Phenology: four current grand challenges

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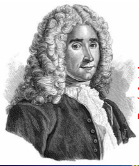
The four grand challenges

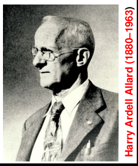
- Challenge 1 (for the statistician & physiologist)
  Reconciling the world's best models and observations.
- Challenge 2 (for the remote sensor & modeller)
  Upscaling: from plant to patch to planet.
- Challenge 3 (for the ecologist & manager)
  Where will biota move to?
  And how quickly?
- Challenge 4 (for the geneticist)
  Will plants keep pace with future climate change?

Progress during the last 275 years

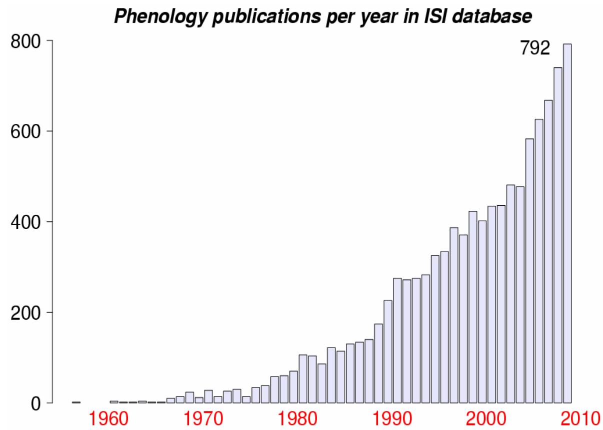


- 1735 **R.A.F. de Reaumur**
  First suggested that the phenological stages of cereal crops were controlled by the sum of mean daily air temperatures.
  (Degree-days)

- 1850 **R.L. Allen**
  Produced a crop of grain from spring-sown winter-wheat seed which had been subjected to low temperatures before seeding.
  (Vernalization, chilling)



- 1920 **W.W. Garner & H.A. Allard**
  Discovered photoperiodism in tobacco – in a mutant variety called Maryland Mammoth.
  (Long-day/short-day)



European phenological response to climate change
Menzel, Sparks et al, 2006

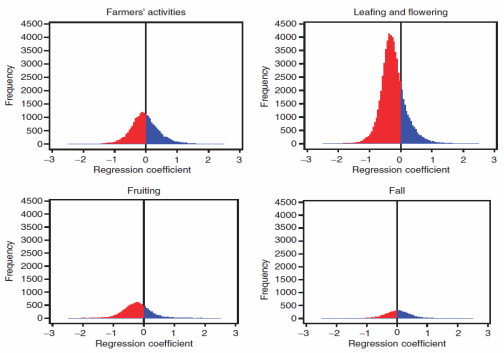


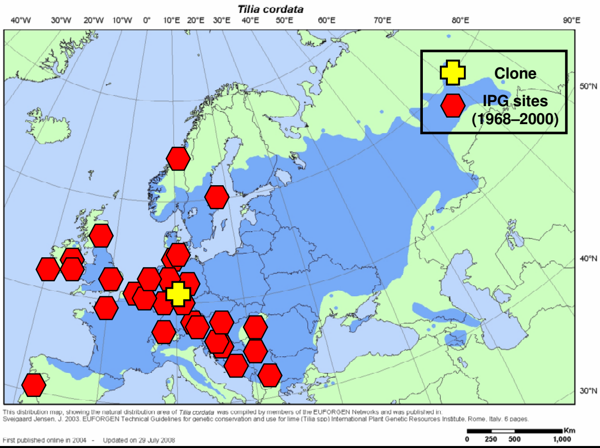
Fig. 3 Histograms of phenological trends in Europe. All temporal trends (1971–2000, time series 15+ years) as linear regression coefficients (days yr^{-1}) systematically reported to the COST725 meta-analysis ($n = 103\,199$) for four different groups.

Challenge 1: Models and observations

Question:

Can the world's best models and observations be reconciled?

- **Observations:**
  Clonal trees and shrubs monitored at International Phenological Gardens (IPG)
- **Model:**
  Degree-day (with inhibitors)

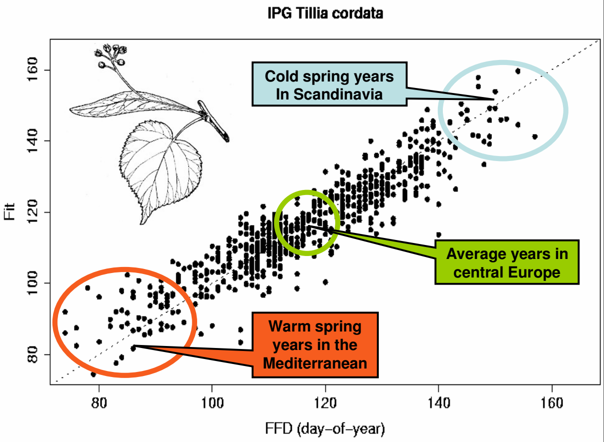


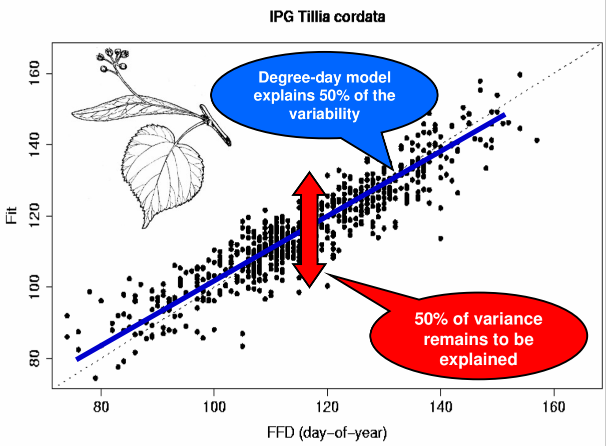
Is spring starting earlier?

$$\mu_i = \sqrt{\frac{2\beta}{m_i + \lambda}} + \frac{\alpha - c_i}{m_i + \kappa}$$

Where, in year i, λ is the rate of change in thermal requirement, β, associated with changes in the duration of winter chilling; α is the thermal threshold; κ is α's rate of change; m is the rate of increase in spring temperature and c is the mean temperature.

The Holocene 2008 18: 95-104. Thompson & Clark



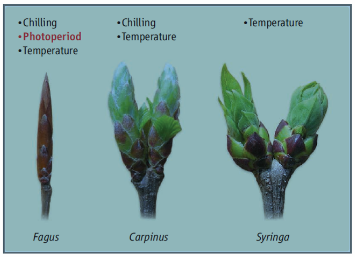


Growing-degree-day parameters and standard errors for Clark-Thompson phenological model (2008) for four plant species.

Taxon	d.o.f	Thermal threshold				Degree-day requirement			
		α	std. error	κ	std. error	β*	std. error	λ	std. error
		(^{o}C)		(^{o}C/day)		(^{o}C.days)		(^{o}C/day)	
Prunus avium Bovenden	676	3.0	0.021	–0.003	0.0006	7.5	0.38	–0.026	0.002
Prunus avium Lutter	574	3.0	0.020	–0.007	0.0004	6.7	0.29	–0.034	0.002
Sorbus aucuparia	481	3.1	0.022	–0.003	0.0007	5.6	0.42	–0.027	0.003
Tilia cordata	681	2.7	0.029	–0.005	0.0012	10.1	0.51	–0.021	0.009

dof Degrees of freedom
α Thermal threshold
κ Inhibitor on thermal threshold
β Degree-day requirement
λ Degree-day inhibitor
β* Square root of the degree-day requirement (β).

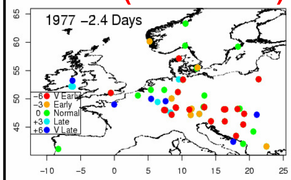
"Phenology Under Global Warming"
C. Körner and D Basler



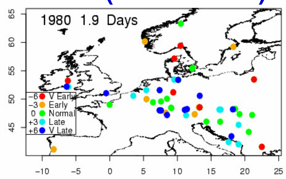
SCIENCE VOL 327 19 MARCH 2010

"The majority of long-lived trees outside of the tropics track the length of the day, or photoperiod. This helps species such as beech and oak avoid growth beginning in the wrong season. By contrast shorter-lived, early successional species like birch, poplar and hazel adopt a more risky life-strategy and so do not take the time of day into account. Because they track photoperiod, longer-lived trees will not benefit greatly from the extended growing seasons generated by climate change."

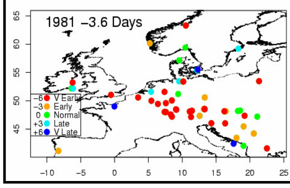
Earlier (than model)



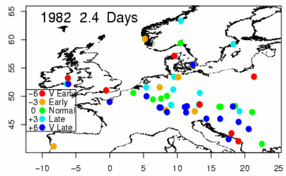
Later (than model)



Earlier (than model)



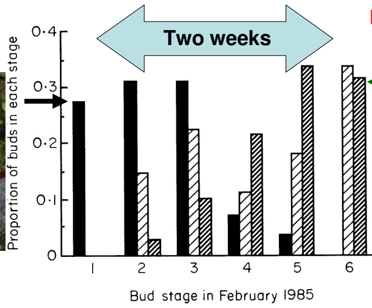
Later (than model)



"In the season following reproduction bud break on fruit bearing shoots was significantly later than on non-bearing shoots."

Newell (1991)

Late



Early

FIG. 3. The effect of 1984 reproduction on bud development of *Aesculus californica* in February 1985. The fraction of buds in each of six stages of development is shown for shoots maturing fruit in 1984 (■), shoots aborting all fruit in 1984 (◻), and for shoots non-flowering in 1984 (▨). Buds in stage 1 were tightly closed, buds in stage 4 had just opened, and buds in stage 6 had reflexed bud scales and expanding leaves.

Summary

Achievements:

- Now widely documented that spring is occurring earlier and earlier at many locations around the world.

Problems:

- 50% of phenological variability remains unexplained.

Future aims:

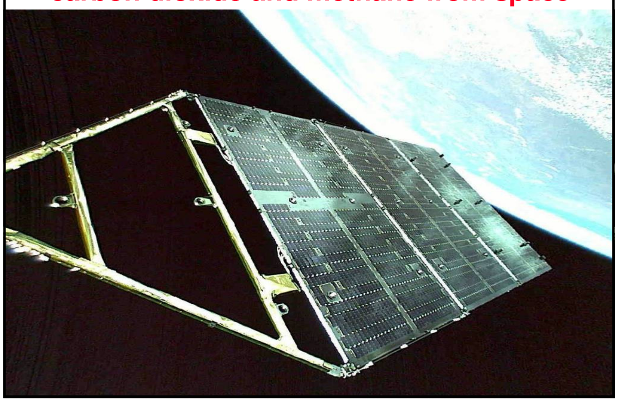
- Accessible global databases.
- Better understanding of internal plant mechanisms.

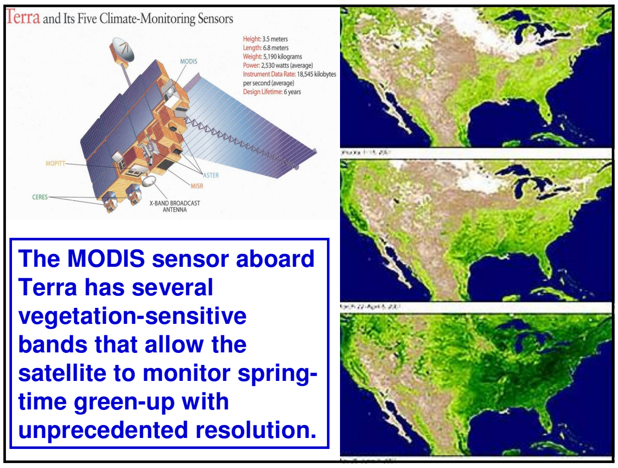
Challenge 2: Upscaling

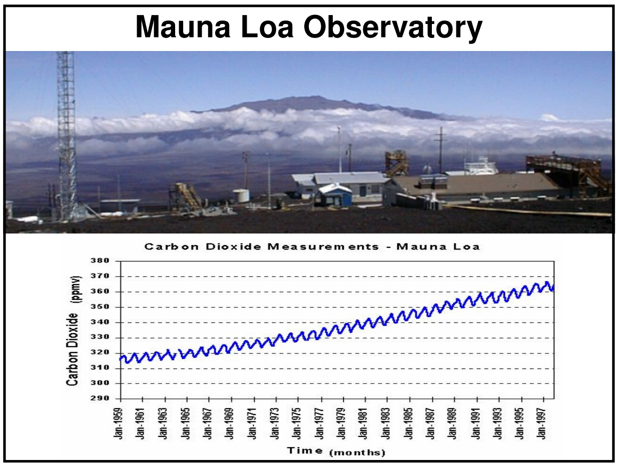
Main Question:

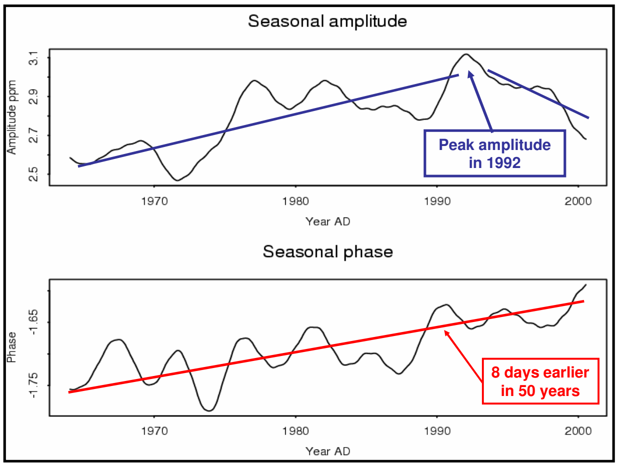
How can botanical processes be represented in order to allow upscaling from plant to patch to planet?

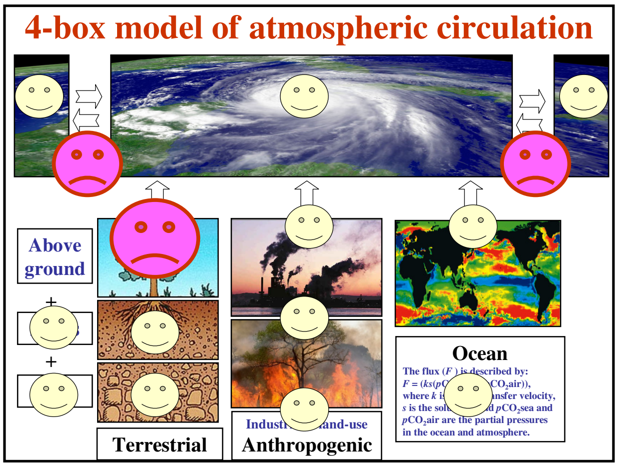
IBUKI - the world's first satellite to measure carbon dioxide and methane from space

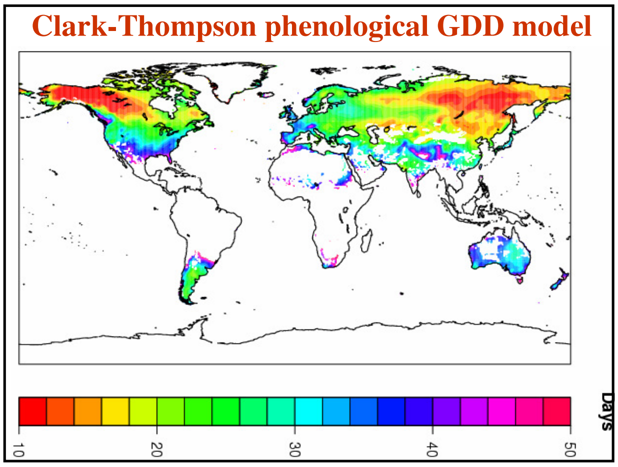


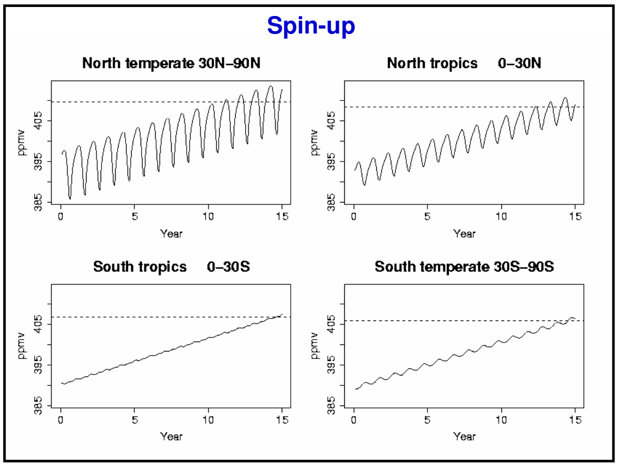

Terra and Its Five Climate-Monitoring Sensors
MODIS
MOPITT
CERES
ASTER
MISR
X-BAND BROADCAST ANTENNA
The MODIS sensor aboard Terra has several vegetation-sensitive bands that allow the satellite to monitor spring-time green-up with unprecedented resolution.


Mauna Loa Observatory
Carbon Dioxide Measurements - Mauna Loa
Carbon Dioxide (ppmv)
Time (months)

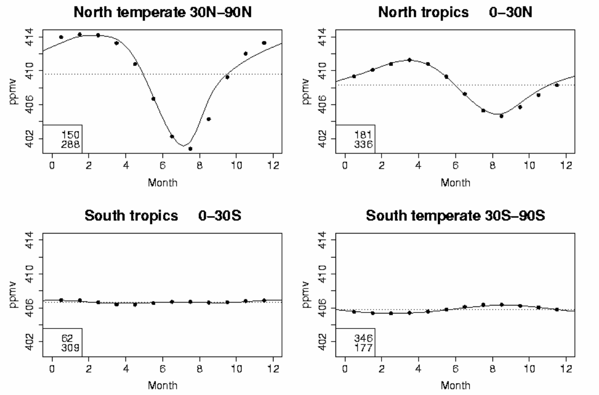

Seasonal amplitude
Amplitude ppm
Peak amplitude in 1992
Year AD
Seasonal phase
Phase
8 days earlier in 50 years
Year AD


4-box model of atmospheric circulation
Above ground
Terrestrial
Anthropogenic
Ocean

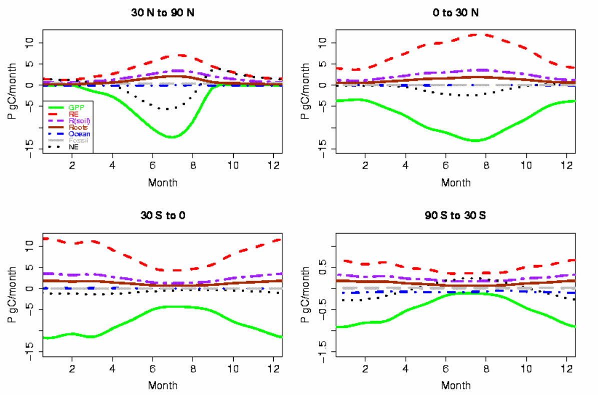

Clark-Thompson phenological GDD model
Days
10
20
30
40
50


Spin-up
North temperate 30N–90N
North tropics 0–30N
South tropics 0–30S
South temperate 30S–90S
ppmv
Year

CO_2 mixing-ratios



CO_2 fluxes



Summary

- **Successes:**

GDD models allow up-scaling from plant to planet.

Springtime advance in global CO_2 matches degree-day phenologies (*if 50% of plants are fully temperature sensitive*).

- **Future aims:**

Add remote sensing of NDVI & CO_2 into the global CO_2 model.

Challenge 3: Phenological extinctions & invasions

Main Question:

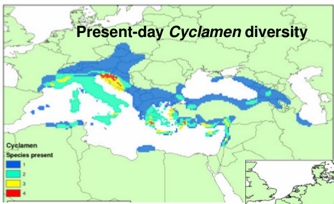
"Where will biota move to and how quickly?" *(Gillson et al, 2008)*

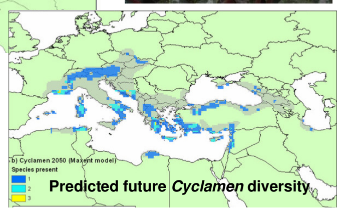
Typical answers 1 & 2:

1. *"No general 'invasive syndrome' seems to exist ... the idiosyncrasy of each invasion [is] context-dependent"*
(Petit et al., 2004)

2. *"There is almost no species for which we know enough relevant ecology, physiology and genetics to predict its evolutionary response to climate change"*
(Holt, 1990)

"For many species [of Cyclamen], there may be no areas with a suitable climate [by 2050], these species are considered to be at high risk of extinction."





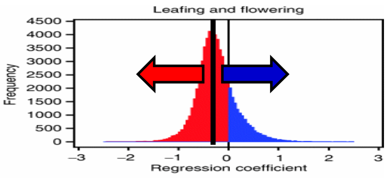
Yesson and Culham 2006 *Evolutionary Biology* **6**:72

Debussche et al. 2004 *Botanical Journal of the Linnean Society* **145**:469–484

Extinctions?

Temperature responsive
↓
High plasticity
↓
'Built-in' mechanism to combat climate change

Photo responsive
↓
Low plasticity
↓
No adaptability



Histogram of phenological trends in Europe (1971–2000) as linear regression coefficients (days yr^{-1})

Menzel et al., 2006 European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**, 1969–1976.

Hence

Answer 3:

" We should expect considerable numbers of extinctions, unless we take special steps to transfer artificially whole groups of species from one geographic region to another."

(Bradshaw and McNeilly, 1991)

Summary

- **Ecosystems will inevitably desynchronise**
- **Many plants and animals will develop 40 days earlier. Photoperiod sensitive taxa will not be able to adjust to climate change.**
- **As natural habitats struggle to adapt, unpredictable changes in the presence and abundance of species will ensue.**
- **Increased extinction risk is very likely.**

Challenge 4: Genetics

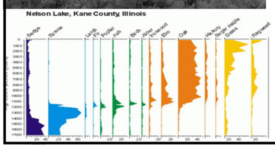
Question: Will plants keep pace with future climate change?

[i.e. will microevolutionary (genetic) responses be able to mitigate against the negative consequences of climate change?]

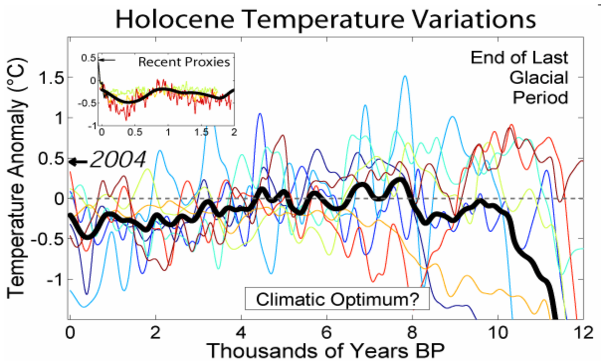
Pollen and historical evidence for plant migrations vs. **Genetic evidence for rapid micro-evolution**

1909

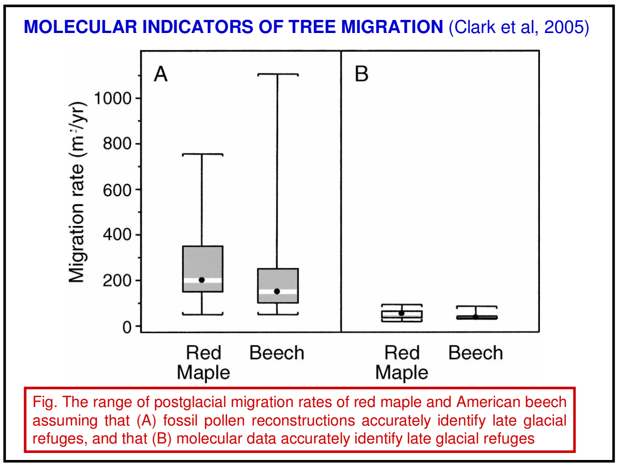
2004

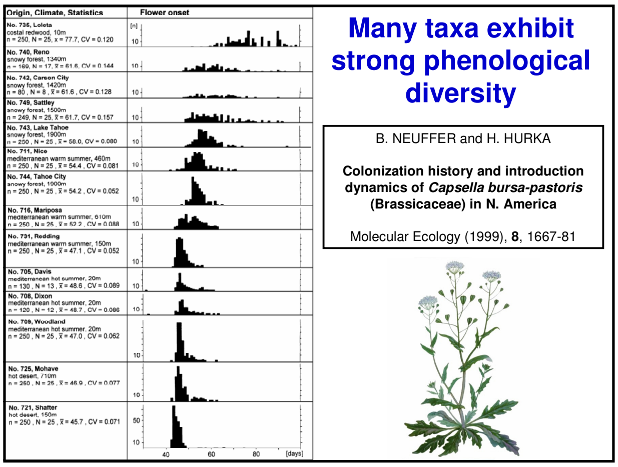


In just over 50 years, the dark, dominant alleled, subspecies of the peppered moth went from making up just 2% of the population to 95%, due to industrial melanism



The Holocene Climate Optimum warm event consisted of increases of up to 4 °C near the North Pole. The average temperature change declined rapidly with latitude so that essentially no change in mean temperature is reported at low and mid latitudes.





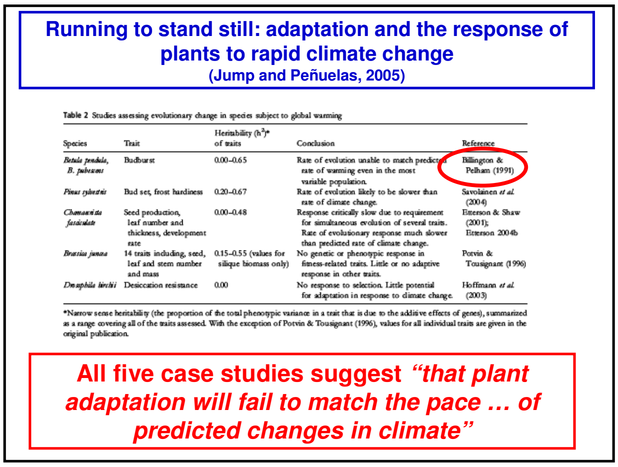


Table 2 Studies assessing evolutionary change in species subject to global warming

Species	Trait	Heritability (h^2)* of traits	Conclusion	Reference
Betula pendula, B. pubescens	Budburst	0.00–0.65	Rate of evolution unable to match predicted rate of warming even in the most variable population.	Billington & Pelham (1991)
Pinus sylvestris	Bud set, frost hardiness	0.20–0.67	Rate of evolution likely to be slower than rate of climate change.	Savolainen *et al.* (2004)
Chamaecrista fasciculata	Seed production, leaf number and thickness, development rate	0.00–0.48	Response critically slow due to requirement for simultaneous evolution of several traits. Rate of evolutionary response much slower than predicted rate of climate change.	Etterson & Shaw (2001); Etterson 2004b
Brassica juncea	14 traits including, seed, leaf and stem number and mass	0.15–0.55 (values for silique biomass only)	No genetic or phenotypic response in fitness-related traits. Little or no adaptive response in other traits.	Potvin & Tousignant (1996)
Drosophila birchii	Desiccation resistance	0.00	No response to selection. Little potential for adaptation in response to climate change.	Hoffmann *et al.* (2003)

*Narrow sense heritability (the proportion of the total phenotypic variance in a trait that is due to the additive effects of genes), summarized as a range covering all of the traits assessed. With the exception of Potvin & Tousignant (1996), values for all individual traits are given in the original publication.