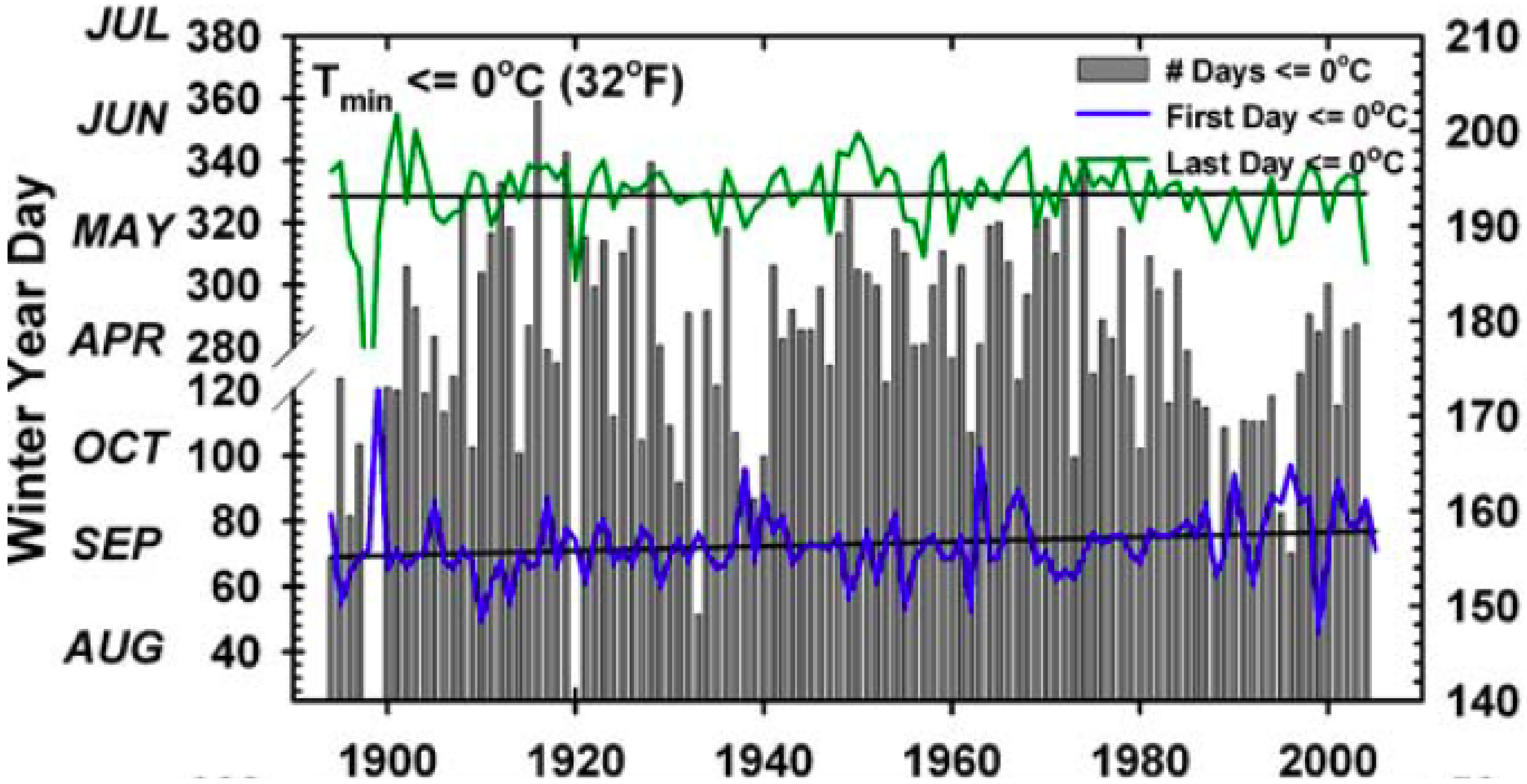
Section 4: Phenology

Learning outcomes

- understand what phenology is and what mechanisms are involved
- give examples of how climate change has affected phenology in species
- explain how changes in phenology affect species interactions

Changes in climate that affect phenology

Western Montana

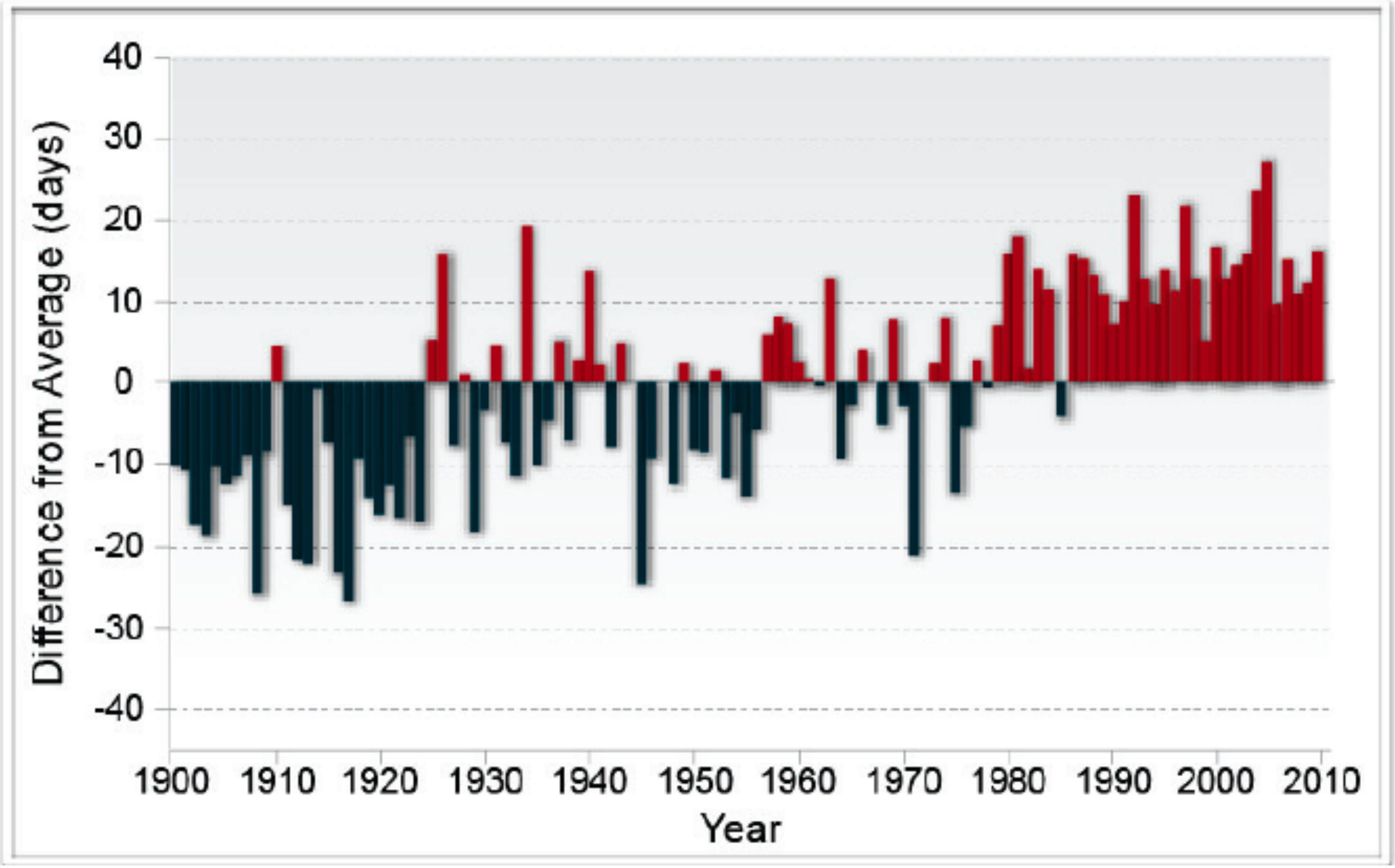


No change in first frost-free day

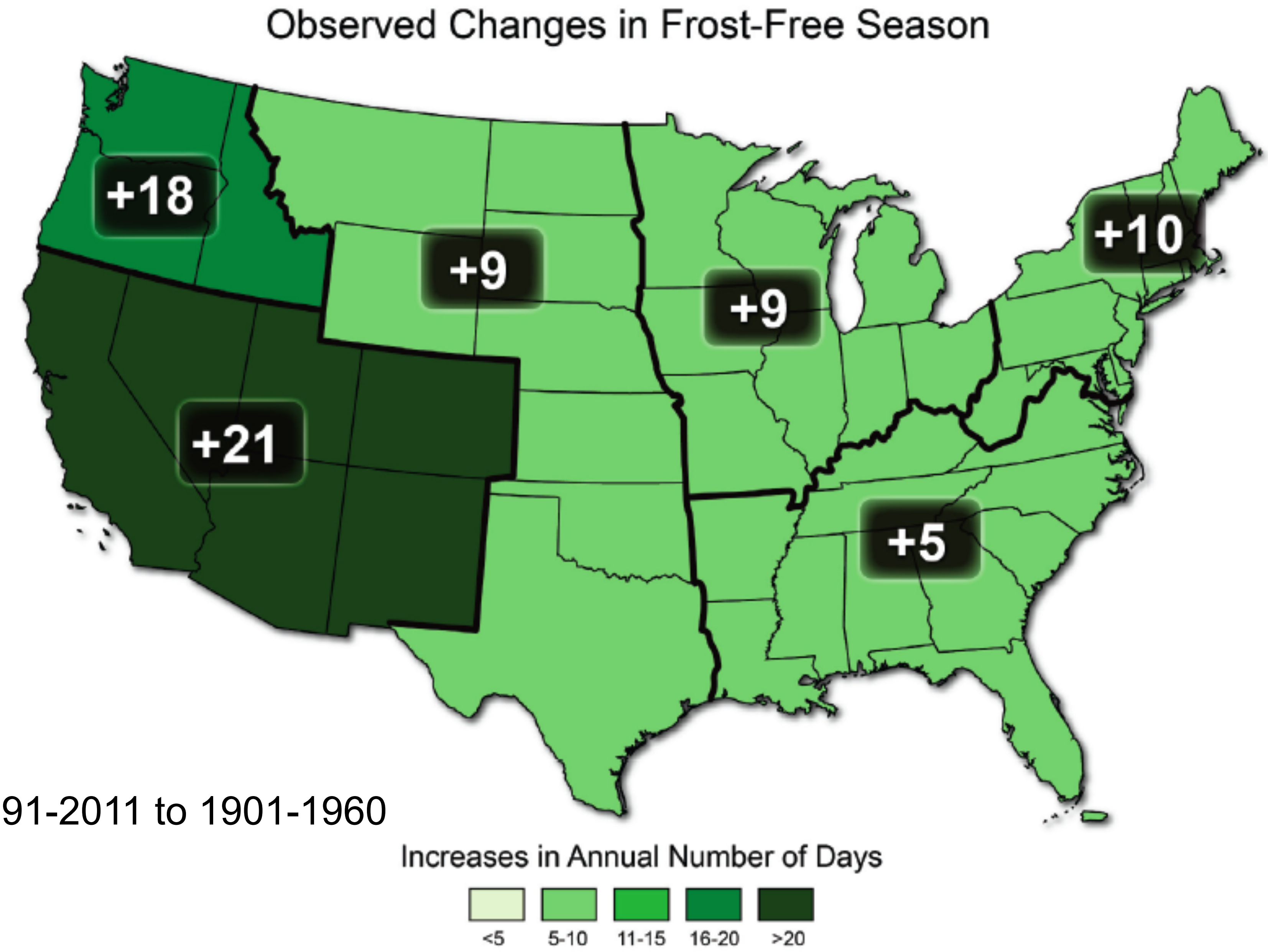
Delay in last frost-free day

Pederson et al. 2010

Southwest Frost-free Season Lengthens



National Climate Assessment Draft Report, 2013



1991-2011 to 1901-1960

National Climate Assessment Draft Report, 2013

Changes in climate that affect phenology

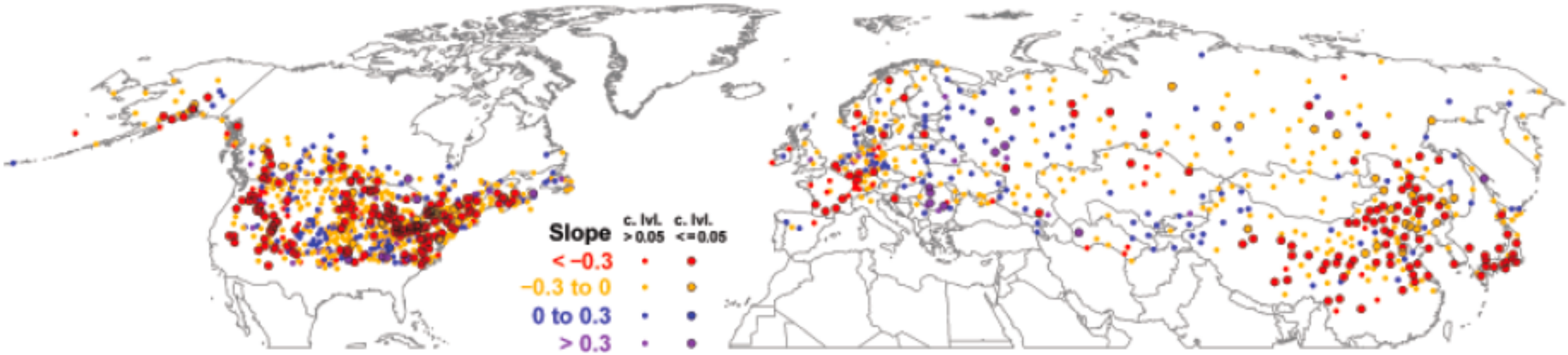


Fig. 3 Last spring −2.2 °C freeze date 1961–2000 trend by station. Details as in Fig. 1.

Last spring freeze date trend

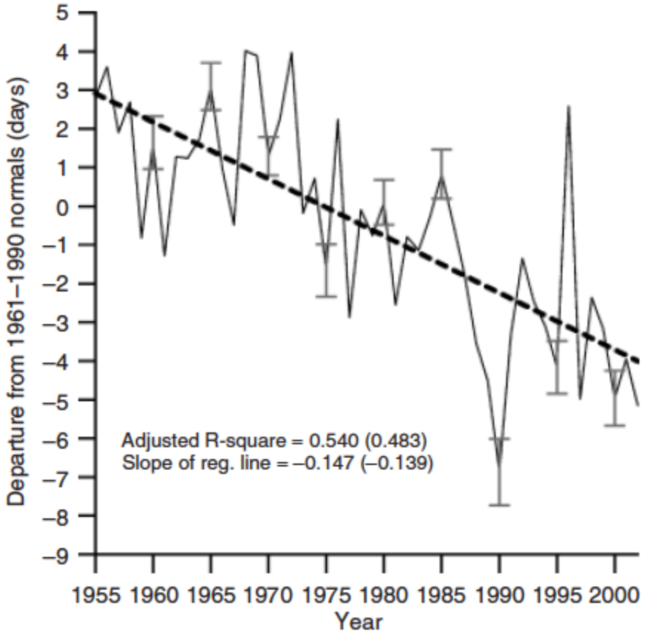


Fig. 4 Last spring −2.2 °C freeze date departures by year across the Northern Hemisphere, 1955–2002. Details as in Fig. 2.

Schwartz et al., Global Change Biology, 2006

Changes in climate that affect phenology

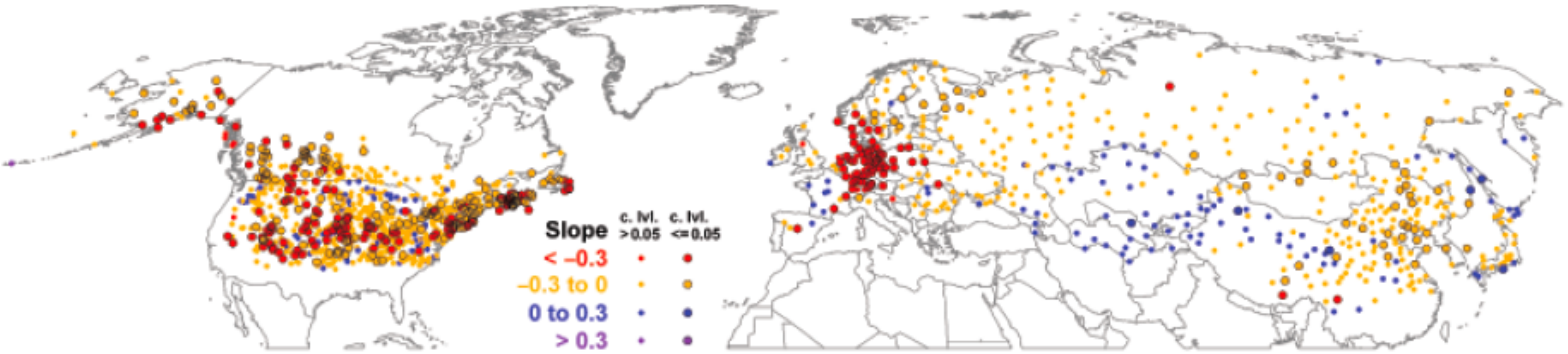


Fig. 1 Spring indices (SI) first leaf date 1961–2000 trend by station. Trend values are i
Stations with trends significant at the 0.05 level or better are shown with larger symbols

Modeled first leaf date trend

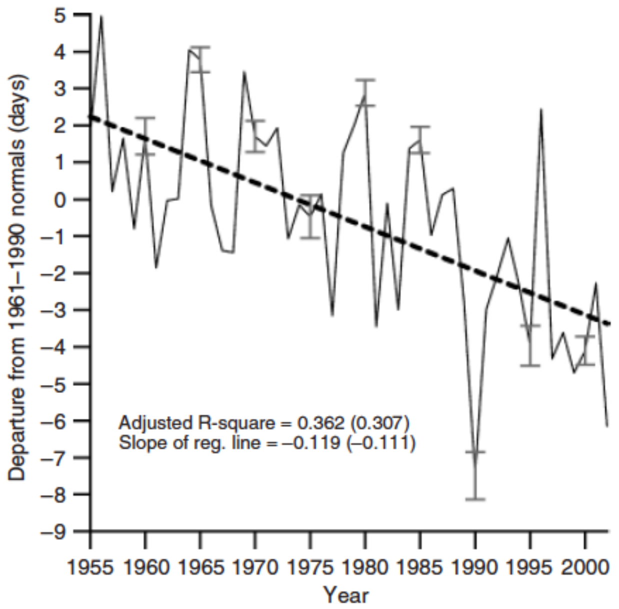
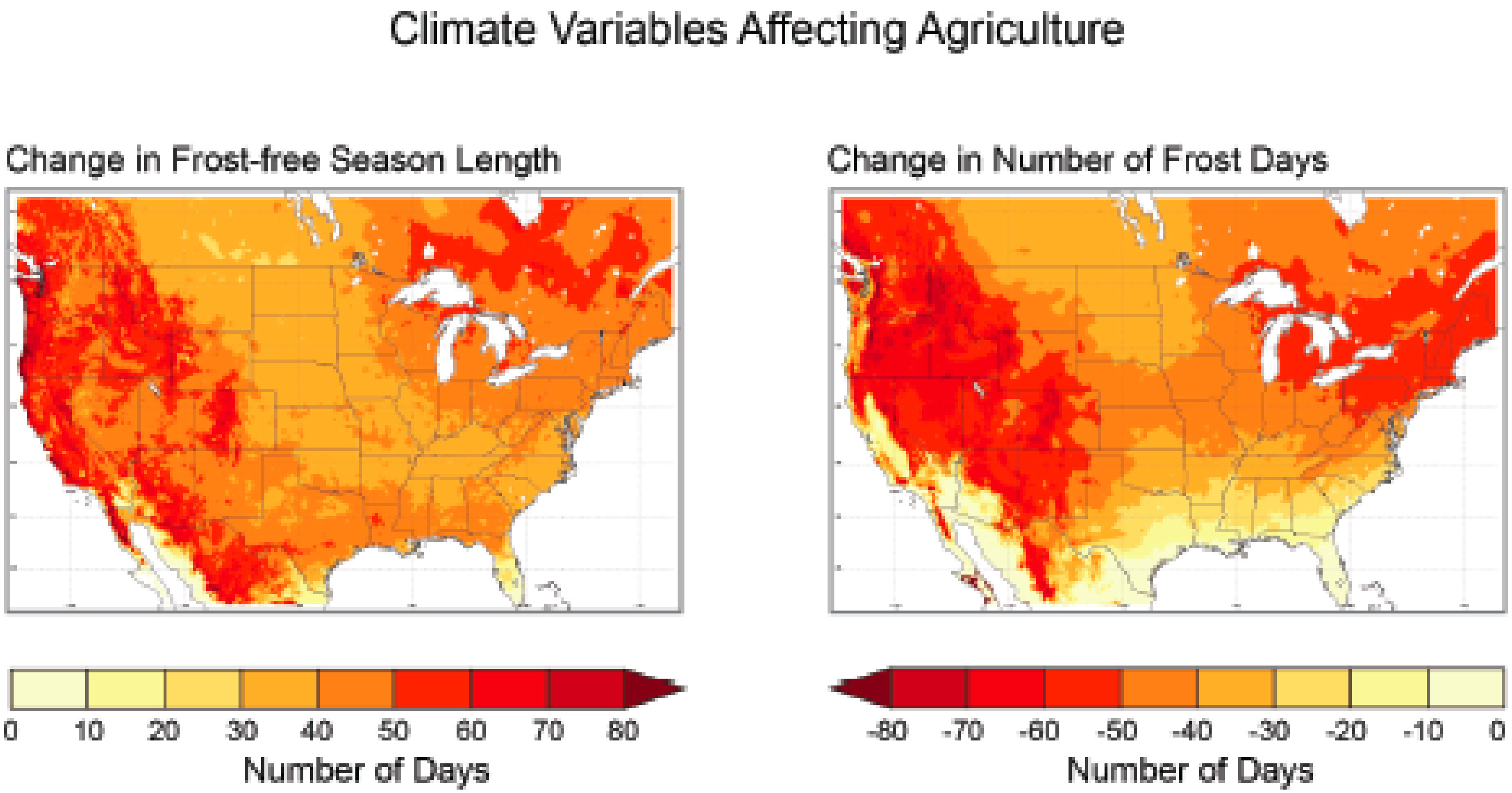


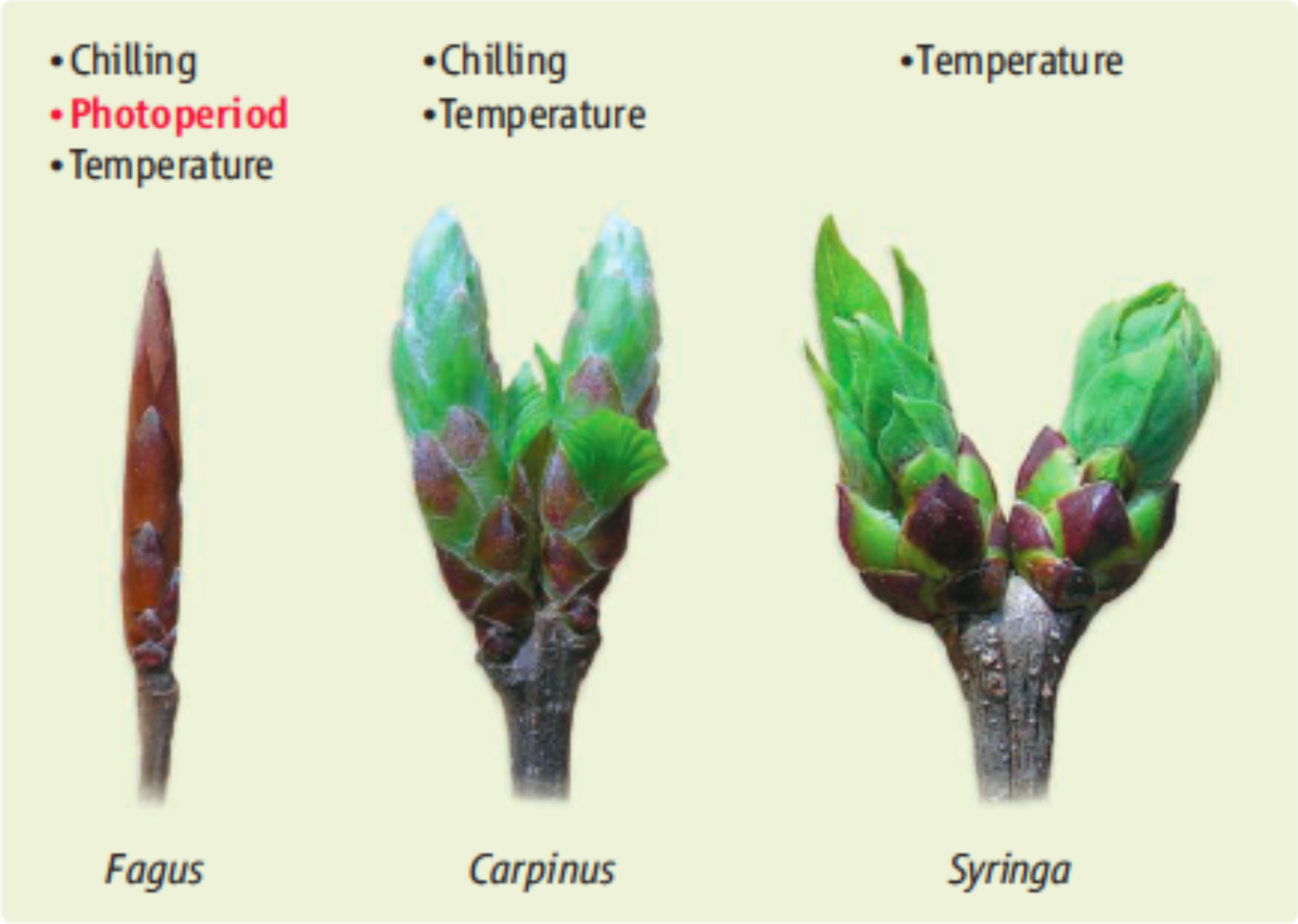
Fig. 2 Spring indices (SI) first leaf date departures by year across the Northern Hemisphere, 1955–2002. Standard error values (± 1) are shown by symbols at 5 year intervals. Linear regression trend shown with a heavy black dashed line. Statistics for the regression line as shown, with values in parentheses calculated after equinox date adjustment (Sagarin, 2001).

Schwartz et al., Global Change Biology, 2006

Projected changes in 2100 under A2 scenario



National Climate Assessment Draft Report, 2013



Not just temperature. Spring development in many ornamental plants from warm regions, such as lilac (*Syringa*), is primarily controlled by temperature, whereas early successional species native to temperate latitudes, such as hornbeam (*Carpinus*), only become temperature-sensitive once their chilling demand has been fulfilled. Late successional taxa, such as beech (*Fagus*), are photoperiod controlled, with temperature only exerting a limited modulating effect once the critical day length has passed. This mechanism prevents such taxa from sprouting at the "wrong" time.

Körner and Basler, Science, 2010

Plant development

Common name	Latin name	Number of growing degree days baseline 10 °C
Witch-hazel	*Hamamelis* spp.	begins flowering at <1 GDD
Red maple	*Acer rubrum*	begins flowering at 1-27 GDD
Forsythia	*Forsythia* spp.	begin flowering at 1-27 GDD
Sugar maple	*Acer saccharum*	begin flowering at 1-27 GDD
Norway maple	*Acer platanoides*	begins flowering at 30-50 GDD
White ash	*Fraxinus americana*	begins flowering at 30-50 GDD
Crabapple	*Malus* spp.	begins flowering at 50-80 GDD
Common Broom	*Cytisus scoparius*	begins flowering at 50-80 GDD
Horsechestnut	*Aesculus hippocastanum*	begin flowering at 80-110 GDD
Common lilac	*Syringa vulgaris*	begin flowering at 80-110 GDD
Beach plum	*Prunus maritima*	full bloom at 80-110 GDD
Black locust	*Robinia pseudoacacia*	begins flowering at 140-160 GDD
Catalpa	*Catalpa speciosa*	begins flowering at 250-330 GDD
Privet	*Ligustrum* spp.	begins flowering at 330-400 GDD
Elderberry	*Sambucus canadensis*	begins flowering at 330-400 GDD
Purple loosestrife	*Lythrum salicaria*	begins flowering at 400-450 GDD
Sumac	*Rhus typhina*	begins flowering at 450-500 GDD
Butterfly bush	*Buddleia davidii*	begins flowering at 550-650 GDD
Corn (maize)	*Zea mays*	2700 GDD to crop maturity
Dry beans	*Phaseolus vulgaris*	1100-1300 GDD to maturity depending on cultivar and soil conditions
Sugar Beet	*Beta vulgaris*	130 GDD to emergence and 1400-1500 GDD to maturity
Barley	*Hordeum vulgare*	125-162 GDD to emergence and 1290-1540 GDD to maturity
Wheat (Hard Red)	*Triticum aestivum*	143-178 GDD to emergence and 1550-1680 GDD to maturity
Oats	*Avena sativa*	1500-1750 GDD to maturity
European Corn Borer	*Ostrinia nubilalis*	207 - Emergence of first spring moths

en.wikipedia.org/wiki/Growing-degree_day

Climate factors that influence bark beetles

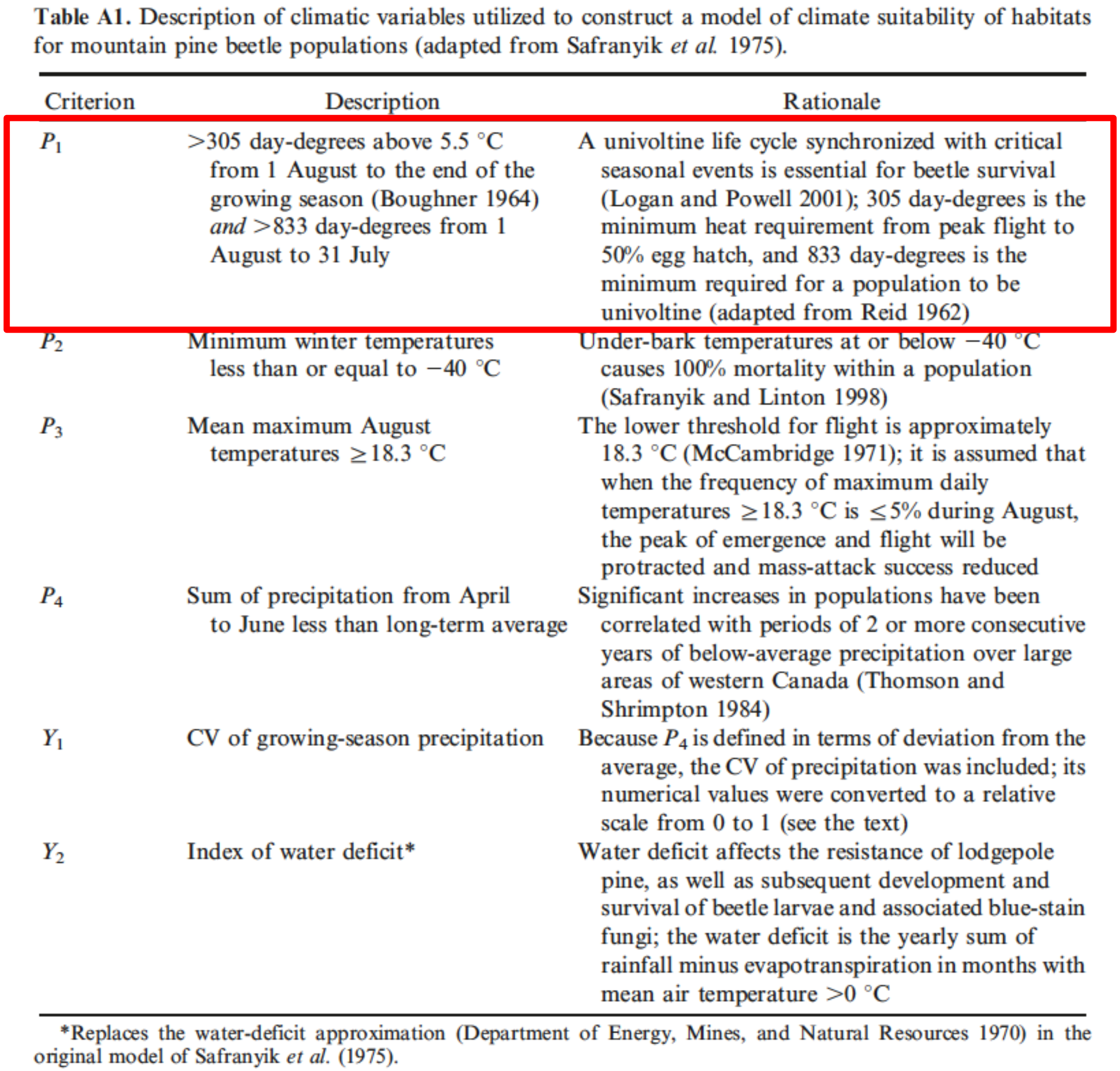


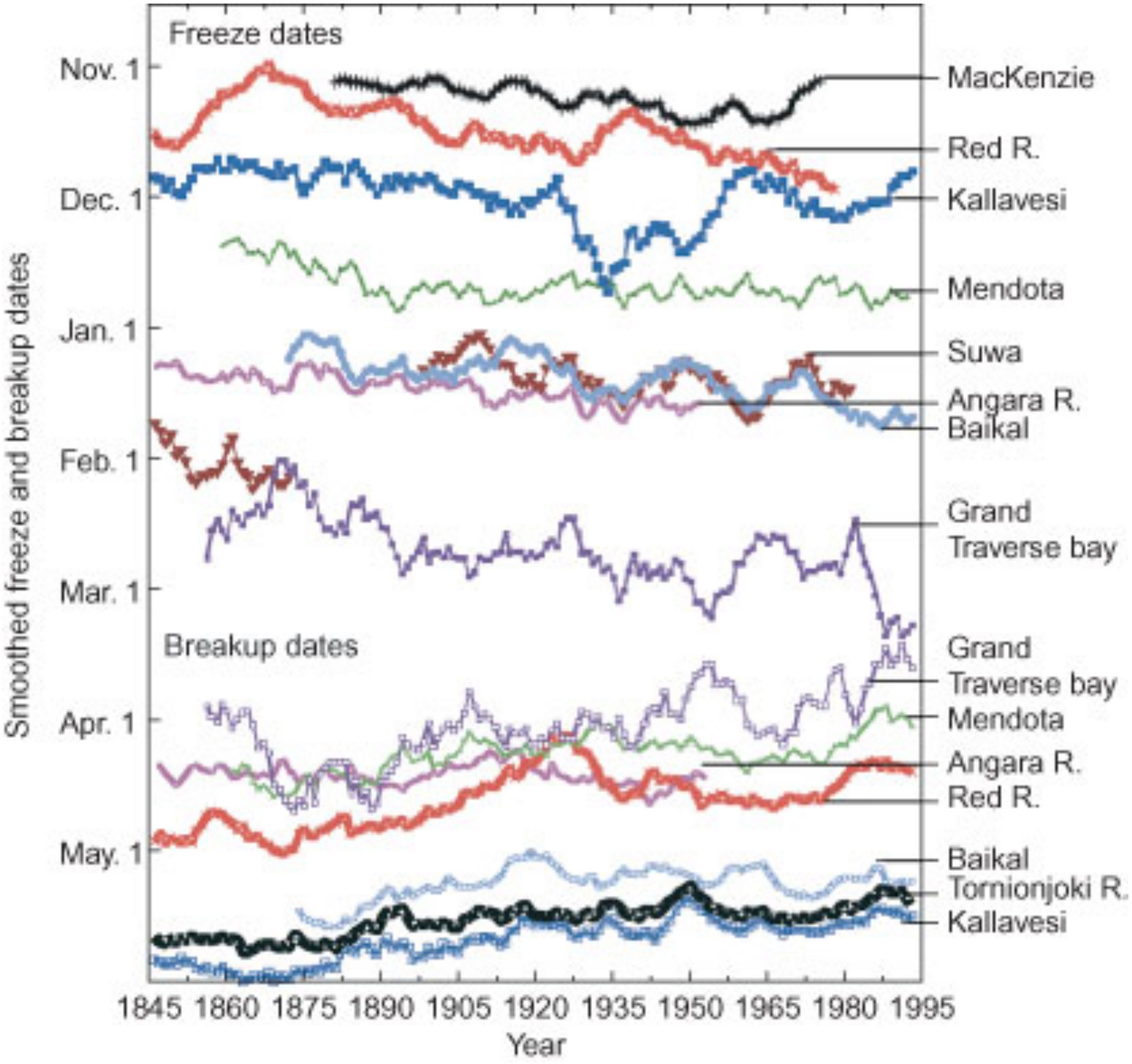
Table A1. Description of climatic variables utilized to construct a model of climate suitability of habitats for mountain pine beetle populations (adapted from Safranyik *et al.* 1975).

Criterion	Description	Rationale
P_1	>305 day-degrees above 5.5 °C from 1 August to the end of the growing season (Boughner 1964) *and* >833 day-degrees from 1 August to 31 July	A univoltine life cycle synchronized with critical seasonal events is essential for beetle survival (Logan and Powell 2001); 305 day-degrees is the minimum heat requirement from peak flight to 50% egg hatch, and 833 day-degrees is the minimum required for a population to be univoltine (adapted from Reid 1962)
P_2	Minimum winter temperatures less than or equal to −40 °C	Under-bark temperatures at or below −40 °C causes 100% mortality within a population (Safranyik and Linton 1998)
P_3	Mean maximum August temperatures ≥18.3 °C	The lower threshold for flight is approximately 18.3 °C (McCambridge 1971); it is assumed that when the frequency of maximum daily temperatures ≥18.3 °C is ≤5% during August, the peak of emergence and flight will be protracted and mass-attack success reduced
P_4	Sum of precipitation from April to June less than long-term average	Significant increases in populations have been correlated with periods of 2 or more consecutive years of below-average precipitation over large areas of western Canada (Thomson and Shrimpton 1984)
Y_1	CV of growing-season precipitation	Because P_4 is defined in terms of deviation from the average, the CV of precipitation was included; its numerical values were converted to a relative scale from 0 to 1 (see the text)
Y_2	Index of water deficit*	Water deficit affects the resistance of lodgepole pine, as well as subsequent development and survival of beetle larvae and associated blue-stain fungi; the water deficit is the yearly sum of rainfall minus evapotranspiration in months with mean air temperature >0 °C

*Replaces the water-deficit approximation (Department of Energy, Mines, and Natural Resources 1970) in the original model of Safranyik *et al.* (1975).

Safranyik et al., 2010

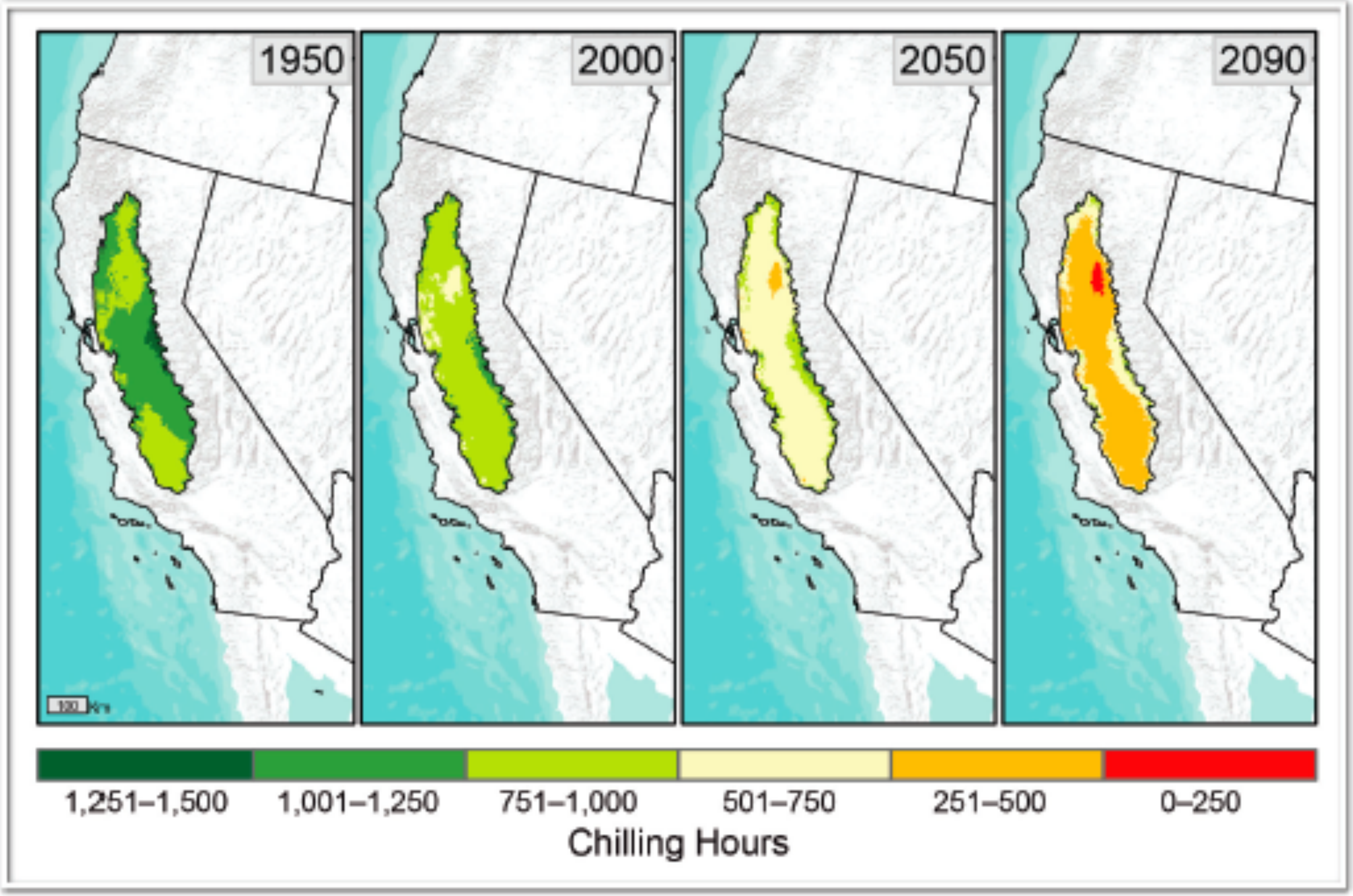
Changes in ice formation, breakup



What are the implications for plants, animals?

Hannah 2011

Many Plants Need Chilling to Produce Fruit — Reduced Chilling is Projected

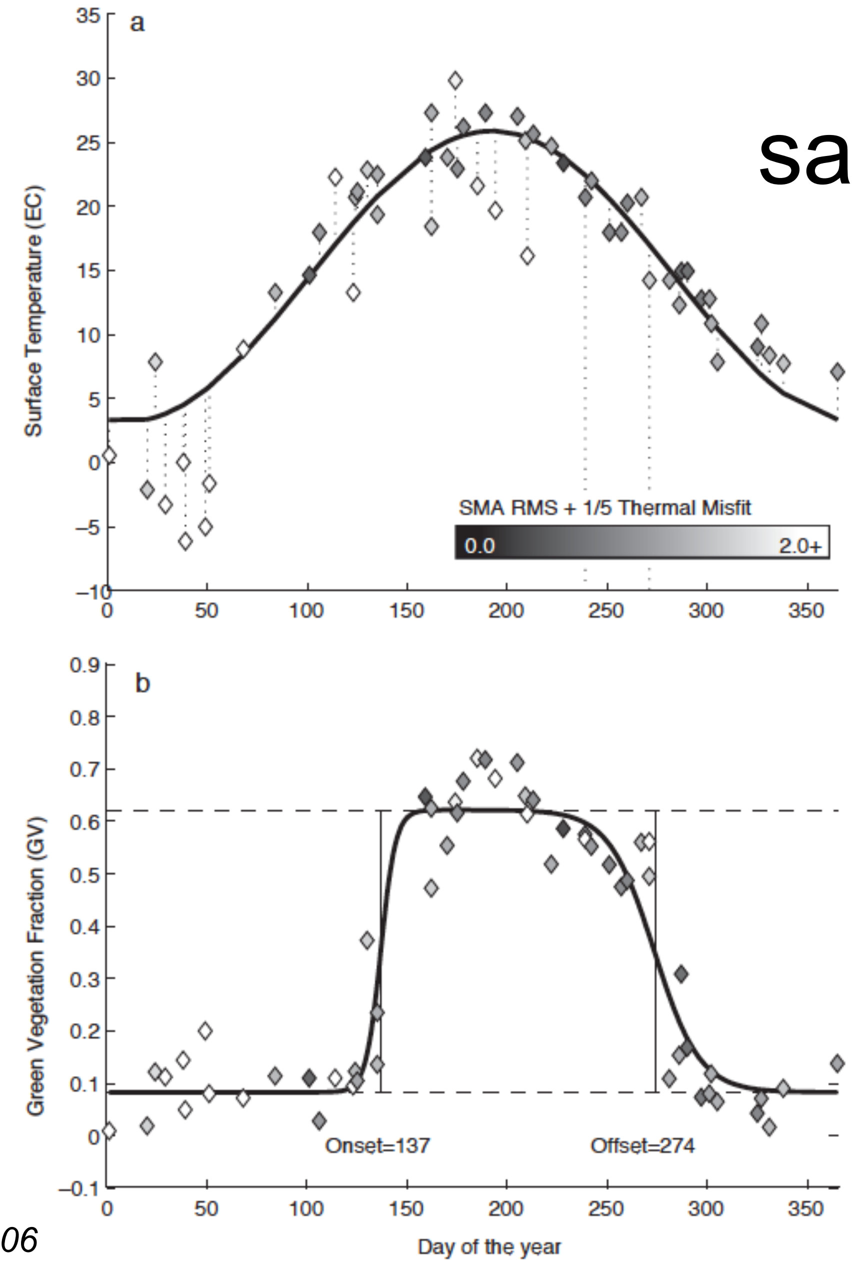


National Climate Assessment Draft Report, 2013

Defining vegetation phenology using satellite remote sensing

estimated surface temperature

greenness index



T used to identify outliers that are then weighted less

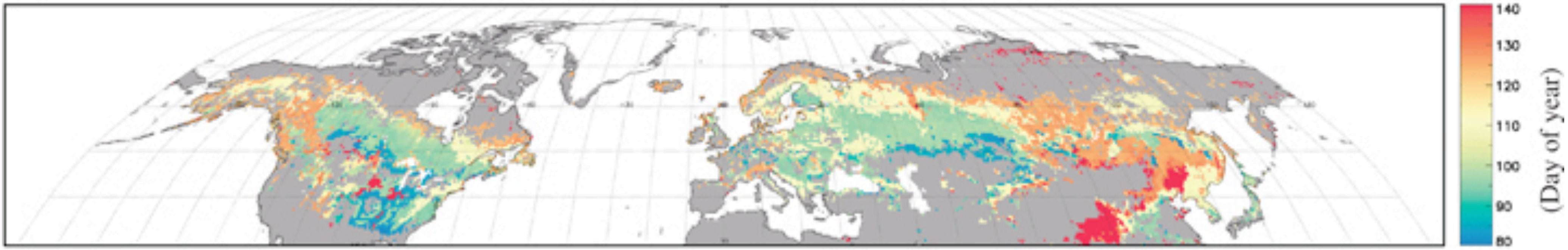
Fischer et al., 2006

Fig. 2. Schematic of curve fitting mechanism. Land surface temperature (a) is derived from Landsat band 6 and fit with a maximizing envelope sinusoid. Data points which fall further from this line are subsequently assigned less weight in the phenological fit. Spectrally unmixed green vegetation fraction (b) is fit with a pair of logistic growth sigmoid functions. Points with the least temperature and spectral error are assigned a greater weight (darker colors in this schematic) in the curve fit. Finally, onset and offset are calculated as the half-maxima of the sigmoid curve.

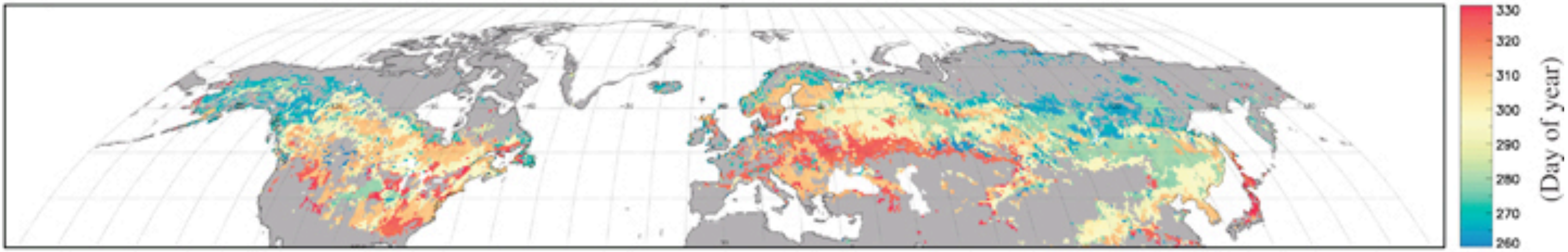
Prof. J. Hicke

Defining vegetation phenology using satellite remote sensing: Climatology

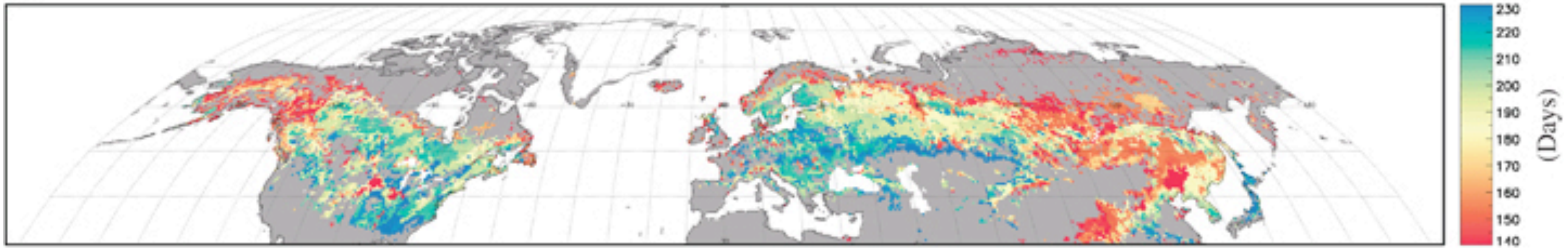
(a) SOS



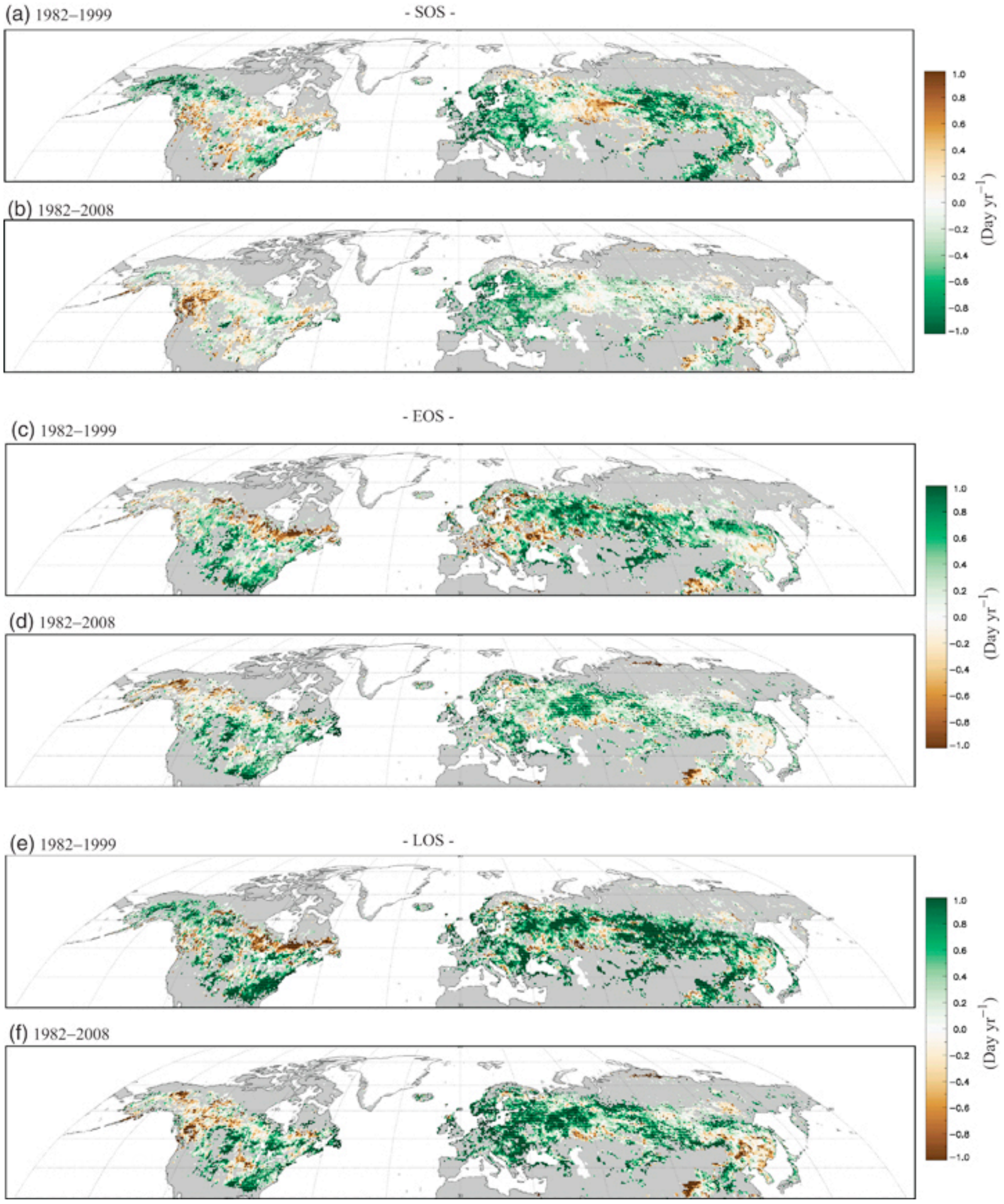
(b) EOS



(c) LOS



Jeong et al., GCB, 2011



Defining vegetation phenology using satellite remote sensing:

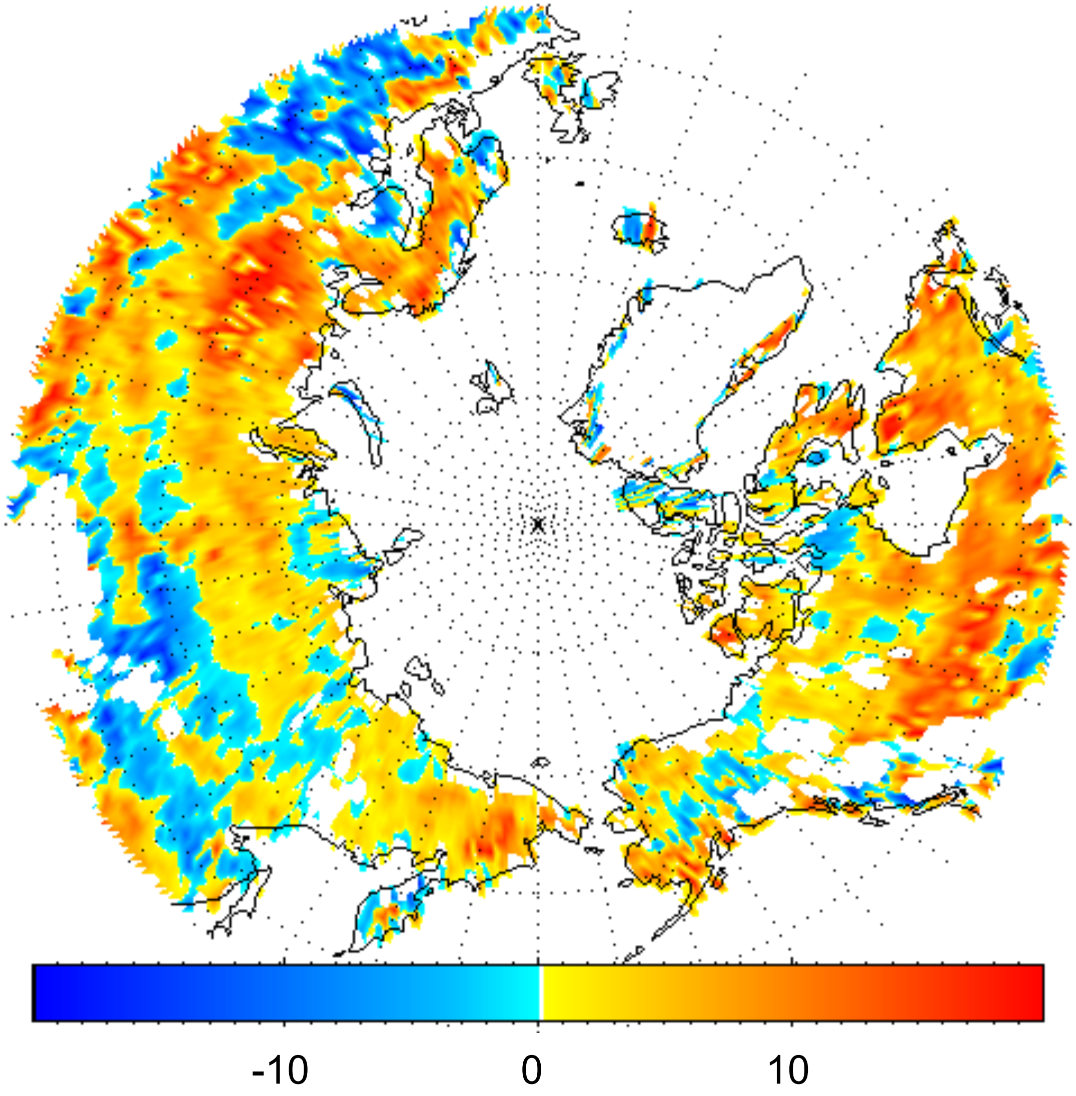
Trends in last decades

Jeong et al., GCB, 2011

Prof. J. Hicke

Satellite-derived increases in growing season length

1982-2005



Smith-Downey et al., 2006

Table 4.2 Studies Showing Earlier Arrival of Spring

Location	Period	Species/Indicator	Observed Changes (Days/ Decade)	References
Western USA	1957–1994	Lilac, honeysuckle (F)	−1.5 (lilac), 3.5 (honeysuckle)	Cayan *et al.*, 2001
Northeastern USA	1965–2001	Lilac (F, LU)	−3.4 (F), −2.6 (U)	Wolfe *et al.*, 2005
	1959–1993	Lilac (F)	−1.7	Schwartz and Reiter, 2000
Washington, DC	1970–1999	100 plant species (F)	−0.8	Abu-Asab *et al.*, 2001
Germany	1951–2000	10 spring phases (F, LU)	−1.6	Menzel *et al.*, 2003
Switzerland	1951–1998	9 spring phases (F, LU)	−2.3 (*)	Defila and Clot, 2001
South-central England	1954–2000	385 species (F)	−4.5 days in 1990s	Fitter and Fitter, 2002
Europe (Int. Phenological Gardens)	1959–1996	Different spring phases (F, LU)	−2,1	Menzel and Fabian, 1999; Menzel, 2000; Chmielewski and Rotzer, 2001
	1969–1998		−2.7	
21 European countries	1971–2000	F, LU of various plants	−2.5	Menzel *et al.*, 2006
Japan	1953–2000	*Gingko biloba* (LU)	−0.9	Matsumoto *et al.*, 2003
Northern Europia	1982–2004	NDVI	−1.5	Delbart *et al.*, 2006
United Kingdom	1976–1998	Butterfly appearance	−2.8 to −3.2	Roy and Sparks, 2000
Europe, North America	Past 30–60 years	Spring migration of bird species	−1.3 to −4.4	Crick *et al.*, 1997; Crick and Sparks, 1999; Dunn and Winkler, 1999: Inouye *et al.*, 2000; Bairlein and Winkel, 2001; Lehikoinen *et al.*, 2004
North America (US, MA)	1932–1993	Spring arrival, 52 bird species	+0.8 to −9.6 (*)	Butler, 2003
North America (US, IL)	1976–2002	Arrival, 8 warbler species	+2.4 to −8.6	Strode, 2003
England (Oxfordshire)	1971–2000	Long-distance migration, 20 species	+0.4 to −6,7	Cotton, 2003
North America (US, MA)	1970–2002	Spring arrival, 16 bird species	−2.6 to −10.0	Ledneva *et al.*, 2004
Sweden (Often by)	1971–2002	Spring arrival, 36 bird species	−2.1 to −3.0	Stervander *et al.*, 2005
Europe	1980–2002	Egg-laying, 1 species	−1,7 to −4.6	Both *et al.*, 2004
Australia	1970–1999	11 migratory birds	9 species earlier arrival	Green and Pickering, 2002
Australia	1984–2003	2 spring migratory birds	1 species earlier arrival	Chambers *et al.*, 2005

*F, flowering; LU, leaf unfolding; −, advance; +, delay; * indicates mean of significant trends only.*

Hannah 2011

Meta-analysis of spring phenology

1. almost all are advances
2. consistent changes across taxa

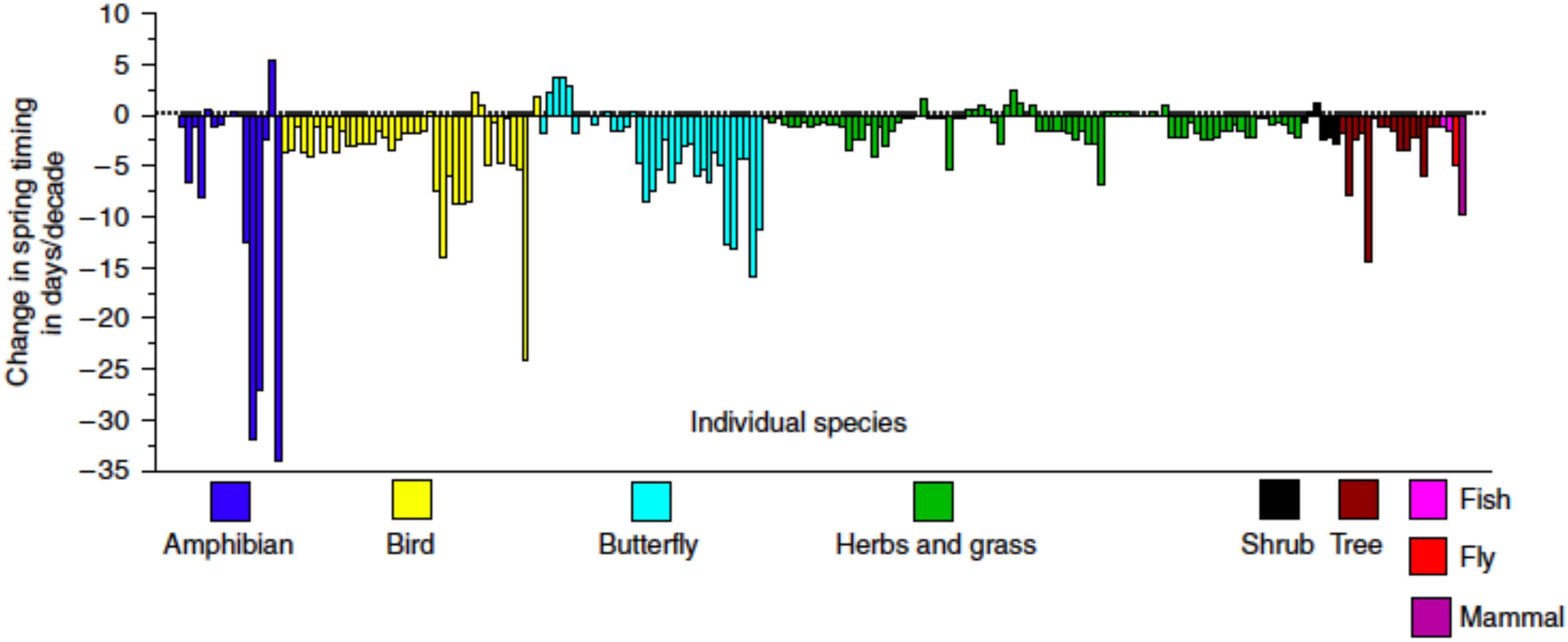


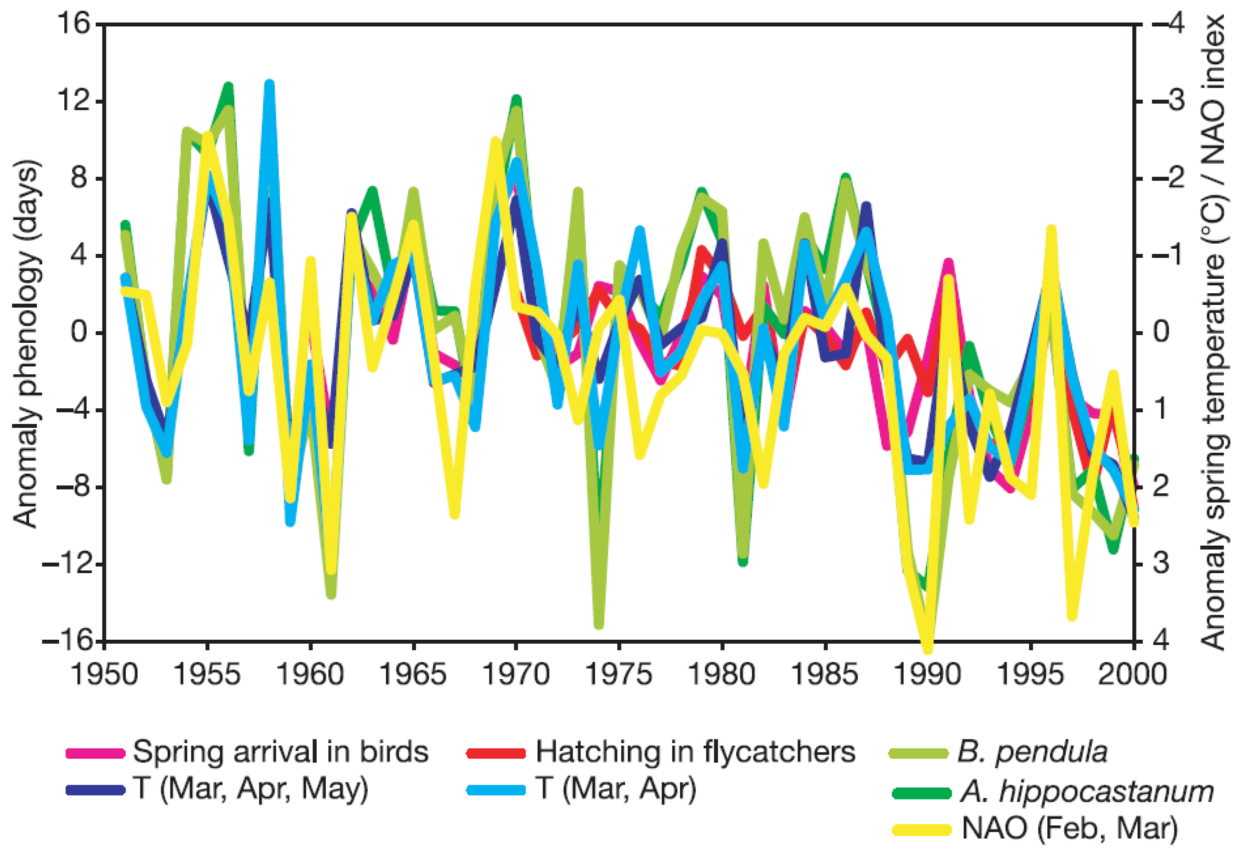
Fig. 2 Changes in timing of spring events in days decade^{-1} for individual species grouped by taxonomy or functional type for the combined dataset. Each bar represents a separate, independent species. Negative values indicate advancement (earlier phenology through time) while positive values indicate delay (later phenology through time).

Parmesan, 2007

Spring warming => biological responses

Later

Earlier



Colder

Warmer

Figure 2 Anomalies of different phenological phases in Germany correlate well with anomalies of mean spring air temperature *T* and NAO index (by P. D. Jones, http://www.cru.uea.ac.uk/cru/data/nao.htm). Temperature taken from 35 German climate stations. Phenological phases used: spring arrival in birds, island of Helgoland, North Sea; hatching in flycatchers (*Ficedula hypoleuca*), Northern Germany; and mean onset of leaf unfolding of *Aesculus hippocastanum* and *Betula pendula*.

Walther et al., 2002

Warming and laying date

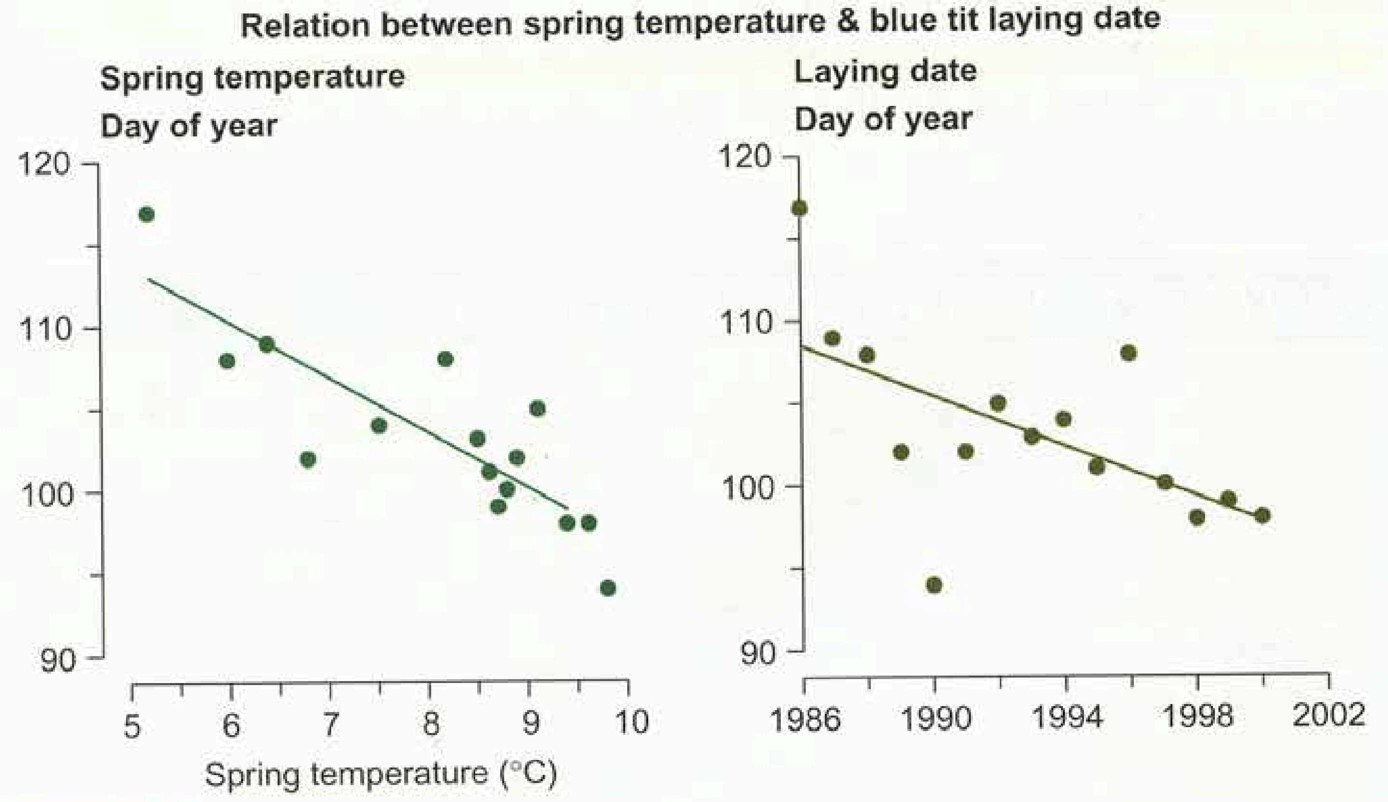


FIGURE 4.5

Blue tit egg laying is earlier in warmer years, and progressive warming is resulting in an advance of more than 10 days in less than two decades. *Courtesy of Environmental Data Compendium.*

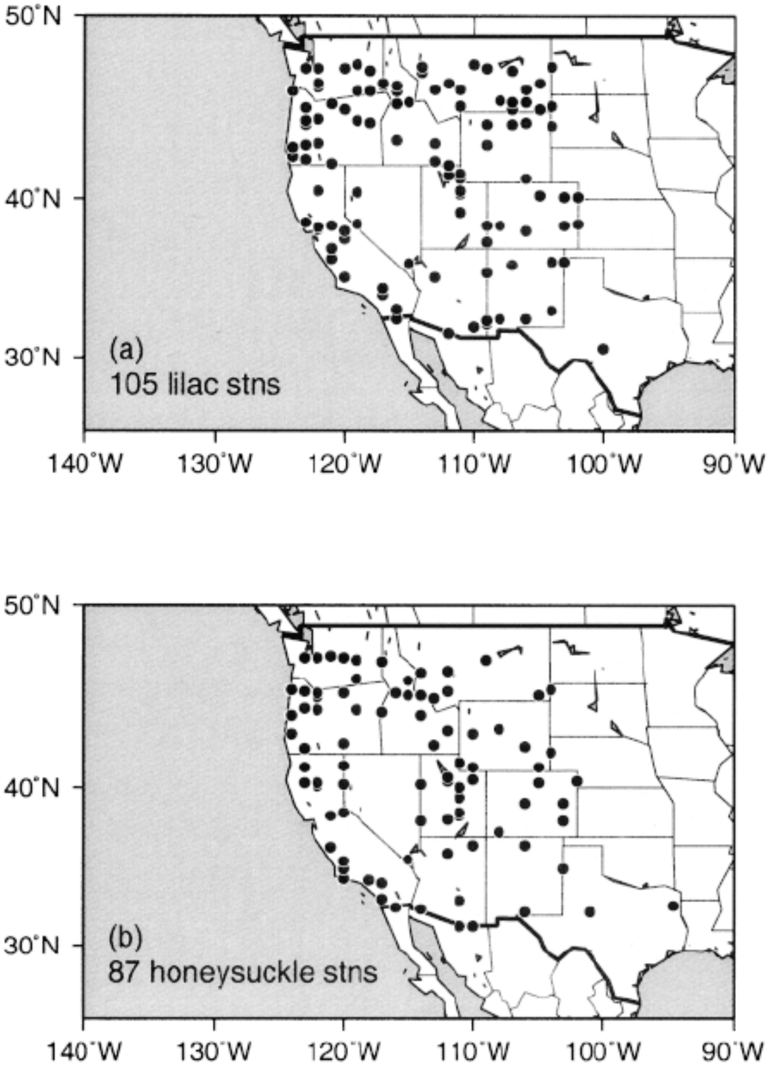
FIGURE 4.4

Blue tit (*Cyanistes caeruleus*) resting on a branch. *From Wikimedia Commons.*

Hannah 2011

Lilac and honeysuckle first bloom dates

Locations



Change in spring T

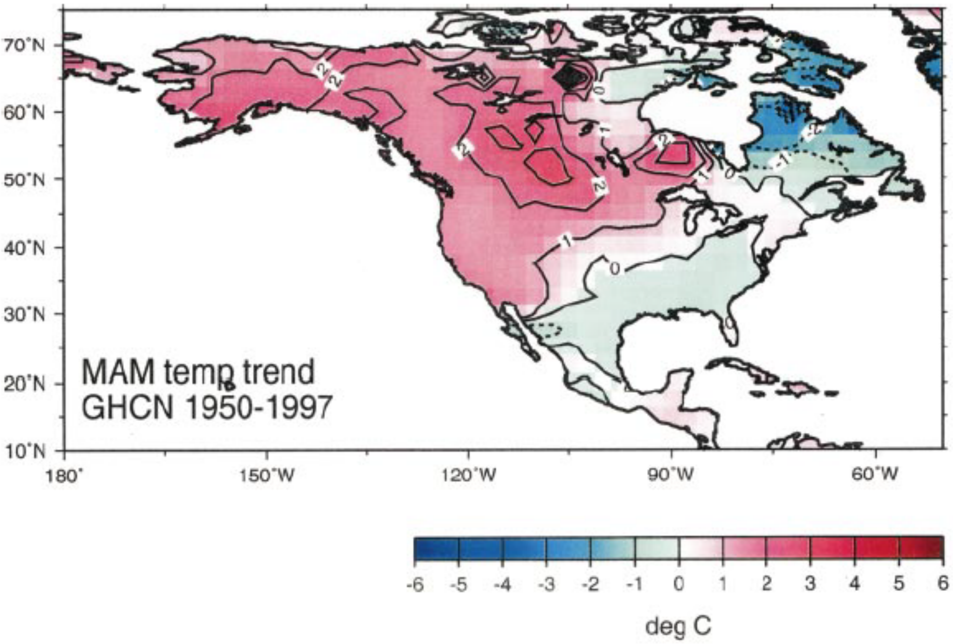
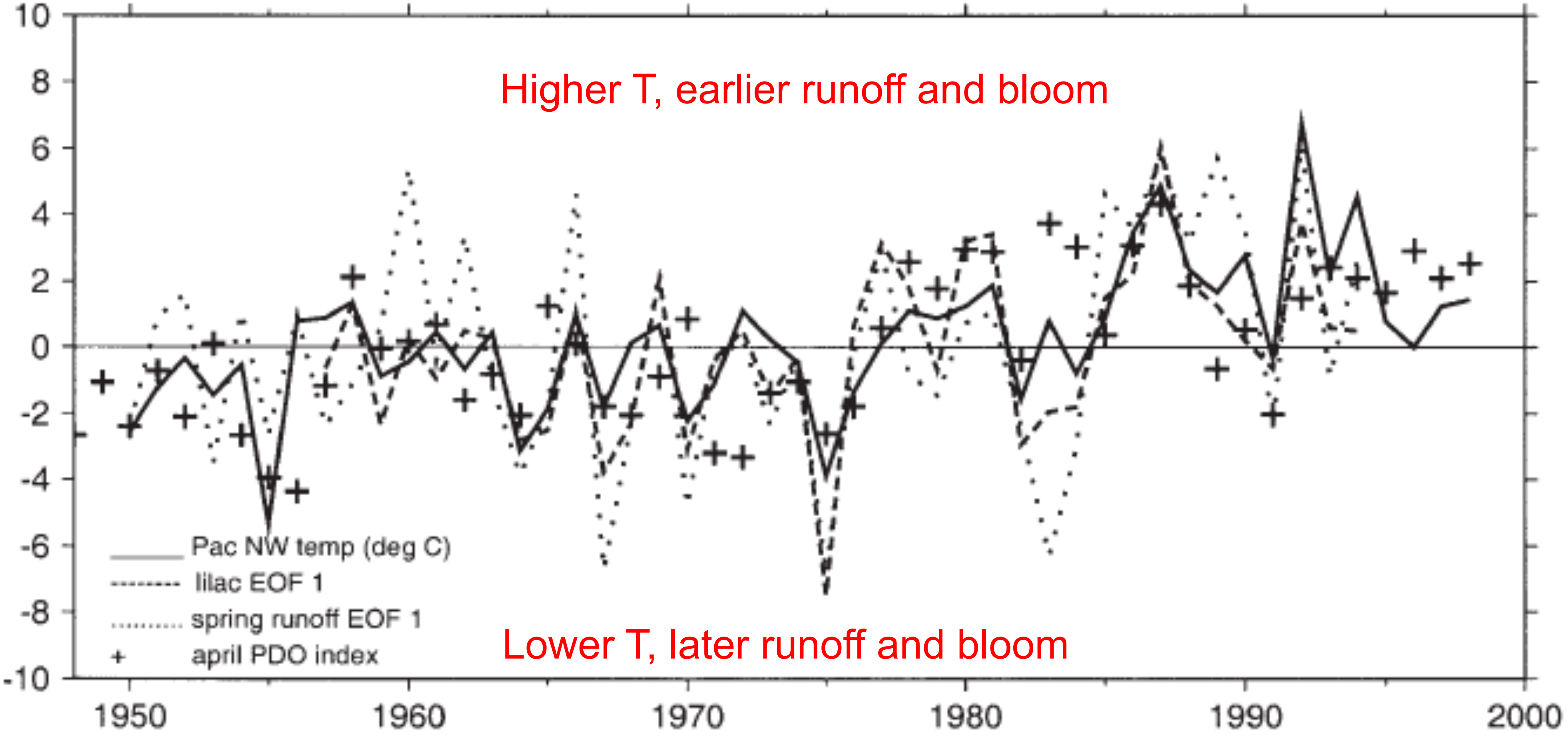


FIG. 1. Linear trend of spring (Mar–May) temperature over North America between 1950 and 1998. Values plotted are the overall change in trend lines (°C) from beginning to end of record.

Cayan et al., Bulletin of Amer. Met. Soc., 2001

Lilac and honeysuckle first bloom dates

Spring warming, earlier runoff, earlier blooming


Higher T, earlier runoff and bloom

Lower T, later runoff and bloom

FIG. 13. Time history of spring (Mar–May) temperature anomalies (solid, °C) averaged over the interior northwestern United States, EOF 1 of lilac first bloom date anomalies (dashes), and EOF 1 of runoff spring pulse date anomalies (dots). Apr PDO (crosses) is also shown. Temperature is the average of eastern Washington, Idaho, western Montana, and western Wyoming divisional values.

Cayan et al., Bulletin of Amer. Met. Soc., 2001

Lilac and honeysuckle first bloom dates

Analysis of lilac first bloom dates in Spokane

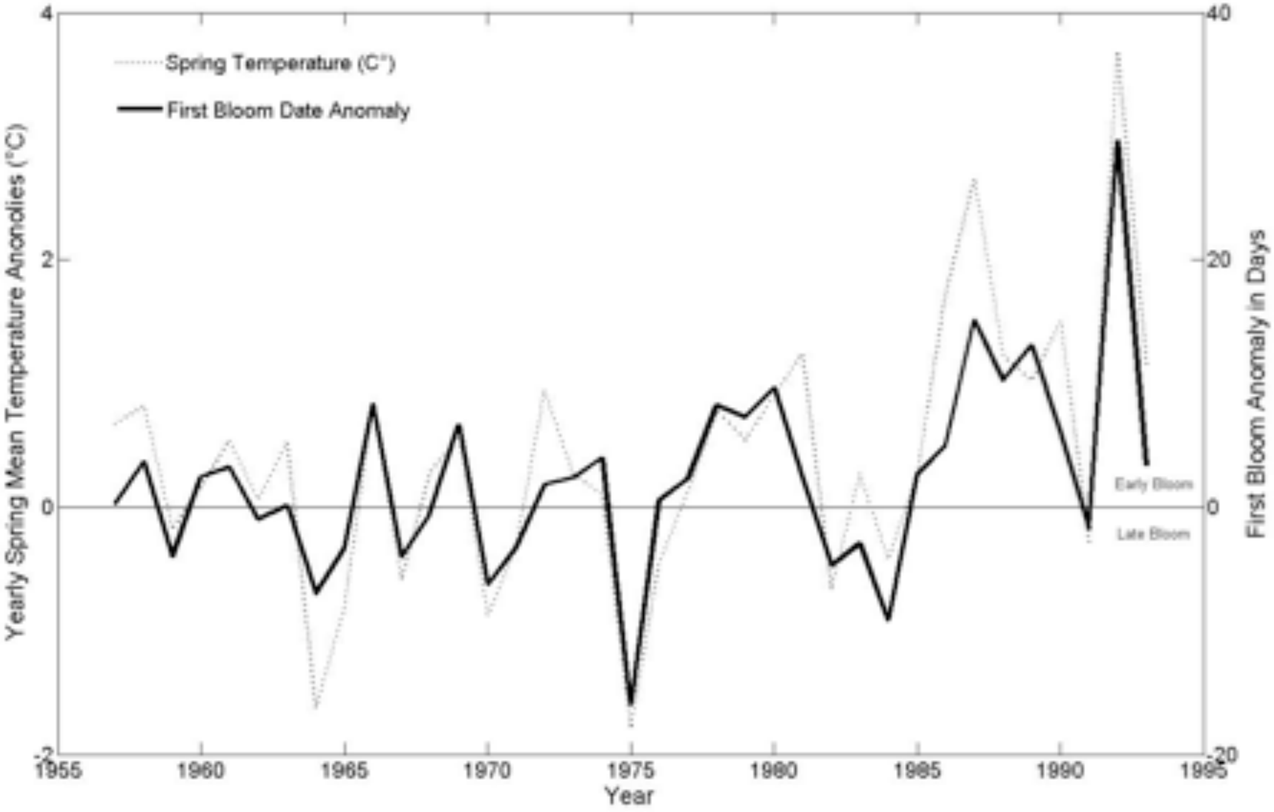
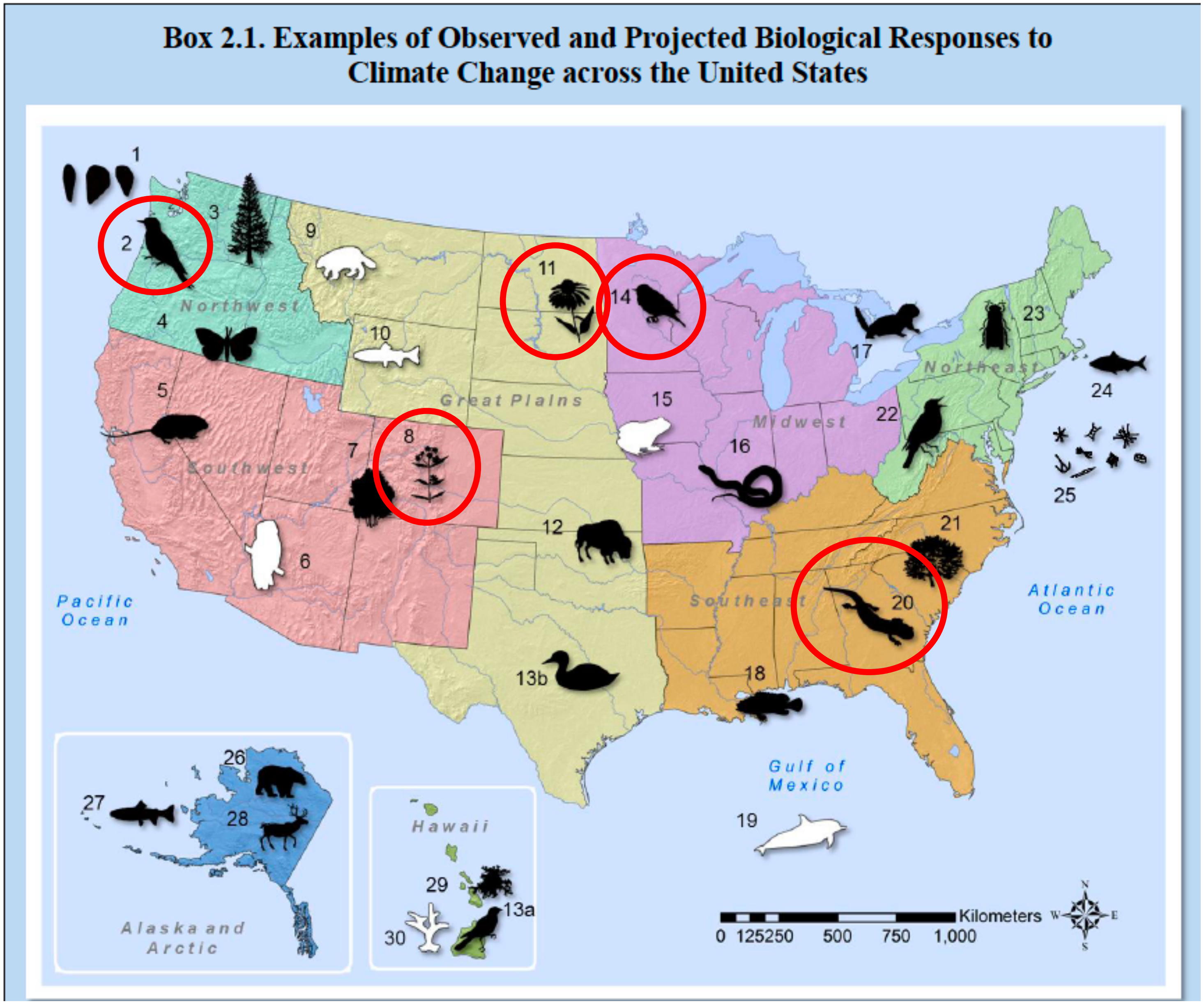


Figure from V. Jansen, UI, climateinw.wordpress.com/2012/05/29/the-lilac-city-and-spring-phenology/

National Climate Assessment: Biological Responses



Box 2.1. Examples of Observed and Projected Biological Responses to Climate Change across the United States

2. N. Flickers arrive earlier, lay eggs earlier due to warming

8. RM high-elevation areas: Flower phenology changes; declines in flower resources that may affect pollinators; earlier growth led to higher susceptibility to frost; decoupling plant/pollinator interactions with earlier plant phenology compared with insects; all due to warming

11. Earlier first flowering dates in 40% of 178 plant species examined; warming

14. Earlier arrival dates of 36% of 44 species of migratory birds; warming in winter

20. Arrival times of amphibians to breeding sites:
    - autumn breeders: later
    - winter breeders: earlier
    - warming nighttime T and precip

Staudinger, et al. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment, 2012

Climate change may lead to seasonal mistiming

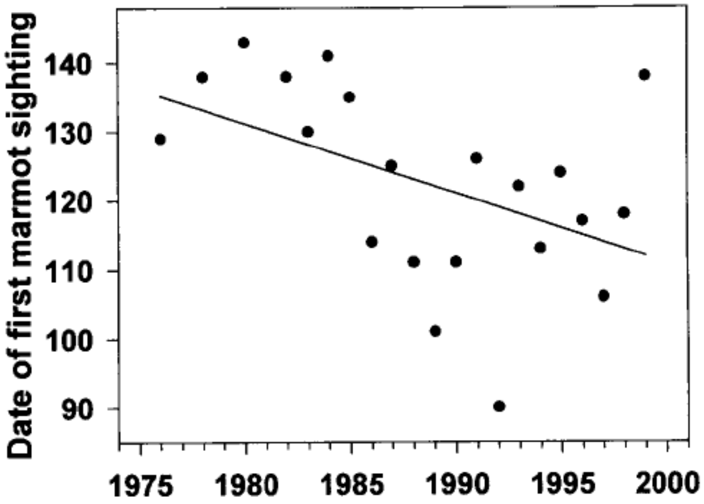


Fig. 4. Date of the first sighting of a marmot at RMBL each year from 1976 to 1999 (data missing for 3 years; Julian date). Regression equation is $Y = 2{,}129.839 - 1.009X$, $r^2 = 0.226$, $P = 0.029$.

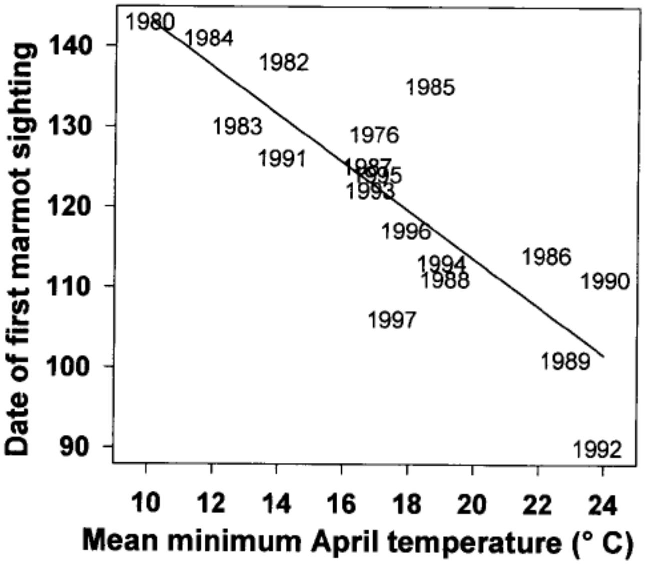


Fig. 5. Date of the first sighting of a marmot plotted against the mean minimum temperature for the month of April in Crested Butte (Julian date). Regression equation is $Y = 171.560 - 2.848X$, $r^2 = 0.596$, $P = 0.0001$.

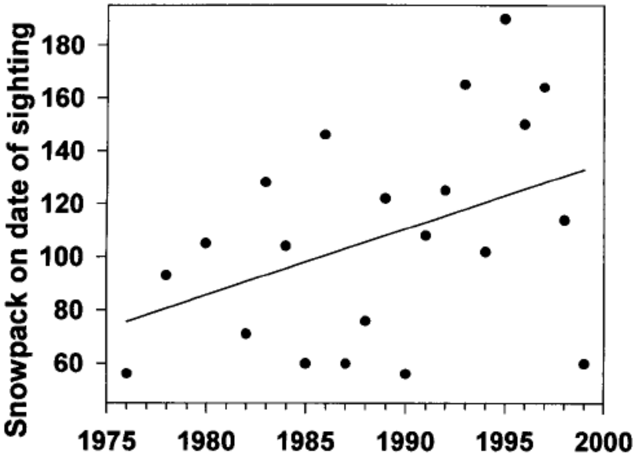


Fig. 6. Depth of remaining snowpack on the date of first marmot sighting at RMBL (Julian date). $Y = 2.498X - 4{,}861.228$, $P = 0.07$.

Consequences for marmot???

Inouye et al., 2000

Climate change may lead to seasonal mistiming

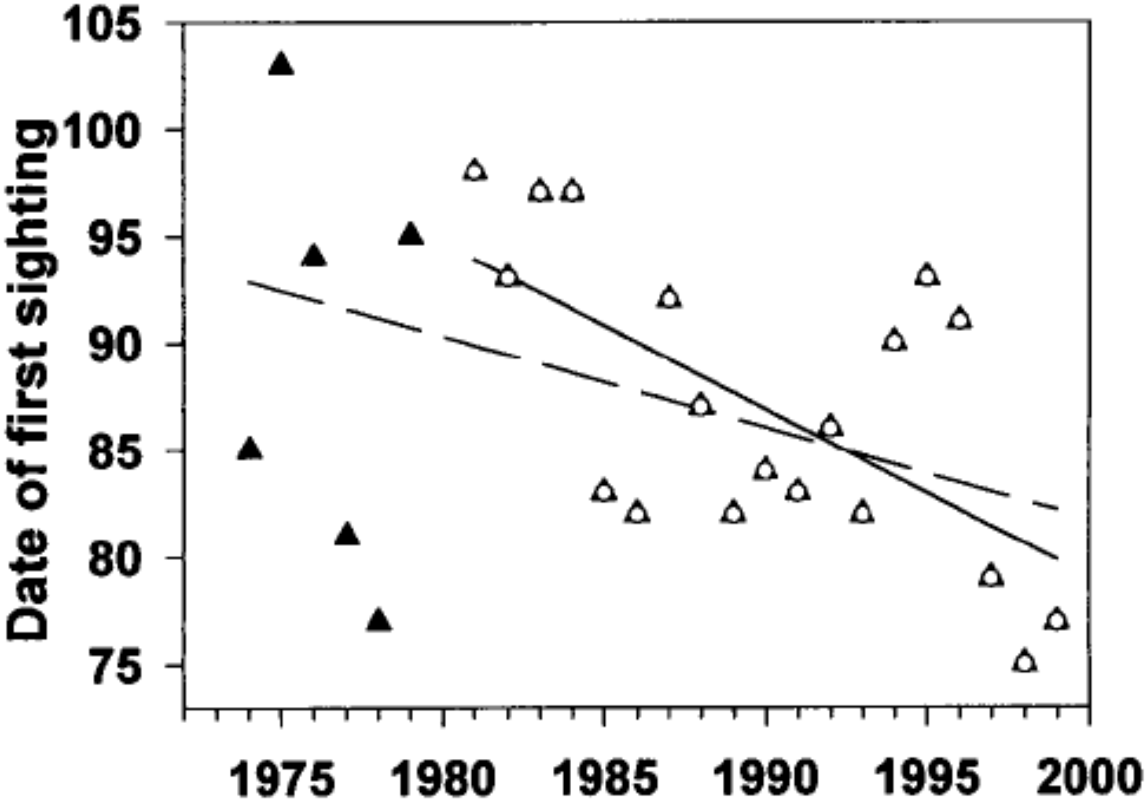
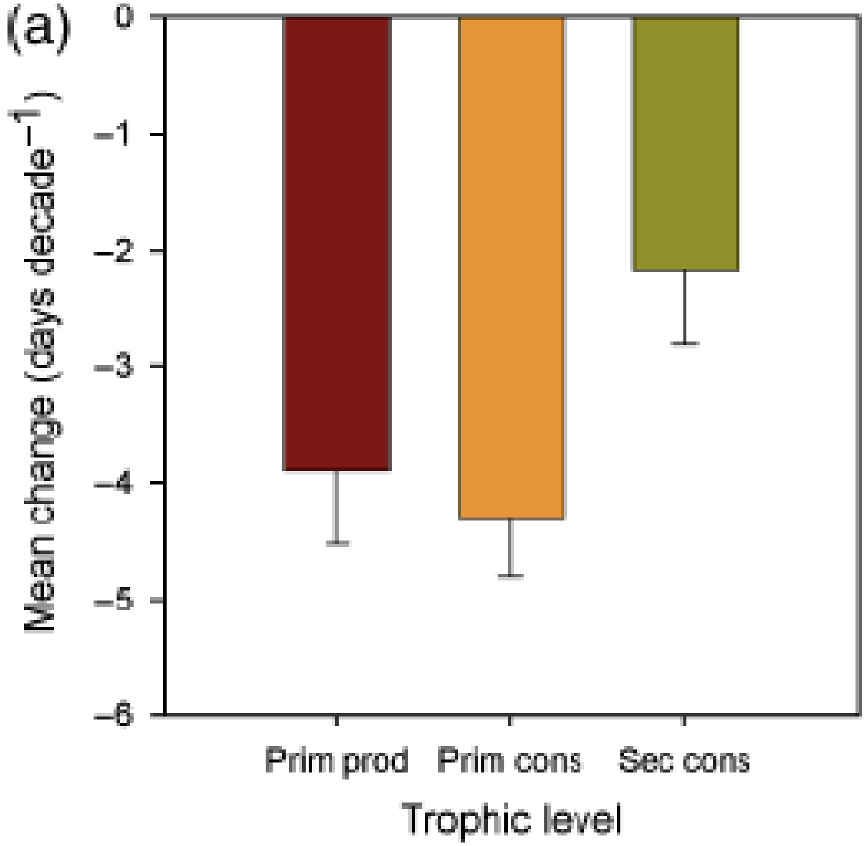


Fig. 3. Date of the first sighting of a robin at RMBL each year from 1974 to 1999 (Julian date). The two lines are regressions, including 1974–1980 (▲ and dashed line; $P = 0.109$) and data from 1981 to 1999 (○ and solid line; $P = 0.003$).

Inouye et al., 2000

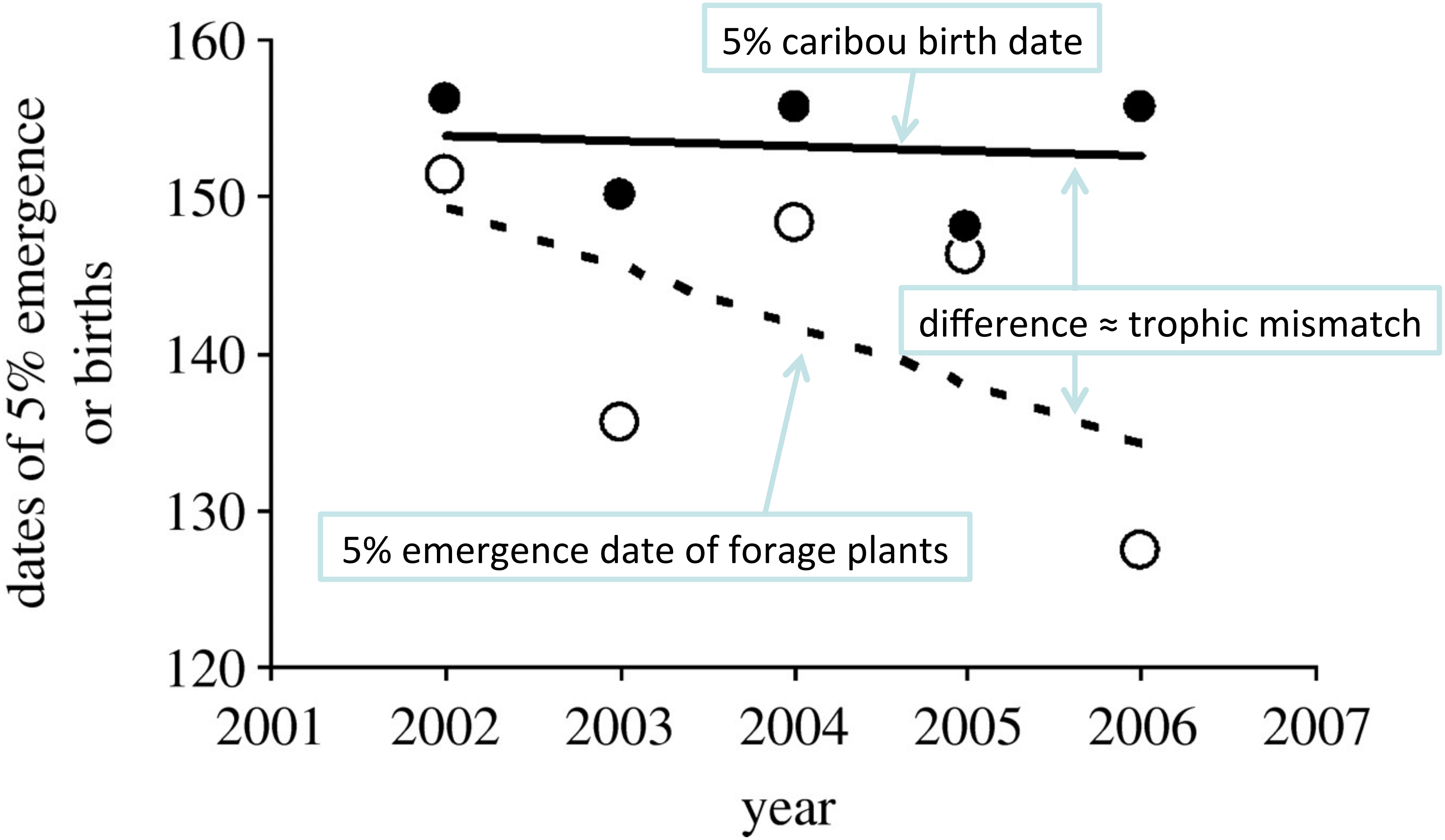
Differential changes among trophic levels

Secondary consumers not advancing as quickly



Thackeray et al., GCB, 2010

Post and Forchhammer (2008) Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch



5% caribou birth date

difference ≈ trophic mismatch

5% emergence date of forage plants

Slide courtesy J. Lichstein, U. FL