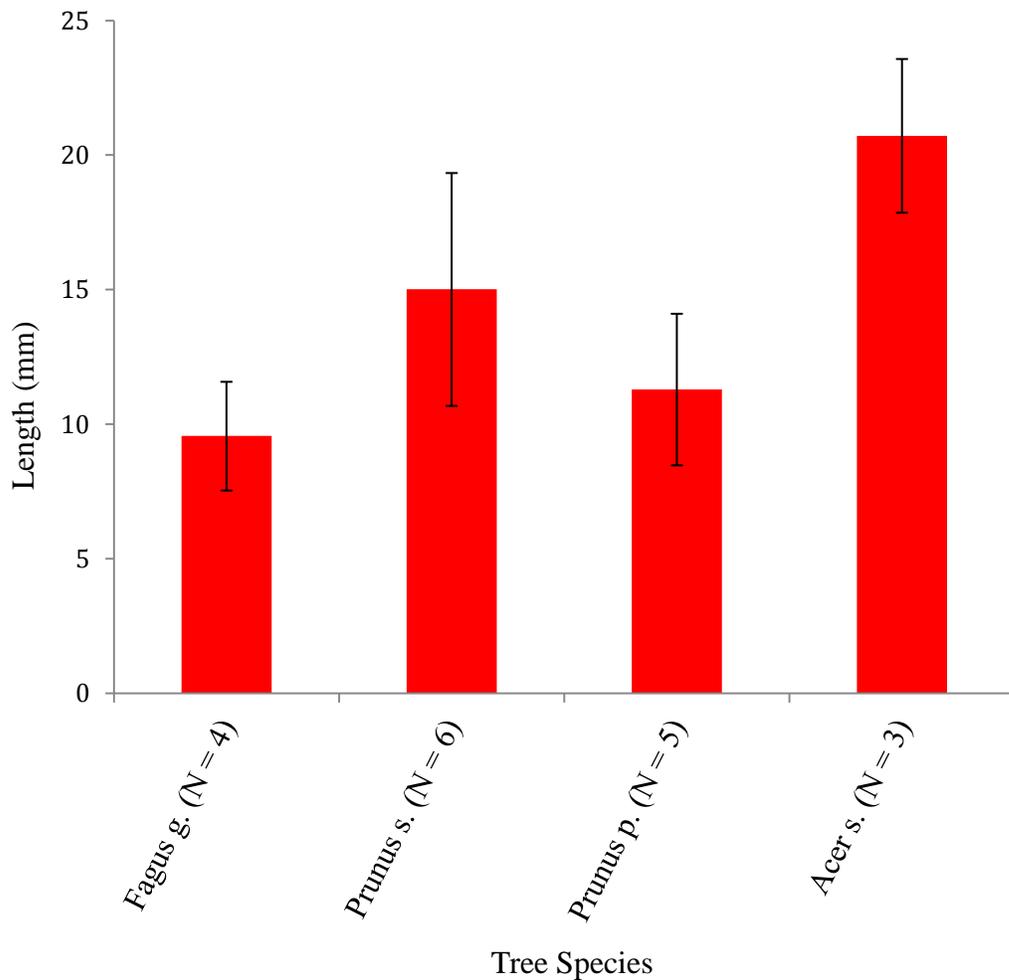


Figure 7. Mean length of *Morrisonia confusa* individuals during June – August 2011 from four tree species in the Allegheny National Forest. Error bars indicate standard deviation.

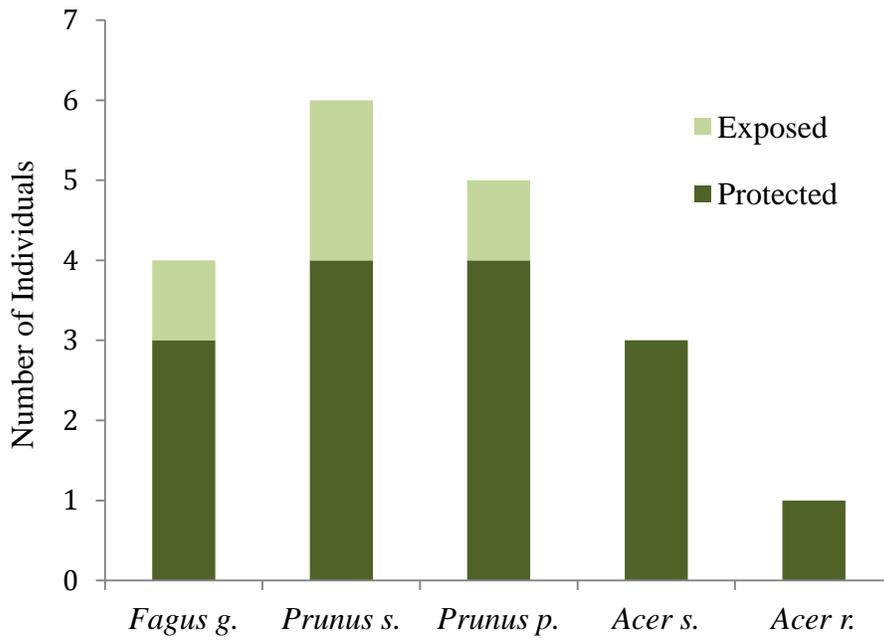


Figure 8. Number of *M. confusa* individuals collected from five tree species either protected or exposed to bird predation during June – August 2011 in the Allegheny National Forest.



Fluid Arches (*Morrisonia latex*)



Global Rank: G5 - secure
State Rank: SNR
State Wildlife Action Plan: None
Climate Change Vulnerability: Presumed Stable
Confidence: High

Life History & Habitat

While the HOSTS database lists only black cherry (*Prunus serotina*) as a host plant of *Morrisonia latex* (Noctuidae: Hadeninae) (Robinson et al. 2012), field collections in 2011 located caterpillars on five tree species, black cherry, pin cherry (*Prunus pensylvanica*), American beech (*Fagus grandifolia*), red maple (*Acer rubrum*), and sugar maple (*Acer saccharum*), and one genus represented by two species, yellow and sweet birch (*Betula spp.*) in northwestern Pennsylvania (Wheatall 2011, Keating 2012). Oak (*Quercus spp.*) are also recorded as host species in West Virginia (Wood and Butler 1989). Data on the mean length of caterpillars found on these tree species (Figure 9, Keating 2012), shows that caterpillars reach comparable sizes on all tree species, providing some evidence that these tree species act as comparable food sources.



Though univoltine, the fluid arches exhibits a rather long flight period, with adults being collected from mid-May through mid-August (Wood and Butler 1989). Wood and Butler (1989) also report peak flight times varying as much as three weeks from year to year, likely a consequence of weather conditions. Larval duration averages 45.3 days in laboratory conditions at 24°C. The fluid arches overwinters in the

larval stage and can often be found feeding into October as far north as West Virginia (Wood and Butler 1989).

Current Threats

Birds prey upon the fluid arches, reducing collected specimen by 44% in June and 63% in July (Figure 10, Keating 2012). The fluid arches is also susceptible to parasitoid attack; at least 27% of larvae from branches protected from bird predators were parasitized (Keating 2012). The impact of birds and parasitoids is not additive, given that

birds may eat caterpillars that have already been parasitized. As with many invertebrates weather likely plays a role in population regulation.

Factors Contributing to Vulnerability

There is a great deal of uncertainty worked into the ranking of the fluid arches because of a lack of studies on its phenology and physiology. Given its broad host range, this species has little risk of host loss under climate change scenarios. The direct impacts of temperature or precipitation on *M. latex* survival or reproduction have not been investigated, but from analogy with other species it is likely that warming will increase growth rates and potentially shorten generation time in this species.

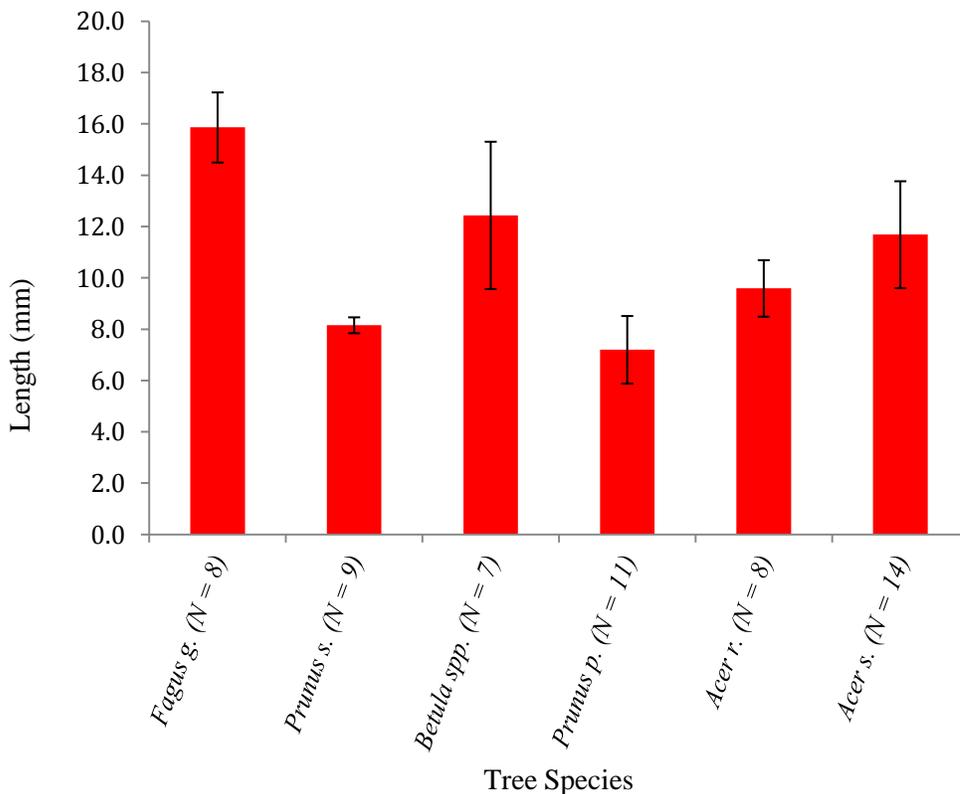


Figure 9. Mean length of *Morrisonia latex* individuals during June – August 2011 on six tree species. Error bars indicate standard error.

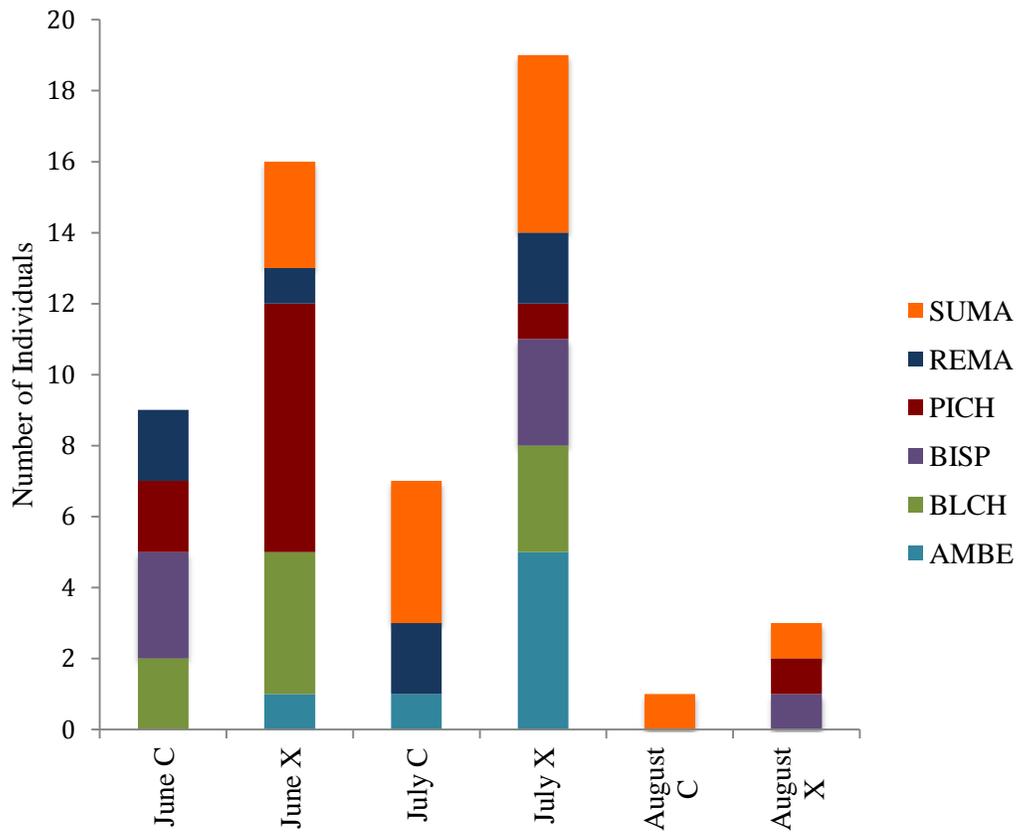


Figure 10. *Morristonia latex* abundance on six tree species during 2011 (C = exposed to bird predators, X = protected from bird predators). SUMA is Sugar Maple, REMA is Red Maple, PICH is Pin Cherry, BISP is Birch Species, BLCH is Black Cherry, AMBE is American Beech.

Whitemarked Tussock Moth (Orgyia leucostigma)



Global Rank: G5 - secure
State Rank: SNR
State Wildlife Action Plan: None
Climate Change Vulnerability: Increase Likely
Confidence: Very High

Life History & Habitat

Orgyia leucostigma (Erebidae: Lymantriinae) is a common species of temperate forests throughout the eastern United States and is widespread in Pennsylvania. The species is considered polyphagous, being recorded from over 140 food plants (Wagner 2005). Though not considered a serious defoliator, the whitemarked tussock often causes extensive damage to orchards and urban shade trees. Howard (1897) noted that, a pest primarily of orchards, the whitemarked tussock became more prevalent in urban areas starting in the mid-19th century. He attributes this to a lack of competitors and predators in these areas. This species experiences two generations in Pennsylvania and overwinters in the egg stage. First instar caterpillars use silk threads to balloon away from their hatching site, while later instars often exhibit extensive wandering.



Current Threats

The whitemarked tussock is not considered a pest species presumably because outbreaks are regulated by weather, predation, and disease. The fungal pathogen, *Entomophaga maimaiga*, originally released for gypsy moth (*Lymantria dispar*)



population control, appears to cause mortality in the whitemarked tussock, but the extent of this mortality in native populations is unknown (Hajek et al. 2004). Bird predation is an important source of mortality for larger, later stage larvae (Medina and Barbosa 2002). Populations are also regulated by nuclear polyhedrosis virus (NPV) infections. Food

quality may affect susceptibility to viral infection, with lower quality food leading to higher mortality (Brodersen et al. 2012).

Factors Contributing to Vulnerability

Many of the biological properties of the whitemarked tussock—broad host acceptability, larval dispersal strategies, wide temperature range tolerance—contribute to low vulnerability ratings. Increases in plant secondary compounds, a common response to stress in plants, appear to improve whitemarked tussock moth fecundity as longer time spent feeding on these plants increases female body size. The slow-growth-high-mortality hypothesis suggests that tussocks spending more time feeding on lower quality plants will be more prone to predators and parasitoids. While birds do remove larger larvae (Medina and Barbosa 2002), parasitization rates on low and high quality plants do not differ (Medina et al. 2005). Host plant quality impacts susceptibility to NPV infection (Brodersen et al. 2012), but the mechanism for this and an appropriate assessment of host plant quality are needed. Certain NPVs may be inactivated with rising ground temperatures (Martignoni and Iwai 1977), which would reduce mortality in whitemarked tussock moth populations. In general climate changes are expected to enhance dispersal and reproduction in this species, but more research is needed to assess impacts on survival.



Eastern Tiger Swallowtail (*Papilio glaucus*)



Global Rank: G5 - secure

State Rank: SNR

State Wildlife Action Plan: None

Climate Change Vulnerability: Increase Likely

Confidence: High

Life History & Habitat

Papilio glaucus (Papilionidae: Papilioninae) is found throughout Pennsylvania from rural forested land into suburban developments and urban areas. Considered polyphagous, it is commonly found on cherry (*Prunus spp.*), birch (*Betula spp.*), willow (*Salix spp.*), ash (*Fraxinus spp.*), and many trees of Magnoliaceae, notably the tulip tree species (*Liriodendron spp.*). Its broad host range allows it to be widespread in various habitats, but it is most prevalent along streams and rivers and in wetlands. In Pennsylvania there are two generations per year. The spring generation of adults relies on nectar from cherry and lilac (*Syringa vulgaris*) and second relies largely on milkweed (*Asclepias spp.*) and Joe-pye weeds (*Eutrichium spp.*) and asters (Asteraceae). The eastern tiger swallowtail overwinters in pupal diapause.

In North America *P. glaucus* was thought to be comprised of three subspecies segregated by latitude until the Canadian tiger swallowtail (*P. canadensis*) was elevated to the species level. Early *Papilio* studies found measurable differences in intra-population variation in upper threshold temperature and development rates, but subspecies did not differ significantly in developmental response to temperature (Ritland and Scribner 1985). However, *P. canadensis* is now known to be temperature-limited, with pupal mortality at temperatures of 36°C or higher preventing populations from moving south of the Great Lakes Region. Hybridization of *P. canadensis* and *P. glaucus* results in decreased pupal mortality at high temperatures. (Scribner et al. 2002).



Current Threats

Thriving in a variety of forest types, including edge habitats and suburban and urban developments, the eastern tiger swallowtail has not faced habitat loss with increasing urbanization in the 20th and 21st centuries. Bird and rodent predation is likely a large source of mortality in this species, as indicated by the use of crypsis and mimicry

to prevent predation during the larval stage (Wagner 2005), and that adult females are dimorphic, with a dark-winged morph mimicking the unpalatable pipevine swallowtail (*Battus philenor*) (Brower 1958).

Factors Contributing to Vulnerability

Though the closely related species, the northern tiger swallowtail (*Papilio canadensis*) appears to be susceptible to increasing temperatures, there is little evidence



that increases in temperature will directly increase mortality in the eastern tiger swallowtail.

Temperatures above 37°C result in poor survival (Scribner and Lederhouse 1983). Average summer highs are not expected to exceed 33°C even in the warmest areas of the state, but it is possible that small microclimates in cities or areas exposed to extreme high temperatures will become inhospitable to the eastern tiger swallowtail. In general, however,

high temperatures lead to faster host plant consumption and faster growth rates in this species (Scriber and Lederhouse 1983). That hybridization with *P. glaucus* reduces mortality at high temperatures in *P. canadensis* indicates that there are alleles related to temperature tolerance in *P. glaucus*.

Swallowtails exhibit a behavior called “puddling” where males gather at puddles to take up electrolytes and amino acids, nutritive elements that significantly improve reproduction potential (Lederhouse et al. 1990). Reductions in available, standing water due to increased temperatures and subsequent evaporation could reduce reproduction rates.



Phenology

Encounter time frames for eleven of the species chosen for Climate Change Vulnerability Impact analysis show staggered occurrence. Three species commonly monitored for high-impact defoliation in Pennsylvania forests, the forest tent caterpillar (*Malacosoma disstria*), eastern tent caterpillar (*M. americanum*) and gypsy moth (*Lymantria dispar*), appeared earlier than other species (Figure 11). *Morrisonia confusa* and *M. latex*, closely related species in the family Noctuidae, showed strong overlap in occurrence. It is possible that *Drepana arcuata*, and the *Melanolophia* species, which overwinter as pupae continue to feed later in August and into September, but that collection stopped prior to the completion of their larval phase (Figure 11).

Bird predation showed little effect on the relative abundance of caterpillars over the course of the season in 2011 (Figure 12) or 2012 (Figure 13), but significantly impacted absolute abundance when caterpillar abundance was highest (Figures 12 and 13, see Keating 2013 for statistical analyses). During 2011 black cherry, pin cherry, and red maple show peak caterpillar abundance in mid-July, whereas American beech, the birch species, and sugar maple show peak abundance in mid- to late August. Peak abundances of cherry species appear to have occurred a week earlier in 2012 (Figure 12 and 13), but sampling differences between years may contribute to this difference because sampling was not conducted July 2 – 6 in 2011. Red Maple showed a striking increase in caterpillar abundance with an increase from 2.01 caterpillars per branch in 2011 (Figure 12 and Table 3) to nearly 3.99 caterpillars per branch in 2012 (Figure 13 and Table 4). This peak also occurred a week earlier in 2012 than 2011. During both years the impact of bird exclusion on American beech was somewhat ambiguous, wherein some weeks more caterpillars were recorded from exposed branches than protected branches.

In 2012 caterpillar species consistently emerged earlier than in 2011 (Figure 17), possibly due to above average spring temperatures in March 2012 (Figure 18). This change in emergence did not result in higher abundance of these caterpillar species (Figure 17), but may have changed the timing of peak abundance (Figure 13). Black cherry and pin cherry reached peak caterpillar abundance during the second week in July during 2011 and the first week of July in 2012, but show comparable peak abundance values over the two years (Figure 13). This timing shift in peak abundance does not appear to have reduced predator impacts on pin cherry, where the average protected branch supported 3.6 more caterpillars than an exposed branch in 2011 and 4 more caterpillars 2012 (using Figure 12 and Table 3). On black cherry birds reduced peak abundance by nearly half in 2011 (approximately 3.1 caterpillars per branch), but only by one third in 2012 (approximately 1.9 caterpillars per branch), potentially an effect of the earlier emergence date.

Community composition of temperate forest Lepidoptera shows strong seasonal variation, with some families also showing annual variation. In general species

belonging to the families Amphispbatidae, Erebidae, Geometridae, and Noctuidae encountered in 2011 were again collected in 2012 (Figures 14, 15, and 16), with the exception of *Acrionicta* species, a diverse genus which showed variation between years (Figure 15). Annual variation in the presence or absence of a particular species may be due to differences in collection sites from 2011 to 2012. Collection of Noctuidae species in 2012 showed marked reduction in diversity from the prior year with the saddled Prominent (*Heterocampa guttivita*) comprising the majority of species collected; Saddled Prominent numbers were over twice as high in 2012 as 2011 and this species emerged a week earlier (Figure 15). Gelechiidae showed a similar trend with a reduction from 5 genera recorded in 2011 to 2 genera in 2012. *Eupethicia* species of the family Geometridae were encountered consistently throughout monitoring in 2012, but only from late May until the first week of July in 2011.

The National Phenology Network collects data to monitor species for shifts in phenology in response to long-term climate changes. Citizen scientists can submit data on phenophase, location, and date into the “Nature’s Notebook” feature which currently tracks 44 charismatic insect species. During the course of our experiments we collected 2 species that the National Phenology Network monitors. The first, *Dryocampa rubicunda*, green-striped mapleworm or rosy maple moth, had 8 records from Maine in 2011. We added our records of 2 individuals in 2011, and 18 in 2012 collected from the Allegheny National Forest of Pennsylvania. The second species, *Malacosoma americanum*, or Eastern tent caterpillar, has 3137 records from 2010 to 2013 from 7 states along the Atlantic coast, ME, NH, NY, KY, MD, VA, NC, but none from PA until we added our 7 caterpillars documented in 2011.

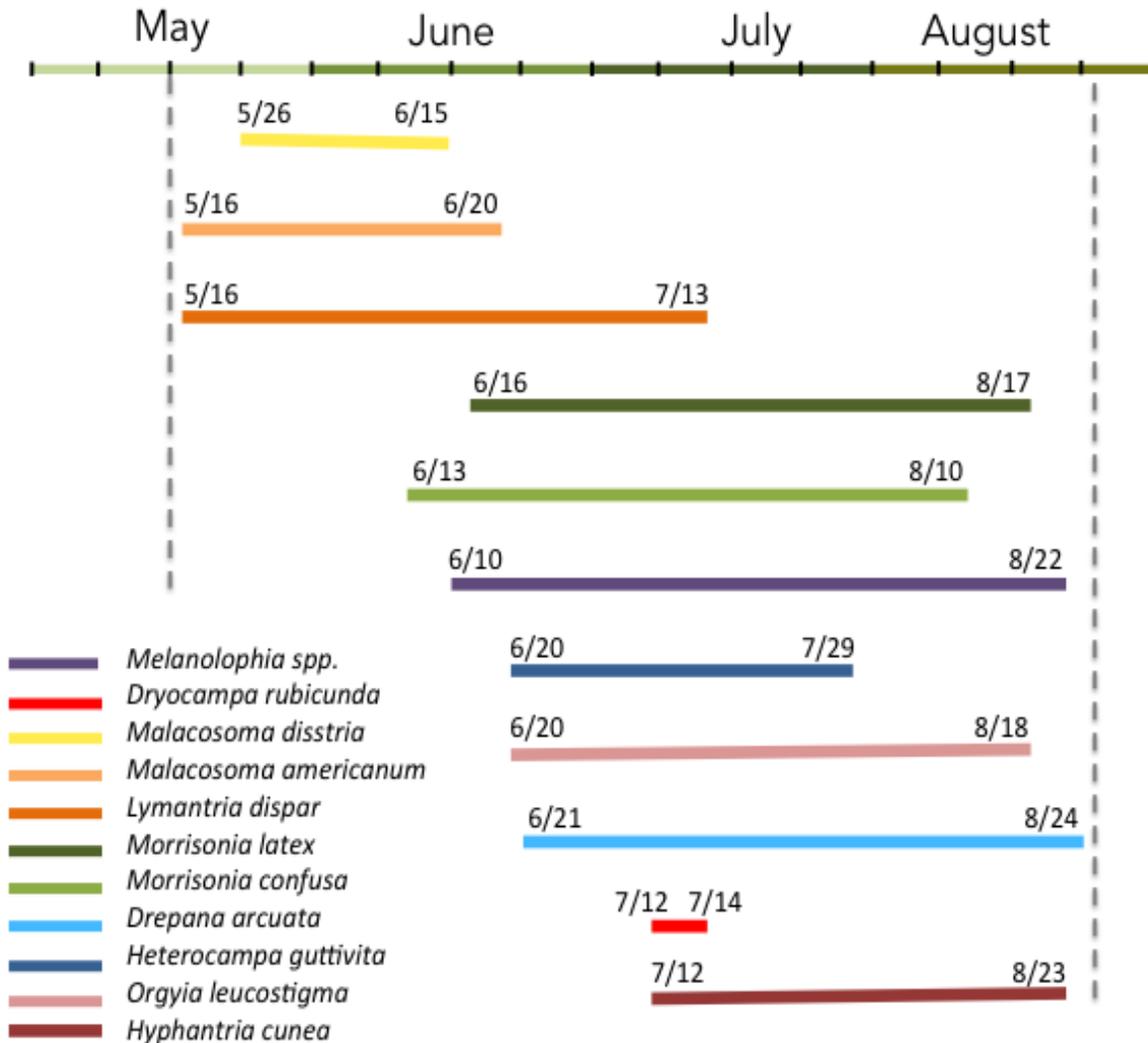


Figure 11. Phenology of eleven Lepidoptera species of climate change vulnerability interest collected during the summer of 2011 in the Allegheny National Forest. Dates of first and last collection are indicated for each species' colored bar; grey dashed lines indicate collection period (May 16 – August 25).



Figure 12. Abundance and phenology of larval Lepidoptera and Symphyta on six species of temperate forest trees during 2011. Green lines indicate branches exposed to bird predation. Black dashed lines indicate branches protected from bird predation. Establishment of treatment occurred during first three collection weeks; for these 3 weeks, differences do not indicate treatment effects.

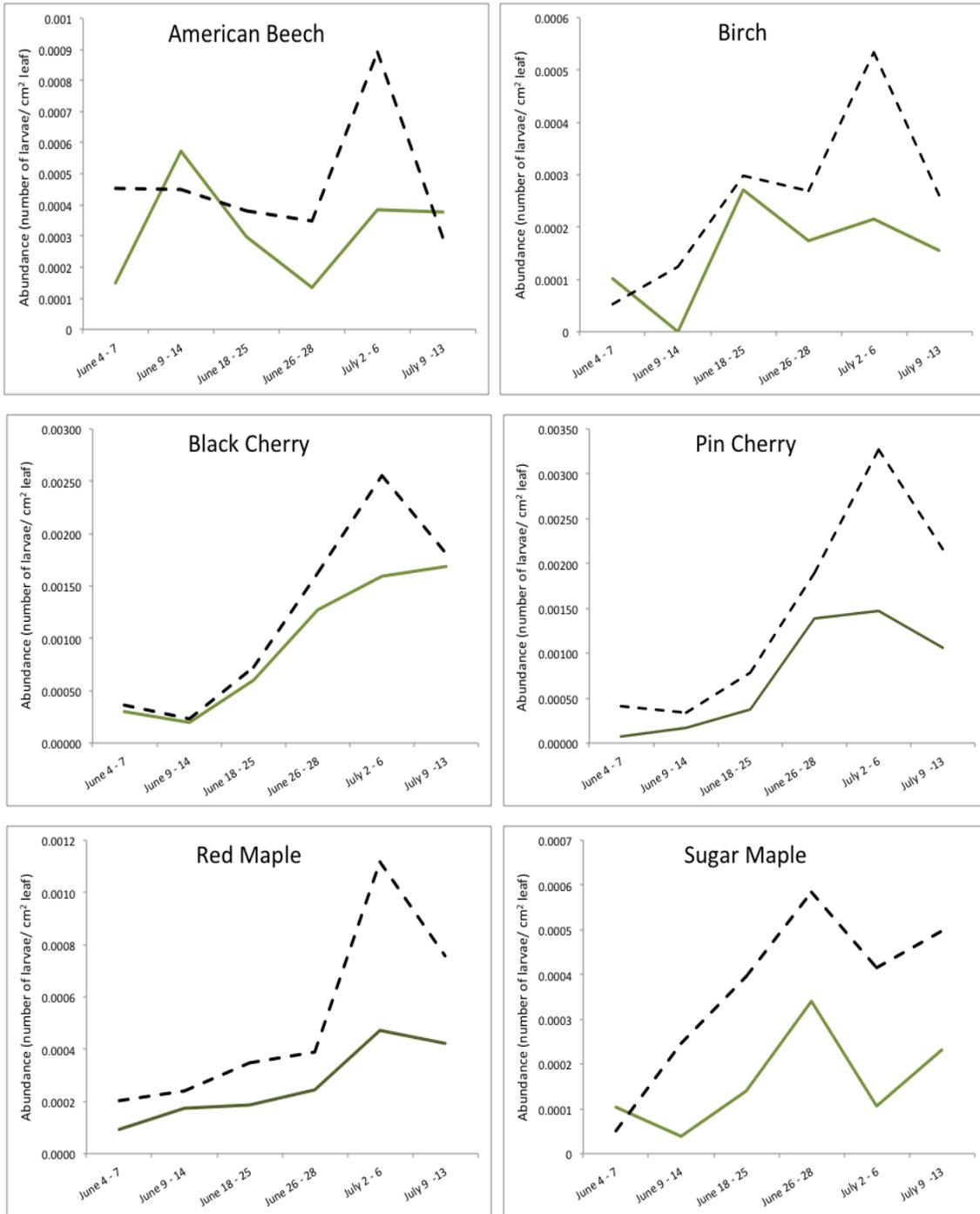


Figure 13. Abundance and phenology of larval Lepidoptera and Symphyta on six species of temperate forest trees during 2012. Green lines indicate branches exposed to bird predation. Black dashed lines indicate branches protected from bird predation. Establishment of treatment occurred during the last three weeks of May and are not included here.

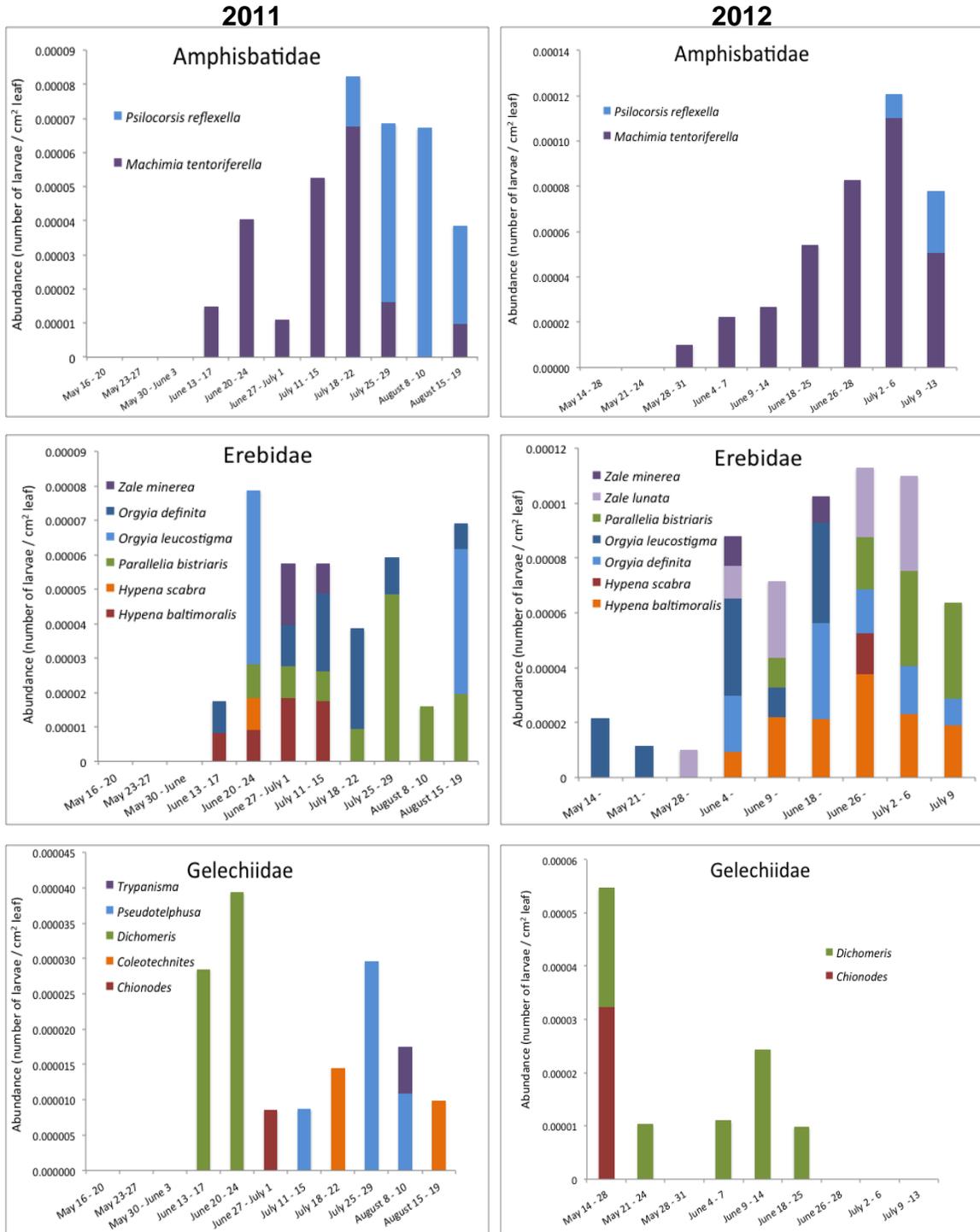


Figure 14. Abundance and phenology of commonly encountered Lepidopteran taxa belonging to Amphisbatidae, Erebidae, and Gelechiidae families during 2011 (left) and 2012 (right) field seasons in the Allegheny National Forest of Northwestern Pennsylvania. Abundance values for branches where caterpillars were found and should be used for relative comparisons.

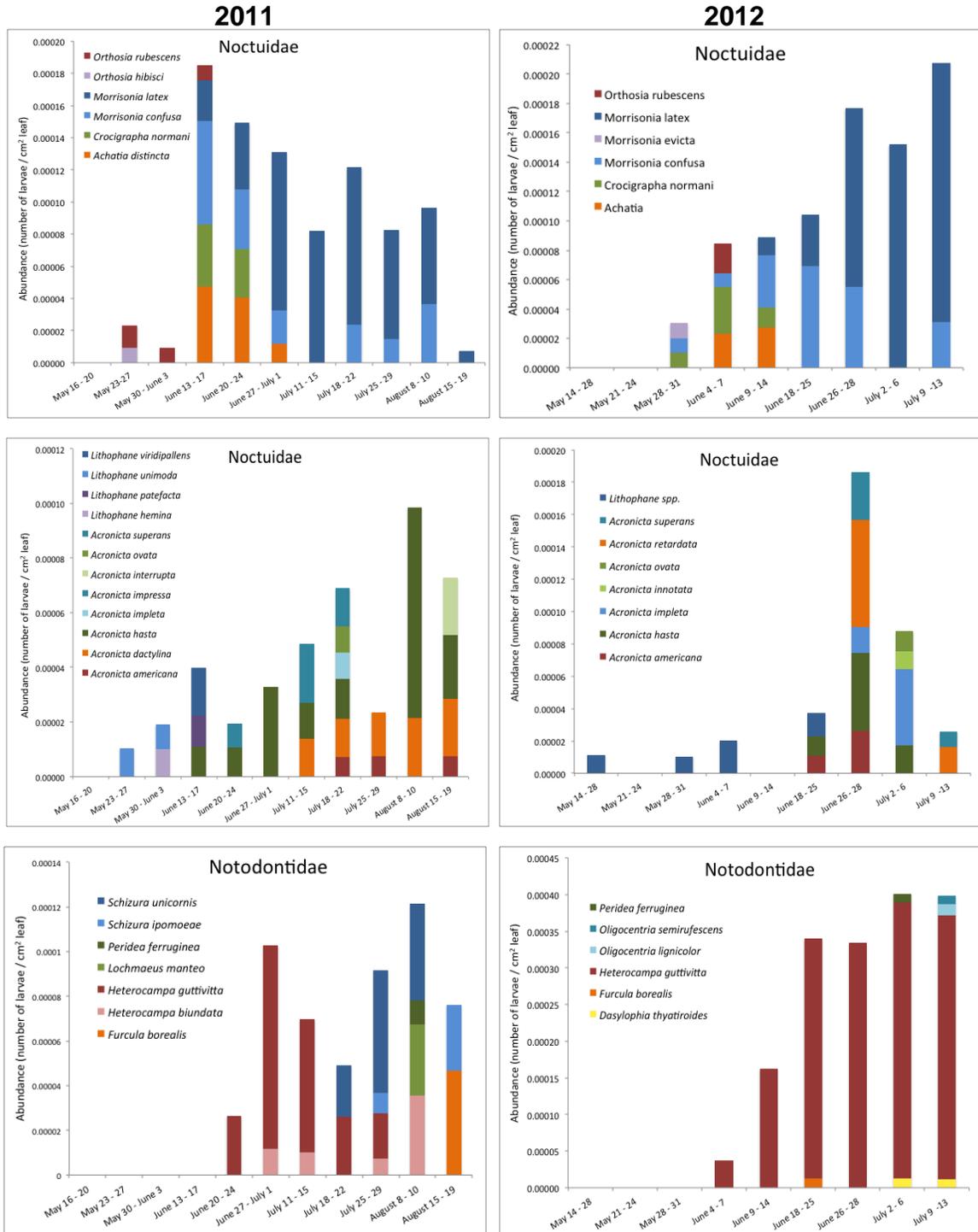


Figure 15. Abundance and phenology of commonly encountered Lepidopteran taxa belonging to Noctuidae and Notodontidae during 2011 (left) and 2012 (right) field seasons in the Allegheny National Forest of Northwestern Pennsylvania. Abundance values for branches where caterpillars were found and should be used for relative

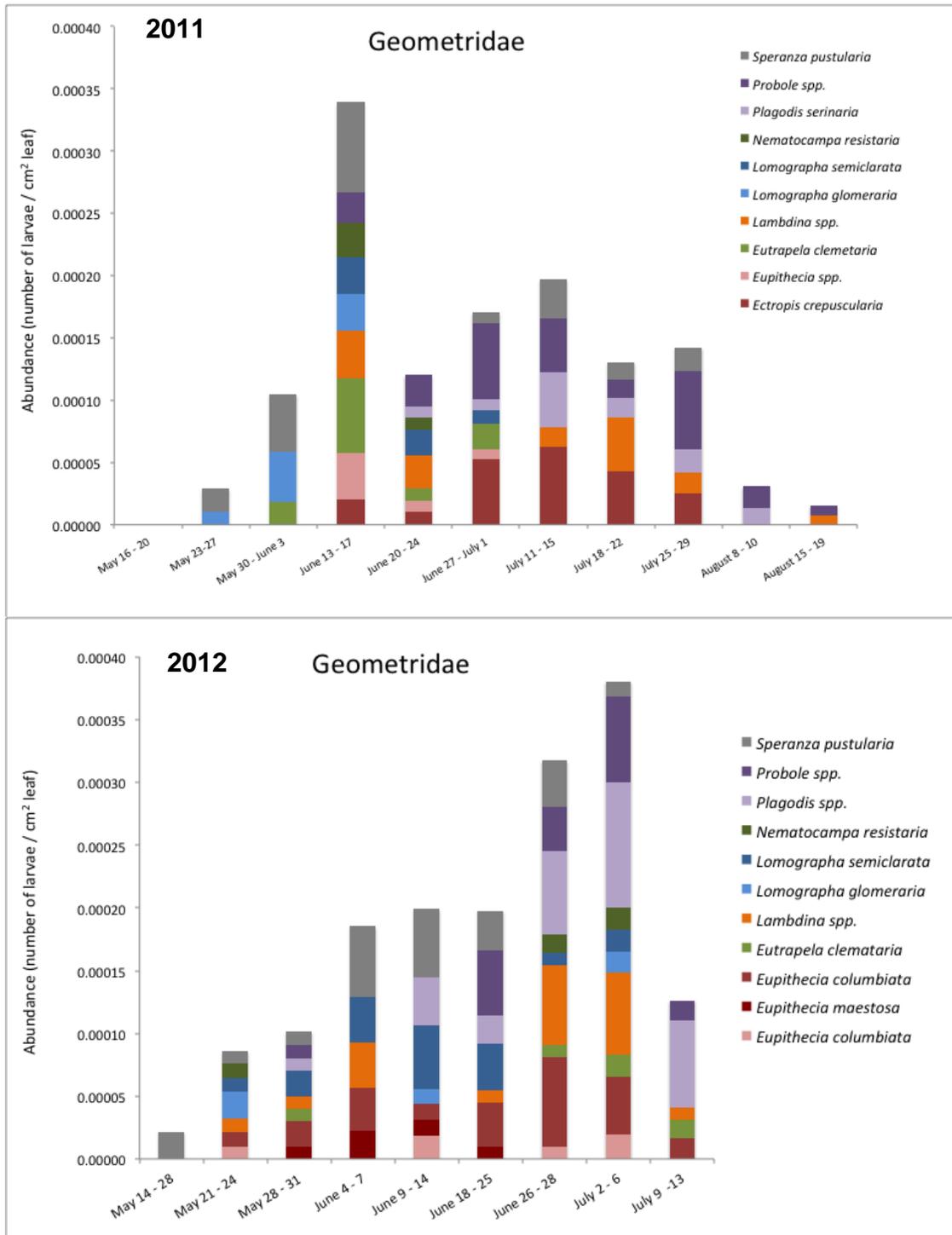


Figure 16. Abundance and phenology of commonly encountered Lepidopteran taxa belonging to the family Geometridae during 2011 (top) and 2012 (bottom) field seasons in the Allegheny National Forest of Northwestern Pennsylvania. Abundance values for branches where caterpillars were found and should be used for relative comparisons.

Table 3. Mean leaf area (cm²) per branch in for six tree species over 11 weeks of sampling in 2011.

TREE SPECIES	May 16 - 20	May 23 - 27	May 30 - June 3	June 13 - 17	June 20 - 24	June 27 - July 1	July 11 - 15	July 18 - 22	July 25 - 29	August 11 - 18	August 20 - 25
<i>Fagus grandifolia</i>	3818	4753	4209	3642	4301	4018	4100	4346	3842	3945	4292
<i>Betula spp.</i>	4445	4570	4591	4942	4710	4860	4949	4534	4651	3810	4376
<i>Prunus serotina</i>	3884	4008	4182	3825	3928	3794	3161	2863	2593	1618	1783
<i>Prunus pensylvanica</i>	4464	4741	4544	4433	4425	3561	2992	2980	2019	1953	1990
<i>Acer rubrum</i>	4498	4468	4473	5072	4621	4508	4792	4380	4479	4502	4245
<i>Acer saccharum</i>	6685	5983	5966	7567	5879	5792	6643	5739	5563	6308	5502
Mean over all species	4632	4754	4661	4913	4644	4422	4440	4140	3858	3689	3698

Table 4. Mean leaf area (cm²) per branch in for six tree species over 9 weeks of sampling in 2012.

TREE SPECIES	May 14 - 28	May 21 - 24	May 28 - 31	June 4 - 7	June 9 - 14	June 18 - 25	June 26 - 28	July 2 - 6	July 9 - 13
<i>Fagus grandifolia</i>	3841	3704	4307	3787	3108	4172	3676	3315	3638
<i>Betula spp.</i>	3933	3518	4049	4444	3433	4252	4275	3809	4236
<i>Prunus serotina</i>	3182	3665	4095	3458	2987	3421	2595	2413	2827
<i>Prunus pensylvanica</i>	3716	4013	4213	3692	3531	3369	2802	2398	2508
<i>Acer rubrum</i>	3856	4194	3958	4407	3811	3947	4423	3590	4366
<i>Acer saccharum</i>	3841	2657	2884	3262	2280	2850	3160	2174	2599
Mean over all species	3728	3625	3918	3842	3192	3668	3489	2950	3362

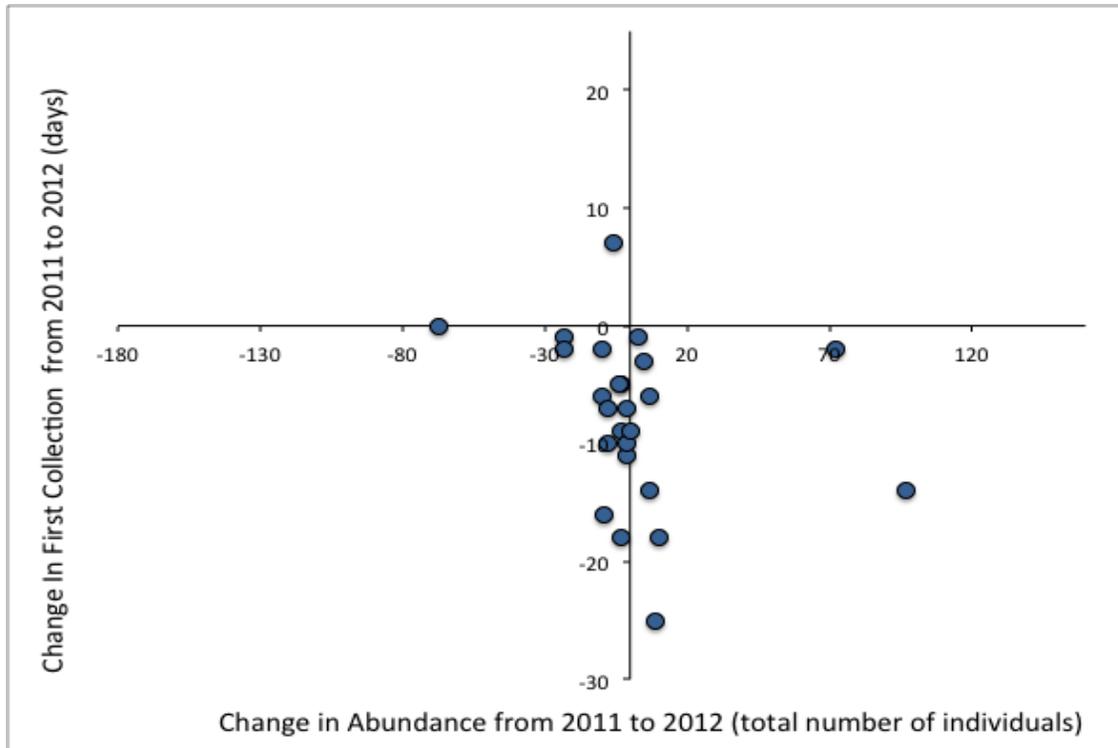


Figure 17. Change in total number of individuals collected (x-axis) by change in date of first date of collection (y-axis) for 26 frequently encountered Lepidoptera species from 2011 to 2012. The distribution of change in abundance is not significantly different than zero (One sample t-test, $p > 0.05$). Change in emergence time is significantly less than zero (One sample t-test, $p < 0.0001$).

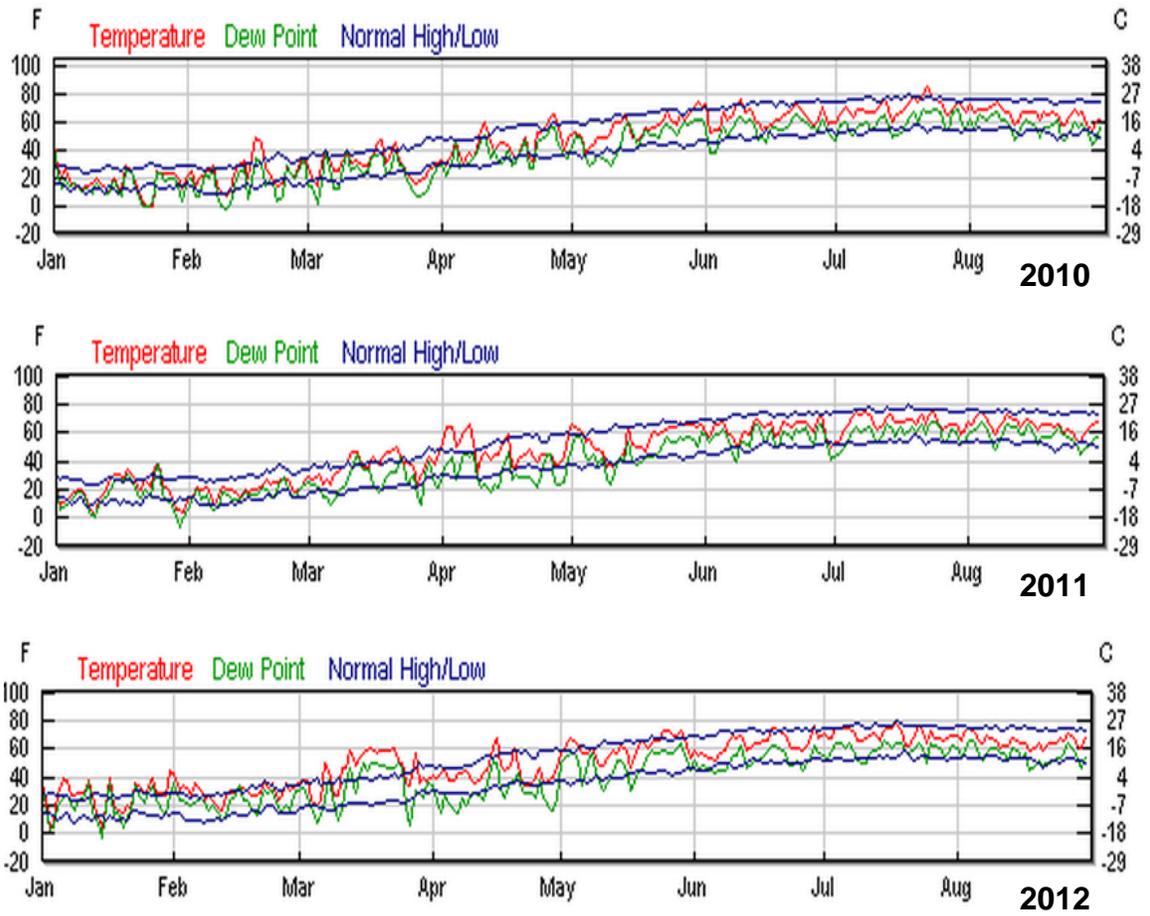


Figure 18. Mean daily temperature (red) and dew point (green) January – August during 2010, 2011, and 2012 for the Allegheny National Forest. Data recorded at Bradford Regional Airport, Bradford, PA. Graphs from www.wunderground.com.

DISCUSSION

Physiological Vulnerability

Unless indicated otherwise by experimental study or natural observation, the direct impact of increases in Pennsylvania's temperature over the next forty years is expected to have little impact or marginally benefit the insects included in this assessment. These species, whose activity is often temperature-limited, are expected to show decreased vulnerability due to rising temperatures. Though a number of Lepidoptera require an overwintering phase and exposure to winter temperatures for development, predicted changes in Pennsylvania's climate are not projected to increase winter temperatures enough to eliminate exposure.

Moisture availability is extremely important for temperate forest Lepidoptera, especially in the larval phase when caterpillars are at a high risk of desiccation. While humidity will influence water loss, most caterpillars gain water from ingested plant material and much of the influence of available moisture will impact caterpillars indirectly through their host plants. Drought may limit the amount of water in plant cells, but also the accessibility of that water as plants thicken cell walls or the cuticle layer to protect from water loss. Given that summer precipitation is not expected to change in Pennsylvania, but that storms are expected to be less frequent and more localized, available moisture may vary greatly across the landscape and throughout the season. While these species' exposure to moisture extremes is not expected to change over their entire ranges in Pennsylvania, specific populations of temperate forest Lepidoptera may decline or be extirpated in areas with flooding or extended droughts.

Role of Host Plants

Host plant specificity emerges as a central element in this assessment of climate change vulnerability in temperate forest Lepidoptera. Because most species assessed here are polyphagous (accepting hosts from a variety of plant families) or oligophagous (restricted to one plant family or genera, but not one host species), changes in host plant distributions are not expected to severely limit potential hosts. It is pertinent to note that polyphagy and oligophagy may exist at three special scales: the individual, the population, or the species. On the individual scale each caterpillar consumes a number of different plant species over the course of their lives. Alternately, at the population scale each individual feeds on only one kind of food plant, but variation exists among individuals in their food plants. At the largest scale each population utilizes a single host, but variation in host plant exists among populations (Singer 2008). Most generalist Lepidoptera are characterized as such at the population scale, and few comparisons of populations over the range of a species are available.

In temperate forest ecosystems tree species are long-lived and likely represent a reliable, predictable food source for phytophagous larvae (Price et al. 1980). But, as Goldstein (2010) notes, “simply because a particular food plant species meets an herbivorous organism’s nutritional requirements and the organism is physiologically capable of growth and development on that food is not an indication that it is an actual, realized host in nature.” It is possible that rapid changes in host plant distribution or forest community composition could reduce temperate forest Lepidoptera diversity if polyphagy exists at the largest scale and localized populations are adapted to specific hosts, as appears to be the case for the imperial moth *Eacles imperialis* (Goldstein 2010). Again, experimental evidence and field surveys are needed to adequately assess vulnerability and risk.

CCVI Assessment Tool

The Climate Change Vulnerability Index is a user-friendly, highly accessible means of assessing species for climate change risk. However, for insect assessments, especially those addressing non-pest, non-threatened species, the tool may lack some specificity required to precisely expose risks. Findings here are likely attributed to our ranking species as having a lack of dispersal barriers, broad host ranges, and ability to persist in a wide variety of temperature regimes (being ectotherms and being historically exposed to variations in temperature). However, insect growth and development often requires specific temperature thresholds or a minimum amount of time exposed to certain temperatures during different stages of development. Climate-induced changes in physiology play a role in digestion, mating, development, and dispersal, but such changes can only be assessed under the broader heading of Physiological Thermal Niche. The assessment is even more complex because holometabolous insects have two distinct life stages (often with fairly distinct physiological requirements) linked by metamorphosis, which may require specific environmental conditions. Generally we assessed species based on the most sensitive aspects of the entire life cycle.

The CCVI tool does not address changes in disease exposure, infection rate, and mortality due to climate change. Bacterial and viral pathogens are known to have measurable impacts on growth, fecundity, and mortality in caterpillars (Anderson and May 1980, Hoover et al. 1998, Evenden et al. 2006), but the role of disease in population regulation may be pronounced primarily when it enhances other sources of mortality (Barryman 1996). A decrease in rain events or cloud cover may decrease viral particles in the environment (since they are susceptible to UV light damage), while increases in season length may increase exposure to pathogens. Viruses also vary in pathology based on temperature, often enacting the most damage at temperatures just below or above those considered optimal for cell growth (Hink and Strauss 1976). The direct impacts of

climate on disease biology should be integrated into assessing how changes in climate may impact infection and mortality.

Finally, changes in host plant physiology due to climate change may have measurable impacts on caterpillars. Host plant quality impacts development time, fecundity, and disease susceptibility (Goulsen and Corey 1995, Hoover et al. 1998). While species assessed here all have a fairly broad host range, those hosts vary in quality, an aspect that we were not able to rate using the CCVI tool. There are, of course, two principal aspects to better assessment of these species: a more precise tool and more specific experimental or field-based evidence; in order to use a more finely tuned tool, we will need data on distributions, movement, disease, and physiology of non-pest, non-threatened insects.

Vulnerability Assessment Research

Areas of vulnerability assessment that are largely lacking for all species assessed here include dispersal capabilities, genetic variation, adult feeding requirements, and modeled responses to climate change. These areas are deficient largely because much of our knowledge of these species comes from community-level surveys of occurrence, not accounts of the behavior or physiology of particular species'. Dispersal in most species is rated as having a neutral response to climate change because aside from experimental or descriptive studies of dispersal in a few pest species, the potential or realized dispersal ability is unknown for many temperate forest species. Aside from *Eacles imperialis* (Janzen et al. 2005), genetic differences or divergence among populations is unknown. While adult feeding is generally conserved at the family level (ie: Lymatriidae and Notodontidae are non-feeding as adult), little is known about nectar sources or the relationship between adult feeding and reproductive capacity in temperate forest moths. While adult feeding may not impact reproduction capacity, limitations in adult feeding could readily impact flight distance and dispersal capability.

Since host plants emerge as the central element through which climate change may impact temperate forest Lepidoptera, surveys to understand host plant use throughout the state would greatly benefit risk assessment. Genetic analyses would bolster our understanding of host plant use, but a more precise occurrence map including distributions of species of interest across host plants and regions of the state would greatly inform assessment of climate change risk. This will need to be coupled with finer scale climate change prediction maps to understand how regional populations may be impacted by specific changes in local climates.

Phenology

During the two years of phenology monitoring, caterpillar communities showed a great deal of overlap and similar patterns of annual variation, with above average spring temperatures potentially contributing to an observed shift in occurrence to a week earlier in 2012. Our results also provide support for the view that bird predators are exerting the greatest absolute effect when prey species are most abundant (Holmes et al. 1979). The timing of bird predation, likely a combination of bird phenology and direct monitoring of prey populations, appears crucial to Lepidoptera population regulation in these instances. For example, during the second week of August in the presence of birds approximately 0.79 caterpillars were collected per branch from American beech (using Figure 12 and Table 3); when birds were excluded this jumped to 2.47 caterpillars per branch. Similarly, during that same week sugar maple showed a difference of over 4.5 caterpillars per branch between control and bird-excluded trees. The findings here highlight both the potential importance of bird predation in Lepidoptera population regulation and the role of those tree species as a source of food during the post-fledging period.

Rearing and fledging, with an increase in population number and individual caloric needs, may be timed to coincide with peaks in caterpillar abundance (Jones et al. 2003), therefore even slight shifts in caterpillar phenology may significantly change food availability to birds (Visser et al. 2006). Our data show they may also contribute to population increases in Lepidoptera due to reduced predation; changes in growth, reproduction, or emergence due to climate change may also have an indirect impacts on population growth via reduced predation pressure. While this kind of data provides a good basis for analysis of the tritrophic impacts of phenological shifts, because sampling stopped in July during 2012 it is not possible to conclusively test changes in seasonal peak abundance values or consequences of bird predation.

Differences in sampling across years and a slightly shorter sampling season in 2012 prohibit some comparisons, but the data presented here provide thorough snapshot of temperate forest Lepidoptera community composition and variation over the course of the season. Phenological data provided in this report are intended to contribute the body of literature monitoring phenology of temperate forests (Sigmon and Lill 2013) and to tests of published theory and models (van Asch and Visser 2007). Data have been deposited in the USA National Phenology Network database (available from <https://www.usanpn.org/data>).

Conclusions

Our results indicate that temperate forest Lepidoptera are fairly robust to predicted climate change in Pennsylvania and may even benefit from milder winters and longer summers. That none of the species assessed in this analysis are projected to show

increased vulnerability due to climate change by mid-century is not surprising given their widespread distributions and that most are recorded from numerous host plants. Changes in host plant distributions, especially changes that take decades, may not severely impact species that are able to switch hosts from generation to generation based on availability. These findings are contrary to the assumed impact of habitat modification and climate on many butterfly species, species that often rely on herbaceous vegetation (potentially more ephemeral than trees) and are oft-cited as bioindicators. Though not species immediately threatened by human modifications to the landscape, pollution, or climate change, these are species maintaining the trophic balance in temperate forests; caterpillars and sawflies are key links making the biomass of temperate forest trees available to neotropical songbirds. Over half of the species assessed here are predicted to increase in number (Table 2), potentially reaching outbreak levels and changing host plant availability for other insects. On the other hand, rapid population increases, even those below an outbreak threshold, may mean a rise in available food for breeding migratory birds. But caution is necessary; while our findings indicate the stability or even release of many of these species, these analyses are based on very little information about historic distributions and host plant use, and even less on experimental evidence for direct impacts of climate change.

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APPENDIX A. Climate change vulnerability rankings for 15 species of temperate forest Lepidoptera assessed in this report.

Scientific Name	Common Name	Range Rel.	Sea level	Natl barriers	Anth barriers	CC mitigation	Dispersal/Movement	historical thermal niche	physio. thermal niche	historical hydro. niche	physio. hydro. niche	Disturbance	Ice/snow	Phys habitat	Other spp for hab	Diet	Pollinators	Other spp disp	Other spp interaction	Genetic var	Gen bottleneck	Phenol response	Doc response	Modeled change	Modeled overlap	Protected Areas
<i>Automeris io</i>	Io moth	Center	N	N	N	SD	N	N	SI-N	N	N	N	N	N	N	SD	N/A	U	U	SI-N	U	SD	U	U	U	U
<i>Choristoneura rosaceana</i>	Oblique banded leafroller	Center	N	N	N	N	SD	N	SI-N-SD	N	N-SD	N	N	N	N	N	N/A	U	U	U	U	SI-N	U	U	U	U
<i>Drepana arcuata</i>	Masked birch caterpillar	Center	N	N	N	N-SD	N	N	SD	N	N	N	N	N	N	SI-N	N/A	U	U	U	U	N-SD	U	U	U	U
<i>Dryocampa rubicunda</i>	Green-striped mapleworm	Center	N	N	N	SD	SD	N	SD	N	N	N-SD	N	N	N	SD	N/A	U	U	U	U	N-SD	U	U	U	U
<i>Eacles imperialis</i>	Imperial moth	Center	N	N	N	SI	SD	N	SD	N	N	N	N	N	N	N	N/A	U	U	SI-N	U	SD	U	U	U	U
<i>Heterocampa guttivitta</i>	Saddled prominent	Center	N	N	N	N	N	N	SD	N	N	SI-N	N	N	N	N-SD	N/A	U	U	U	U	SI-N-SD	U	U	U	U
<i>Hyphantria cunea</i>	Fall webworm	Center	N	N	N	SD	N	N	N	N	N	N	N	N	N	SD	N/A	U	U	U	U	N-SD	SD	U	U	U
<i>Lymantria dispar</i>	Gypsy moth	Center	N	N	N	SD	N	N	SD	N	N	N-SD	N	N	N	N	N/A	U	U	U	U	N-SD	U	U	U	U
<i>Malacosoma americanum</i>	Eastern tent caterpillar	Center	N	N	N	N	SD	N	SD	N	N	N	SI-N	N	SI-N	SI	N/A	U	U	U	U	SD	U	U	U	U
<i>Malacosoma disstra</i>	Forest tent caterpillar	Center	N	N	N	SD	N	N	SD	N	N	N	N	N	SI-N	SI	N/A	U	U	U	U	SD	U	U	U	U
<i>Melanolophia spp.</i>	Melanolophia	Center	N	N	N	SD	N	N	SD	N	N	N	N	N	N	SD	N/A	U	U	U	U	SD	U	U	U	U
<i>Morrisonia confusa</i>	Confused woodgrain	Center	N	N	N	N	N	N	N-SD	N	N	N	N	N	N	N	N/A	U	U	U	U	SI-N-SD	U	U	U	U
<i>Morrisonia latex</i>	Fluid arches	Center	N	N	N	N	N	N	N-SD	N	N	N	N	N	N	N	N/A	U	U	U	U	N-SD	U	U	U	U
<i>Orgyia leucostigma</i>	Whitemarked tussock moth	Center	N	N	N	N-SD	N-SD	N	SD	N	N	N	N	N	N	N	N/A	U	U	U	U	N-SD	U	U	U	U
<i>Papilio glaucus</i>	Eastern tiger swallowtail	Northern	N	N	N	N	N	N	SD	N	SI-N	N	N	N	N	N	N/A	U	U	SD	U	SD	U	U	U	U

GI: Greatly increase vulnerability, Inc: Increase vulnerability, SI: Somewhat increase vulnerability, N: Neutral, SD: Somewhat decrease vulnerability, Dec: Decrease vulnerability, U: Unknown