Lecture 4, Characterizing the Vegetation, Part V: Phenology

- Outline
- Phenology, Defined, Quantified, Observed, Modeled
- Discuss Trends with Climate, Latitude, Global Change
- Discuss impact of phenology on agriculture, ecology, weather and climate

Phenology

– Study of the Timing of Natural Phenomena, like flowering, bud break, full leaf expansion, & leaf fall
– Derived from Greek word *phaino,* meaning to show or appear,

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Phenology is a classic topic of biometeorology. The timing of many of life's events are cued by such factors as accumulated heat units and day length, things we measure and study.

Why Study Phenology?

- Determine structural and functional state of leaves, flowers and fruits
  - Know when leaves are present/absent, functioning and senescent
    - Photosynthesis, Transpiration, Albedo, VOC emissions
  - Know when flowers emerge and are pollinated
    - Fruit and reproduction

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Deciduous plants operate is a quasi on/off mode, in either the deciduous and dormant stage or the leafed and photosynthesizing stage. Knowing when leaves leaf-out and how long they are active play important roles on how much carbon can be assimilated and how much water can be transpired from a vegetated landscape.

Description of principal growth stages of herbs

Stage	
0	Germination / sprouting/ bud development
1	Leaf development (main shoot)
2	Formation of side shoots / tillering
3	Stem elongation or rosette growth / shoot development (main shoot)
4	Development of harvestable vegetative plant parts (beet, tuber) / Booting (=swelling of panicle, ear, ...) (main shoot)
5	Inflorescence emergence (main shoot) / heading
6	Flowering (main shoot)
7	Development of fruit
8	Ripening of fruit and seed
9	Beginning of dormancy, die off of leaves, stem, ...

Life stages and history of an annual crop plant.

Phenological States of a Forest: Phenoseasons

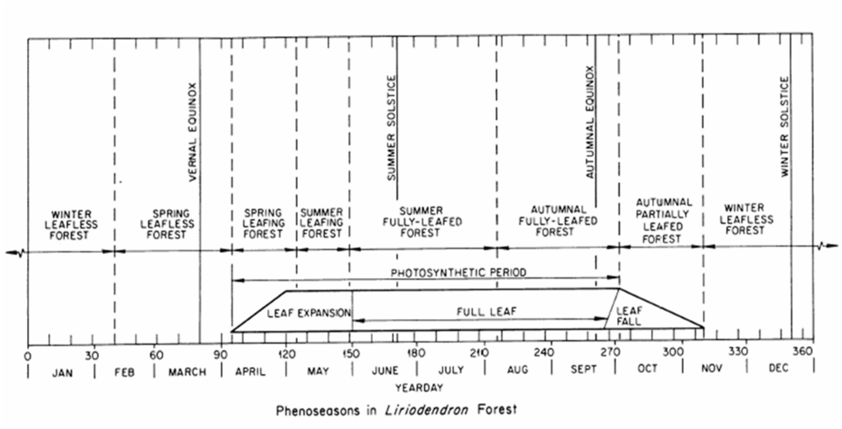
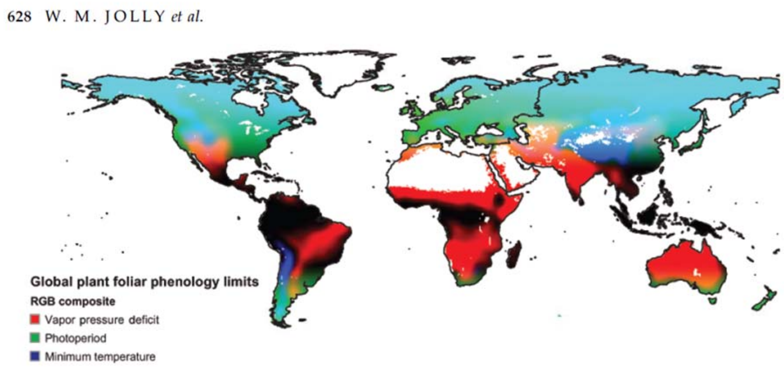


FIG. 2. Phenoseasons in the tulip poplar forest. ORNL Dwg. 74-11562.

Hutchison and Matt, 1977 Ecol Monograph

Life history of the phenoseasons of a deciduous forest.

Regional Variations in Controls on Phenology



Sub-Tropics are Drought Deciduous

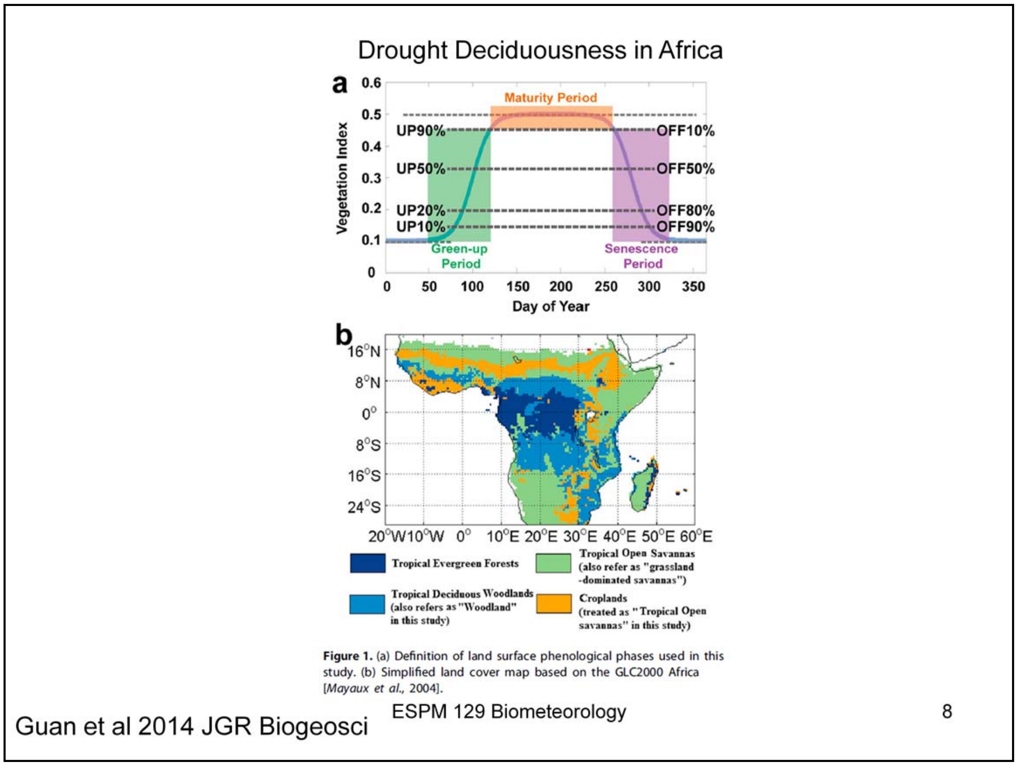
Temperate and Boreal Zones are Queued by Temperature and Daylength

One size does not fit all when describing and predicting phenology. In the warm, wet tropics, deciduousness can occur due to seasonal drought.

Drought Deciduous Forest in Thailand

http://www.ecology.kyoto-u.ac.jp/~atto/Thailand_ENG.html

Sakaerat Environmental Research Station. I was recently at the AsiaFlux meeting and was astounded to see the state of this drought deciduous tropical forest in Thailand. My prior impression was that drought was relative and only a few leaves fell.



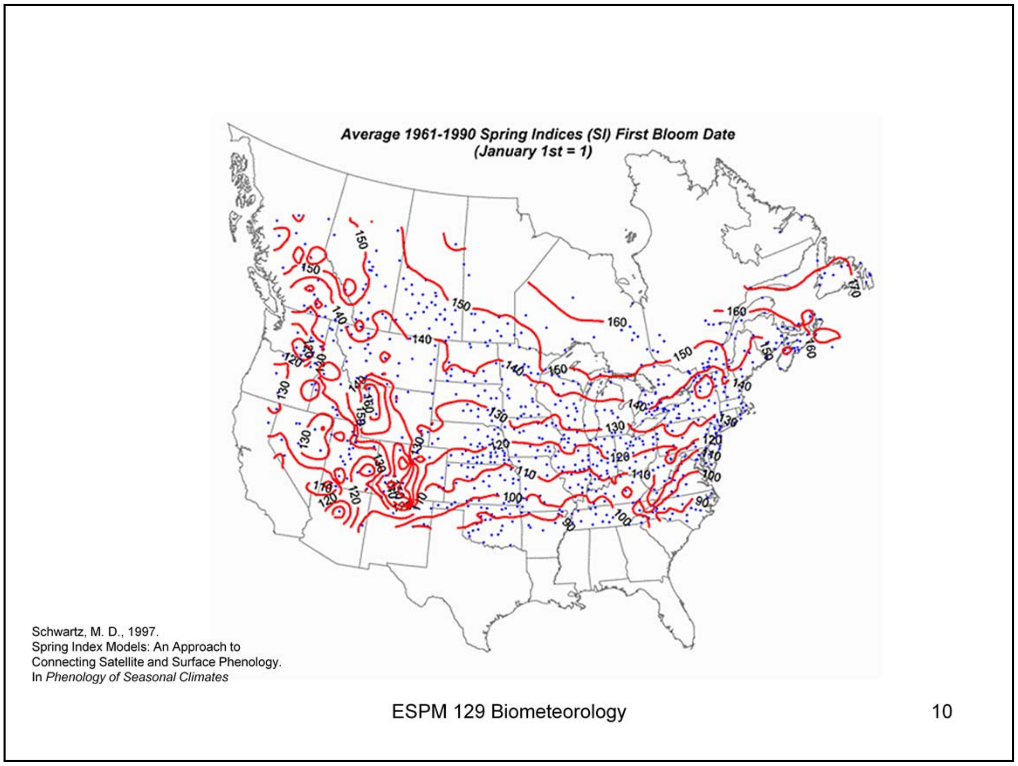
Timing of Drought Deciduousness across Africa. Guan et al 2014 JGR Biogeoscience

Hopkins Law of Phenology

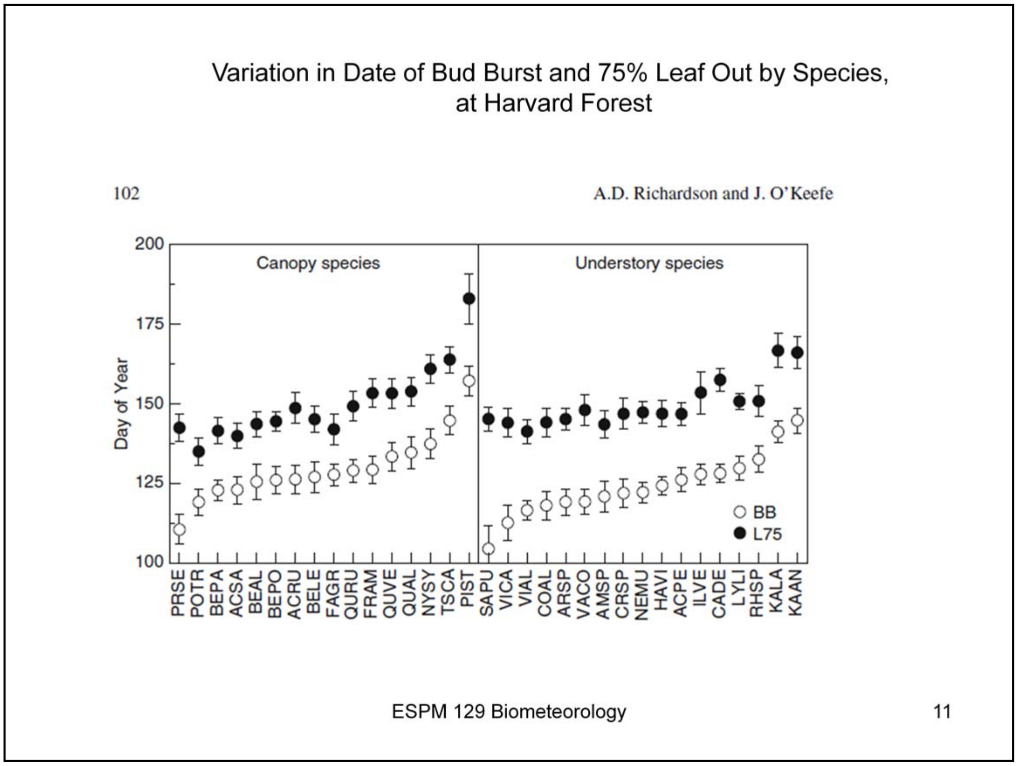
- Phenology-of plants in the temperate deciduous forest biome-differs by four days for every degree of latitude, every 5 degrees of latitude and every 400 feet of altitude

Andrew Delmar Hopkins

A simple biogeographical rule, indicating how phenology, as defined by bud break or first bloom, will change with latitude and altitude.



The timing of first bloom is very distinct as one moves from south to north across the eastern half of North America. Bloom can happen as early as day 90 (end of March) in Tennessee and is as late as day 150 (end of May) in the northern tier of the US. The timing of first bloom, as determined by isolines, is very convoluted across the Rocky Mountains due to elevation.



While there are geographical patterns to phenology, they can differ at a locale by species, too. Here are data from a mixed hardwood forest at Harvard Forest. Data of Richardson and O'keefe.

Growing Season Length, as Detected by MODIS

S. Ganguly et al. / Remote Sensing of Environment 114 (2010) 1805–1816

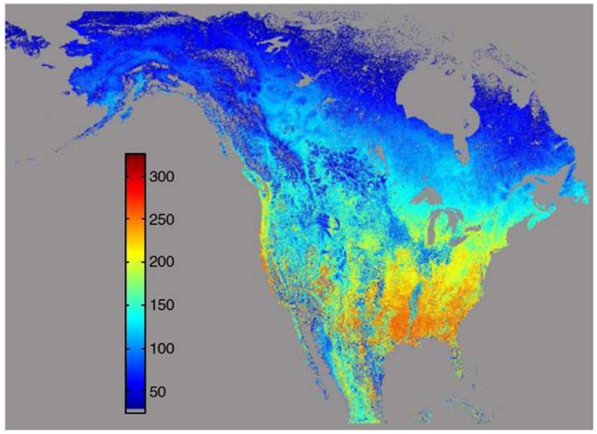
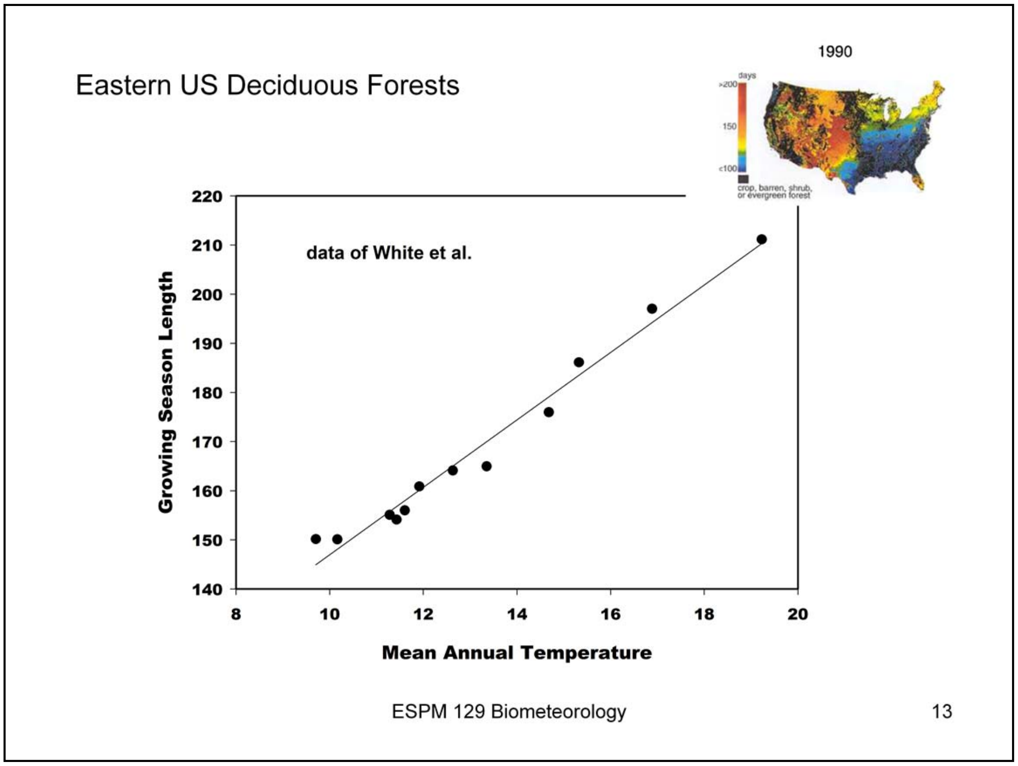
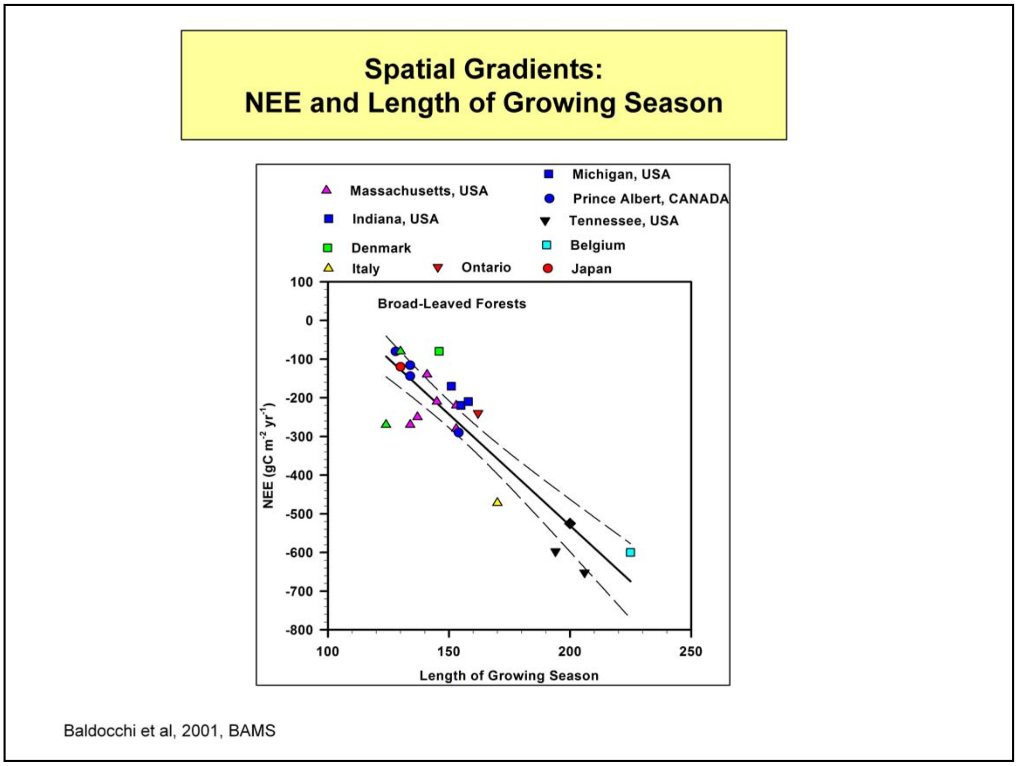


Fig. 1. Mean growing season length in days for North America for the period 2001–2006 derived from the MLCD product.

One of the key phenological metrics is length of growing season. Using reflection measurements from space, scientists are able to detect the start and end of the growing season and reconstruct maps of growing season. Along the Pacific Coast and the South, growing season exceeds 300 days. Along the Mississippi River and the Corn Belt we see a short growing season. This is not the true growing season length, but the effective growing season of the annual crops planted in these regions. The Rocky Mountains and Sierra Nevada experience less than 130 days in many areas

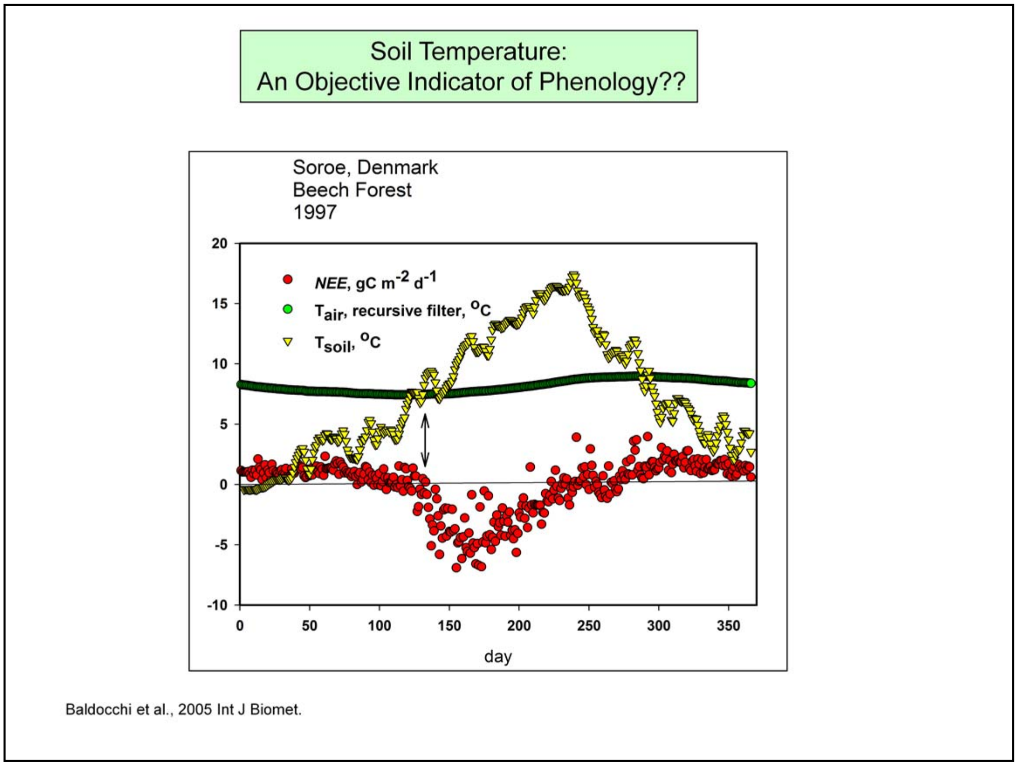


Scientists show a strong correlation between mean annual air temperature and growing season length.

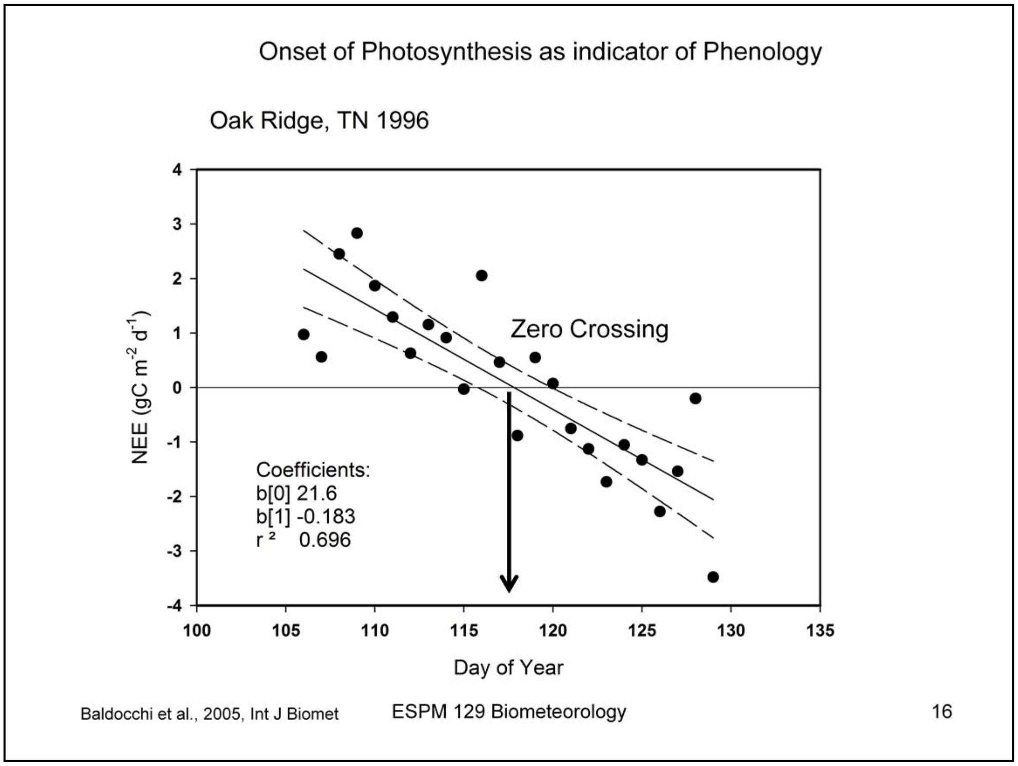


Length of growing season has an important influence on the amount of carbon taken up by temperate forests.

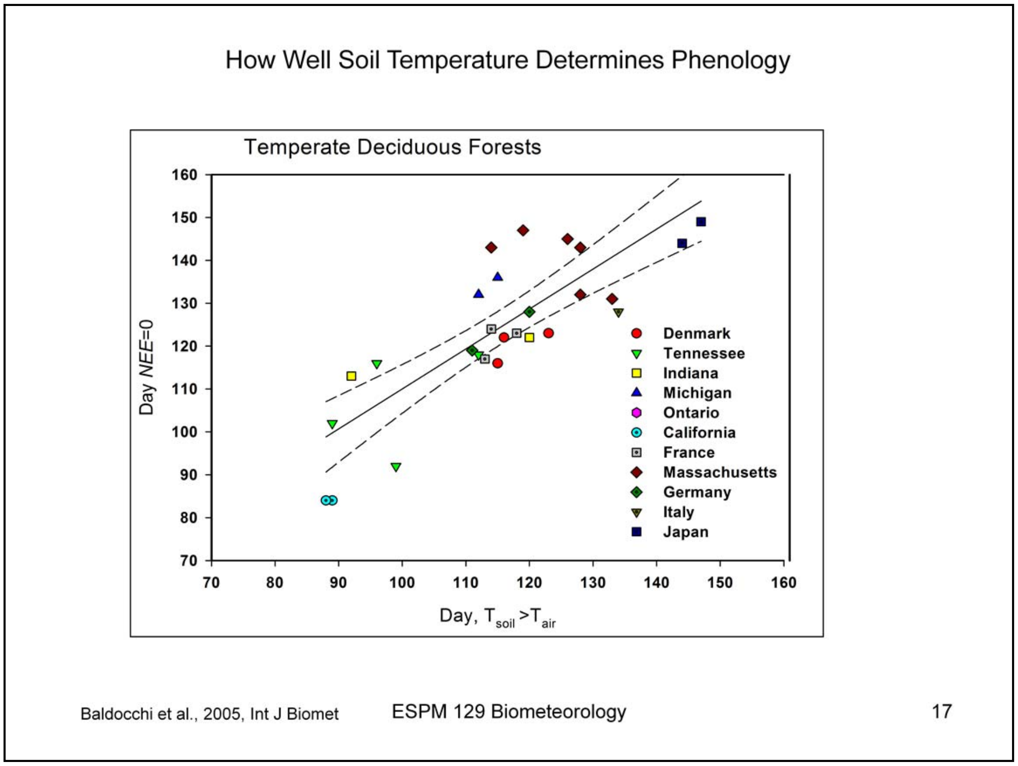
Coherent response among sites, impact of length of growing season. Does not account for interannual variability at a site, due to snow cover, drought, cloudy vs clear summers etc.



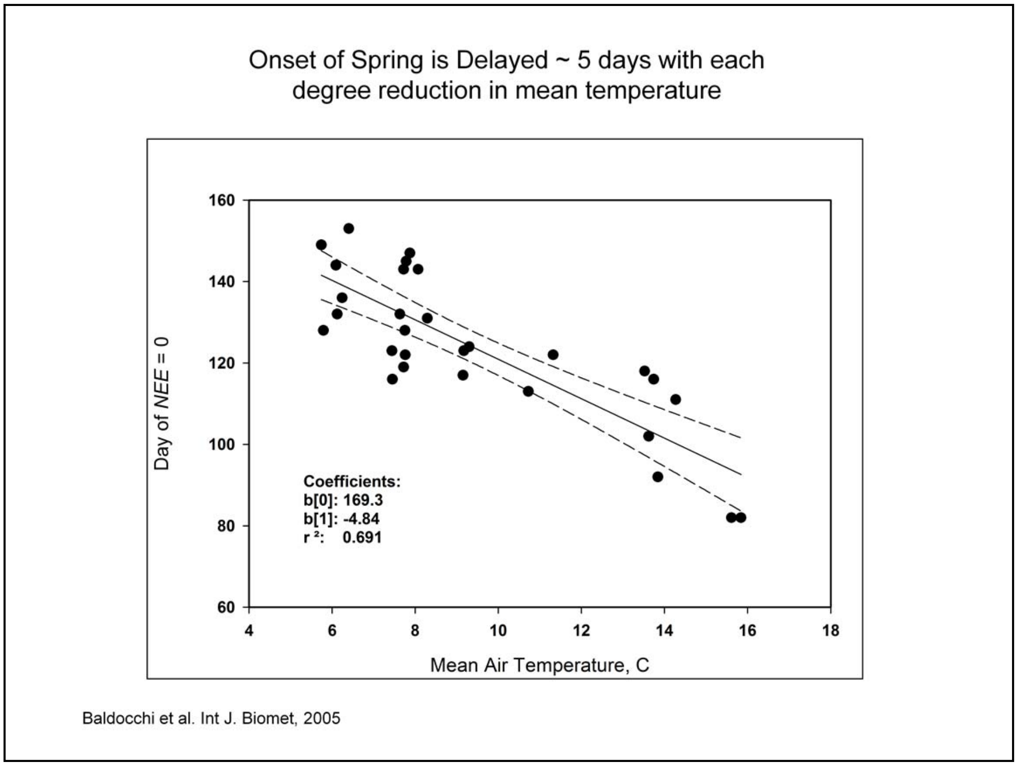
We found an interesting relationship between the start of the photosynthetic season when soil temperature cross over the mean annual air temperature. The question to be asked is if plants are in synch with their local environment. It makes some sense to start the growing season when the mean temperature is achieved, as in the spring. If leaves are launched too early there is a good chance they will experience extremely cold events. If they launch too late they miss out on important days of photosynthesis.



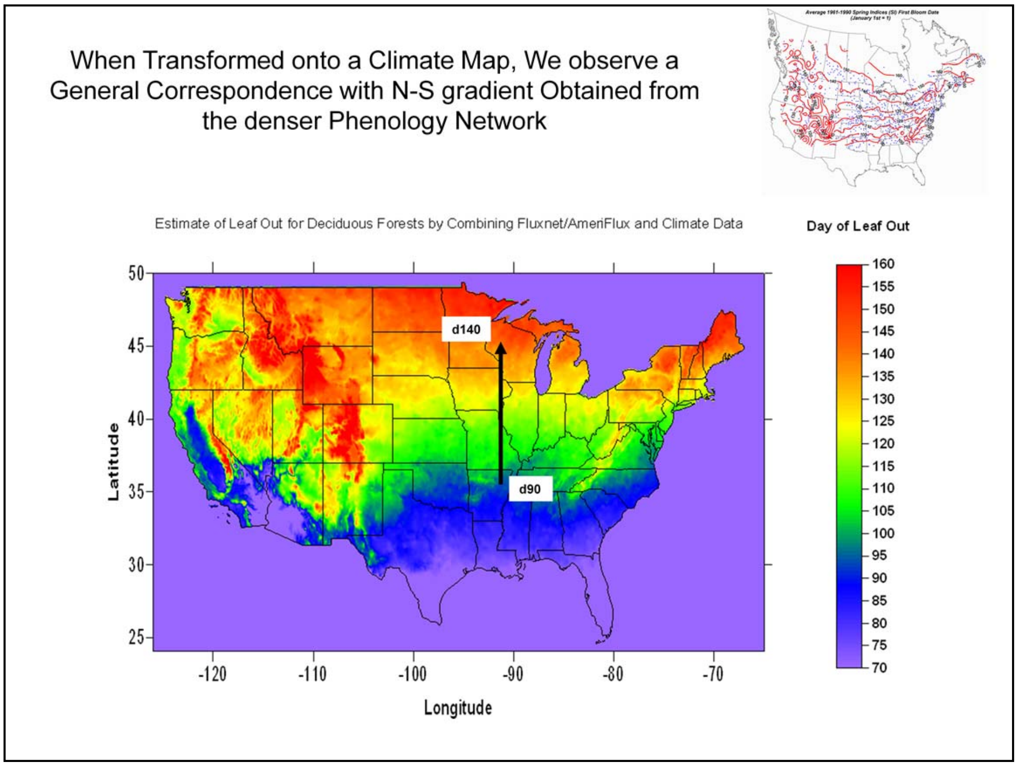
Using Carbon flux data we were able to id the critical day



We then applied this approach to a network of sites across the world and it works reasonably well, without tuning.

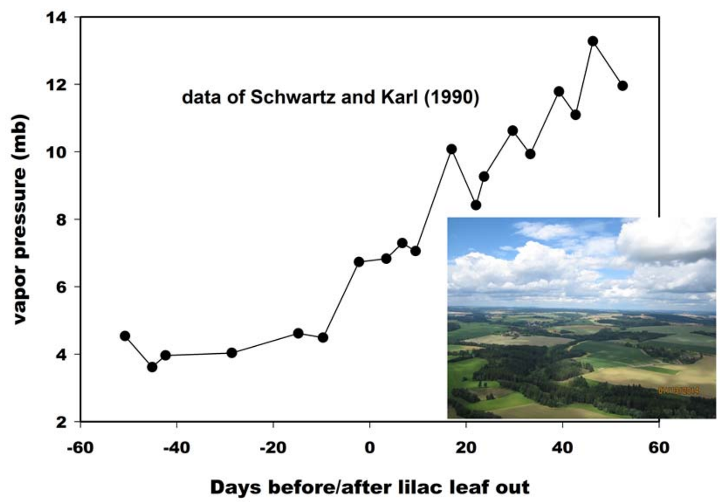


To upscale this idea regionally, we plotted the zero crossing day with the mean air temperature



Using GIS we created a map of the spring wave.

Phenology and Humidity, Eastern US



Schwartz and Karl (1990)

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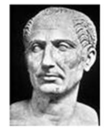
The presence and absence of leaves has a critical impact on the humidity of the air. The air is much drier without leaves. I also notice flying north south during the spring green up that on ‘clear’ days I don’t see cumulus clouds develop over the leafless forests, but they due over those with leaves and are transpiring. A classic example of plant-atmosphere interactions and feedbacks.

Caveat Emptor



- Growing Season Length has More Explanatory Power across a Latitudinal Gradient than at an Individual Site
- Additional factors explaining annual NEE at a Single Site include:
  – Absence/presence winter snow
  – Occurrence of Summer Drought
  – Extent of cloudiness

Also recognize that sometimes an earlier growing season may not yield more carbon uptake. There is a growing association that years with impending drought have an early spring, but then the soil water profile is depleted sooner, which reduces photosynthesis later in the season. So an increase in annual carbon uptake does not occur.

Dormancy

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Length of Growing season is dictated, in part by the length of the Dormant period and when that Dormant period Breaks. In this next section we will discuss methods to understand the duration of dormancy and when it breaks

Image of Steve McMillan.
http://www.sonic.net/aquatint/ART/art2Sonoma/art2pages/art2_a_fg.html

Heat Units and Phenology

- Growing Degree Days, GDD
  - Sum of Average Temperature above reference
- Chill Degree Days, CDD
  - Sum of Average Temperature below Reference, e.g. 7 C and above a threshold, e.g. 0 C
- Chill Hours
- Chill Degree Hours
- Heat Degree Days

$$GDD = \sum \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right)$$

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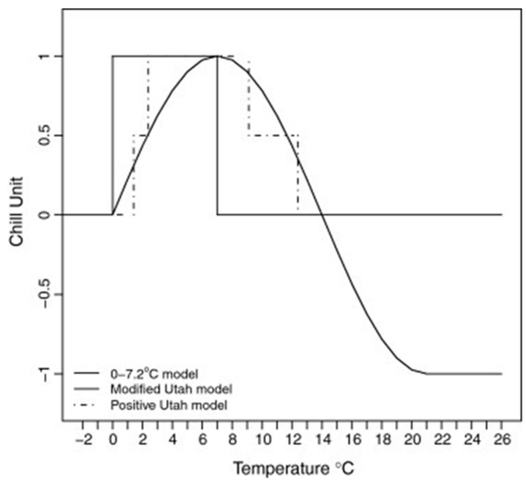
Simple heat unit models have been popular for decades to inform nut and fruit tree breeders how much cold they need to acquire to rest and break that rest. It also instructs farmers on where and where not to plant certain cultivars and species. Growing degree days and chill degree days are the simplest. You can also use this idea for heating homes. ‘days’ are counted in terms of the number of degrees warmer than some reference temperature. Degrees are not counted if temperature exceeds a critical value. Average temperature is the mean between maximum and minimum temperatues.

Winter Chill Models



Darbyshire et al 2011. AgForMet

Functional shape of simple and more complicated winter chill models. The simple chill degree method is denoted by the simple delta function. Better and more modern methods, like the Modified Utah method, penalize and subtract chill units if the temperature is too warm.

Processes

Temperature and Water Driven Phenology

Rest: is a function of a sum of sufficient chilling

$$S_{chill} = \sum_{t_1}^{t_n} R_{chill}(T)$$

Quiescence: is a function of thermal forcing

$$S_{quiescence} = \sum_{t_1}^{t_n} R_{quiescence}(T)$$

Frost Hardiness:

Bud Burst: After Cumulative Chilling and Forcing Temperatures Exceed Threshold

Bud Burst, too Early: Risk of Frost Damage

Bud Burst, too Late: Missed Opportunity for Carbon uptake

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Other models are separating the Dormant period into one requiring enough chill to achieve rest, followed by enough warmth to break that rest.

Terminology

Dormancy: is a state of reduced growth rate, with few or no cell division in terminal or lateral meristems (Perry, 1971 Science); Dormancy Requires a Chill Requirement

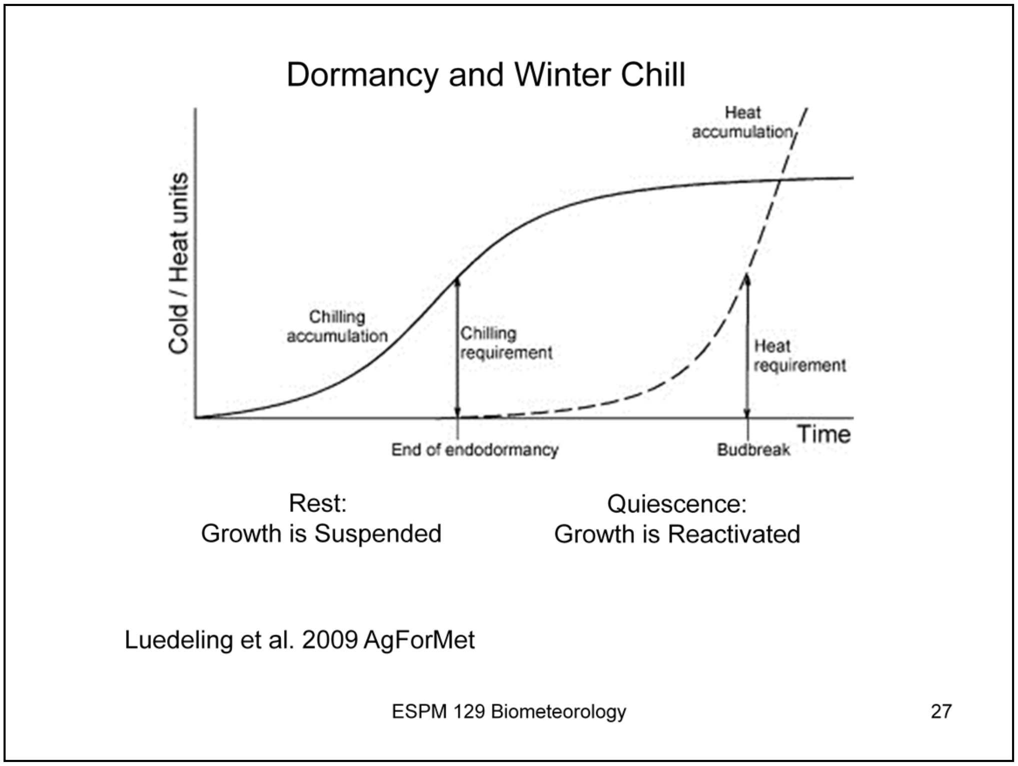
Dormancy can be Induced and Broken, Naturally or Artificially

Stages of Dormancy, Rest and Quiescence

Rest is a period when buds are dormant due to physiological conditions
Rest Ends when Chill Requirement is Fulfilled

Quiescence is a period when buds remain dormant due to unfavorable conditions; Quiescence ends when Forcing is fulfilled

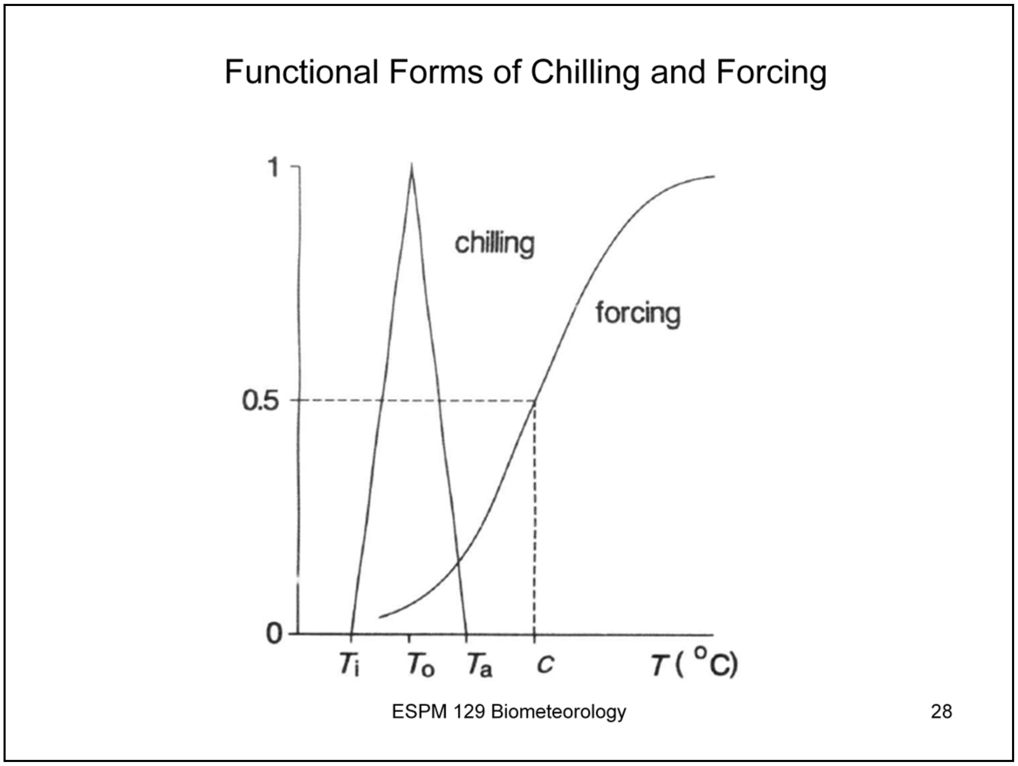
Bud break and blooming are activities that are visible and signify the End of Dormancy. It is easy to measure and observe the occurrence of bud break and blooming. But what factors lead to these events and how can we quantify them? To answer these questions let’s first examine Dormancy.



At the onset of dormancy, the buds are in a resting stage. This is a period of reduced growth rate,

with few or no cell division in terminal or lateral meristems (Perry, 1971 Science). Dormancy during the Rest phase Requires a Chill Requirement, so this is the period of Chill Accumulation. Once this Chill requirement is met, the end of dormancy needs some forcing, produced by hormones and triggered by Heat requirements

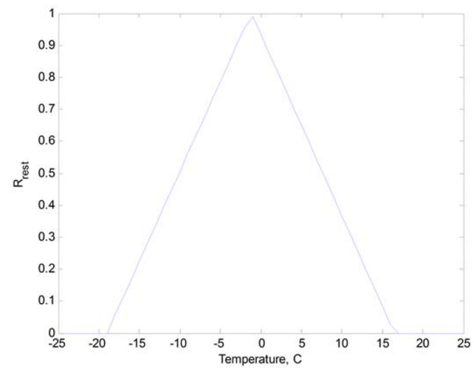
I am seeing some contradiction in the literature and terminology. A number of modelers (Chuine, Kramer) speak of quiescence occurring after the Chill requirment is met. Others are calling quiescence the initial phase. TBA



Simple models by scientists like Kramer 1994; Hanninen 1990; Chiune (1999) sum the chilling and the forcings functions based on the temperatures during the dormant seasons. Here are visual shapes of these forms.

Accumulation of Thermal Heat Units for Rest, or chill

$$R_{rest}\begin{cases}0, \quad T(t) < T_{\min} \\ \dfrac{T(t)-T_{\min}}{T_{opt}-T_{\min}} \quad T_{\min} < T(t) < T_{opt} \\ \dfrac{T(t)-T_{\max}}{T_{opt}-T_{\max}} \quad T_{opt} < T(t) < T_{\max} \\ 0, \quad T(t) > T_{\max} \end{cases}$$



$$S_{rest} = \sum_{t_1}^{t_n} R_{rest}(T)$$

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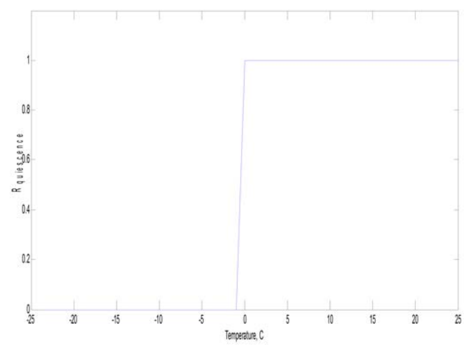
Functional Forms to define Rest.

Sources: Koen Kramer and H. Hanninen

Quiescence/Forcing



$$R_q = \begin{cases} 0, \; T(t) < T_{\min} \\ \dfrac{1}{1+\exp(a_0 T(t) + b_0)}, \; T(t) >= T_{\min} \end{cases}$$

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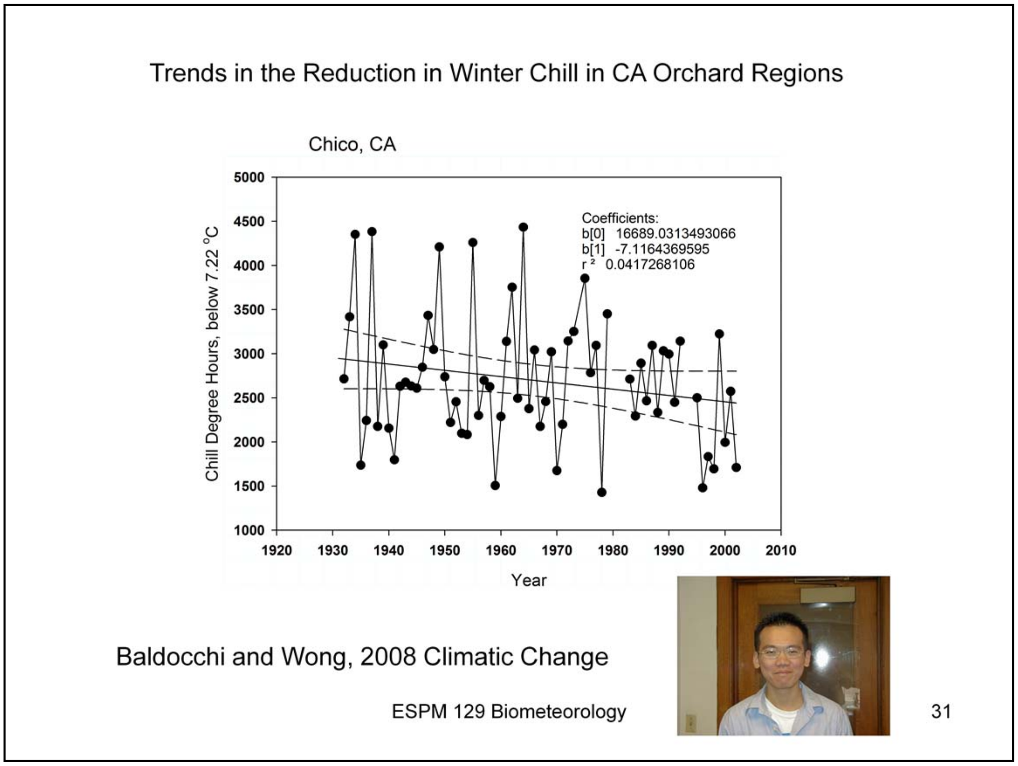
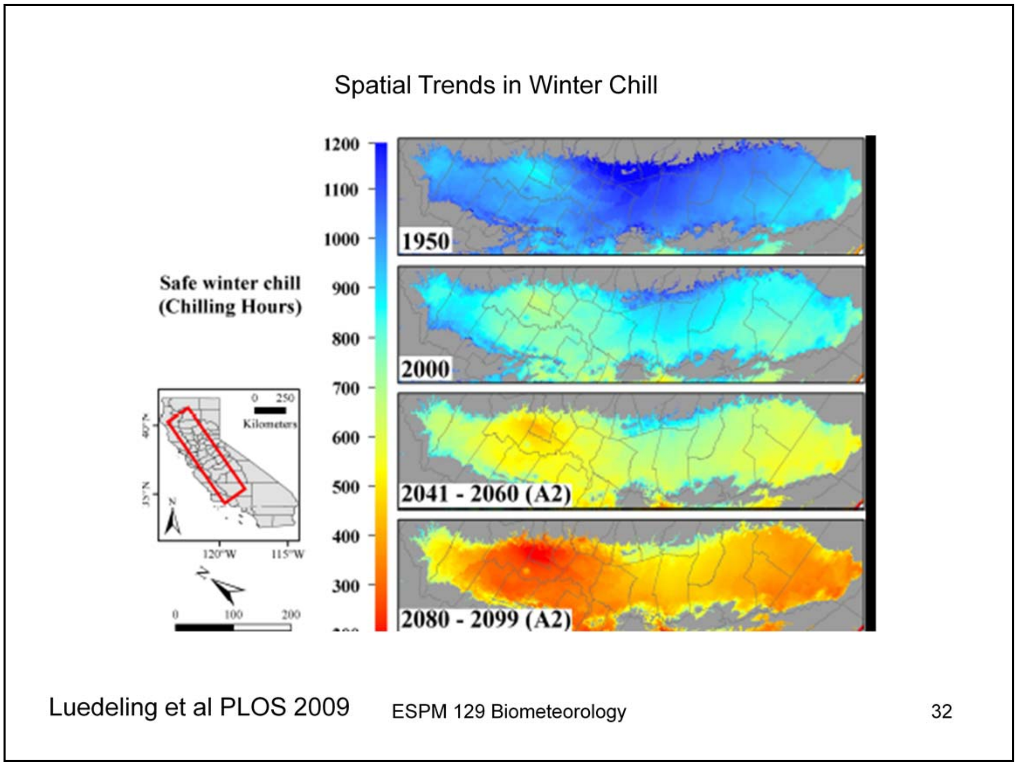
Mathematical Functions and Functional shape of Forcing function

Kramer, 1994 Chuine et al 1999 PCE



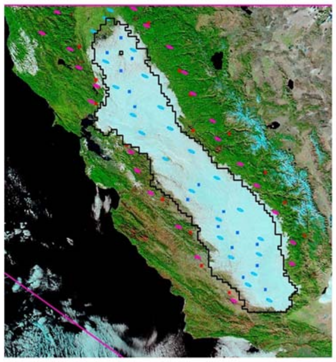
Using simple Chill method, an undergraduate student, Simon Wong, and I inspected if there are trends in winter chill as California faces and is experiencing global warming. We see lots of year to year variation, but we also found trends in decreasing winter chill across the fruit growing region of California. In sufficient chill can affect flowering, flower abortion and fruit set.

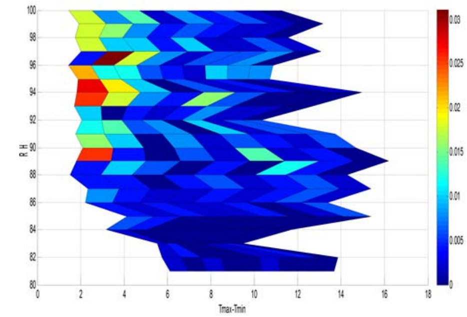
The idea for this work was catalyzed by a conversation I had with my cousin, a cherry rancher, after I gave a talk at the local farm bureau. He reflected that his cherry crops were not as productive in the past because he was not getting enough winter chill. His option was to apply an expensive plant hormone to mimic the effects of chill.



Eike Luedeling, at UC Davis has spatialized past, current and future sums of winter Chill across the Central Valley of California. This is the power of GIS, to take simple point based analyzes and spatialize them and produce maps.

Winter Chill is Promoted by Valley Fog





Baldocchi and Waller, 2014 GRL

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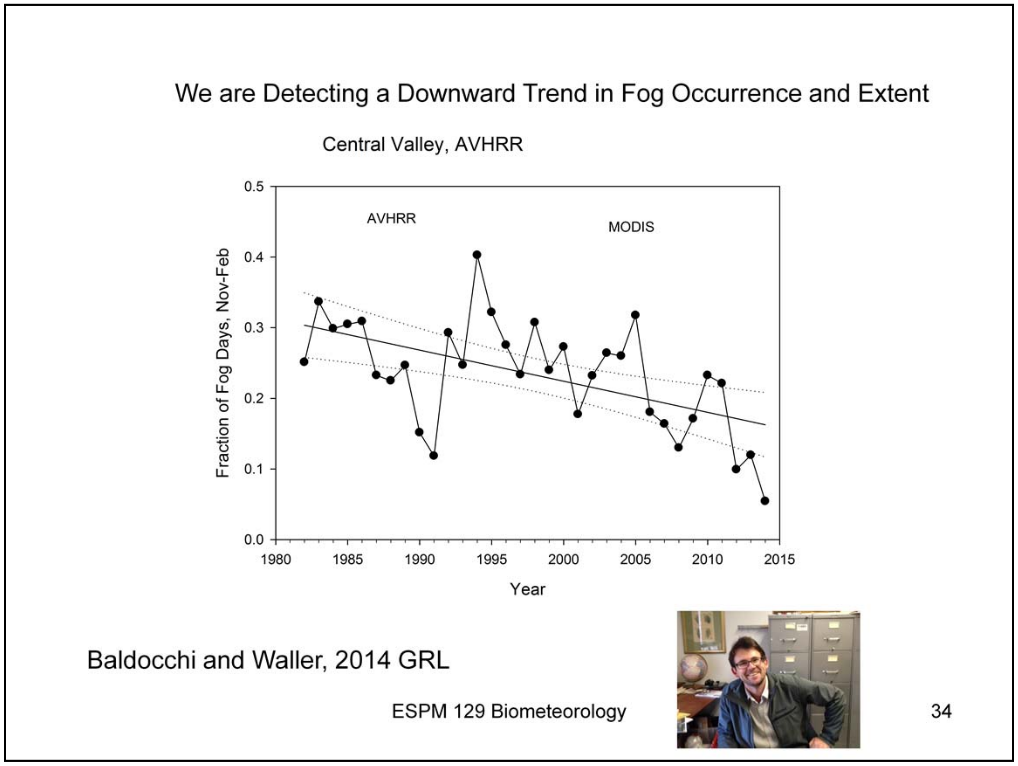
As scientists we also want to know How and Why, in addition to What. With regards to winter chill, many of us native to the Central Valley have notices we are getting less winter fog. Is this real and could it contribute to less chill. Remember with less fog, air temperatures are higher and the energy balance on the buds is greater, increasing their surface temperature. In other words, Fog keeps the buds cool, so they can accumulate chill. This is a classic example of applied biometeorology.



Why may Chill be declining? One idea is that we are experience less winter fog. Over the period of satellite remote sensing we have seen a 40% decline in the number of foggy days.

To answer this question, I collaborated with a graduate student, Eric Waller, Ph.D.. We acquired satellite data from the MODIS and AVHRR sensors. The time series goes back to 1981. We then focused on California and attempted to count the number of days each winter we could see regions of the valley in fog. We found a downward trend in the number of fog events each winter. Again lots of year to year variation with wet and dry years. But the trend is significant.

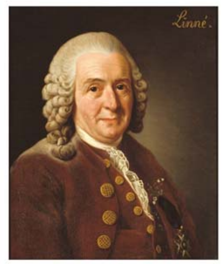
How it is Studied and Quantified

- Phenology Gardens
  - Blooming of lilac, honeysuckle or native plants
  - European Phenology Network'
    - http://www.dow.wau.nl/msa/epn/index.asp
  - National Phenology Network
    - http://www.uwm.edu/Dept/Geography/npn/
- Remote Sensing
  - Satellites
  - Digital Camera
  - Light Transmission
- Eddy Flux Measurements of Carbon Dioxide Exchange
- Models based on Thermal Time

Phenology is determined both indirectly and directly.

Phenology History

Robert Marsham
Britain, 1736…



Carl Linnaeus

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The longest records are observations at botantical gardens or country estates on the dates of first birds, first leaf, first flower etc. In Europe and Japan, some records span several hundred years. According to the history of phenology http://budburst.org/phenology_history the Japanese have been recording the timing of cherry blossoms for over 1200 years. Linneaus and Robert Marsham started observations in Sweden and Britain, respectively, in the 1700s.

Observations are also a great course of citizen science projects for school children.

Location of Phenology Gardens in North America

SPRING PHENOLOGY IN NORTH AMERICA 2339

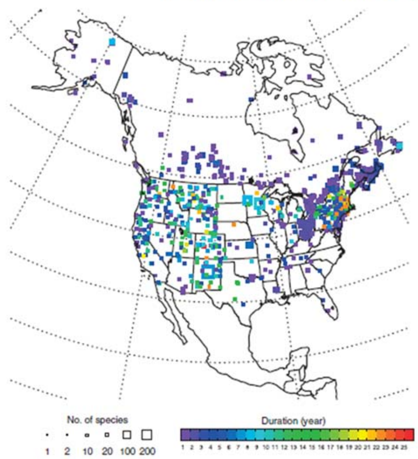

Fig. 1 Ground phenology records. Boxes show: location, center of box; number of species, box size; number of years observed at each site over the 1982–2006 study period, box color.

White et al, 2009, GCB

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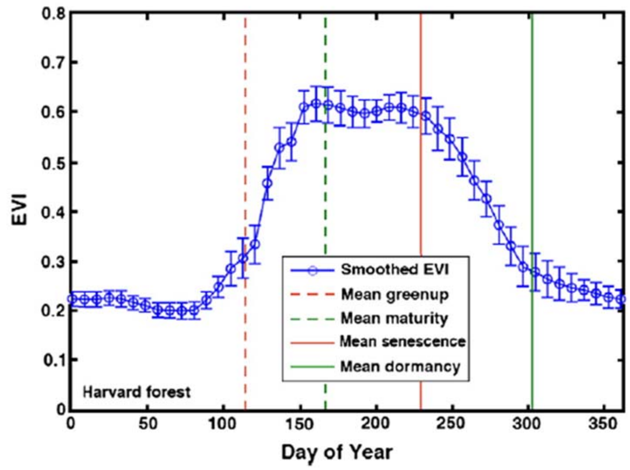
Map of Phenology Gardens

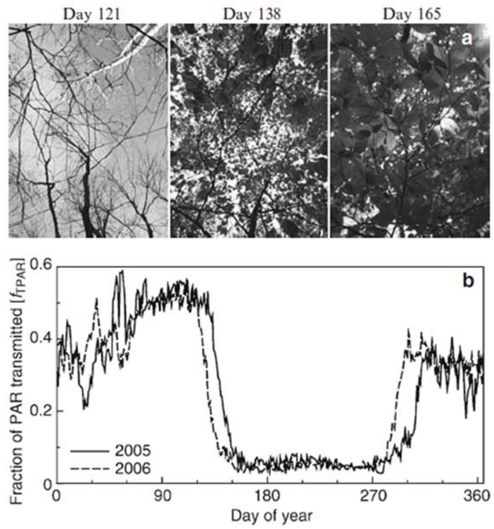
Detecting Phenology with Remote Sensing, using Normalize Vegetation Difference Indices



Ganguly et al 2010 RSE

Normalized Difference Vegetation Indices, like NDVI and EVI, enable one to study phenology from space and produce regional maps.

Light Transmission through Harvard Forest



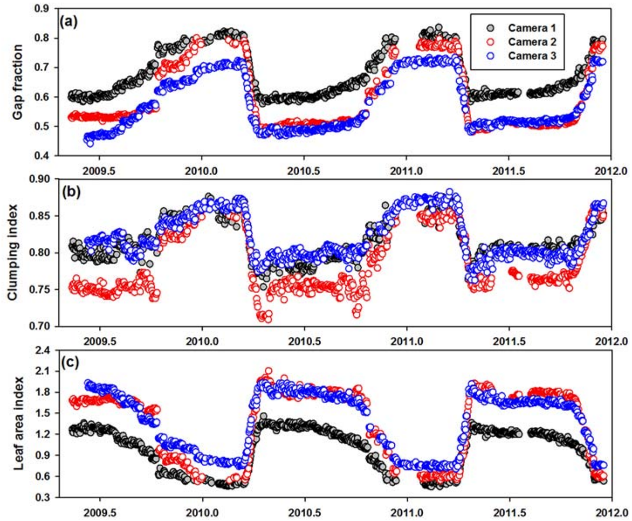
Richardson and OKeefe

Measurements of Light transmission through Forests is a good measure of dates of leaf on and leaf off.

Tram to Measure Light Transmission

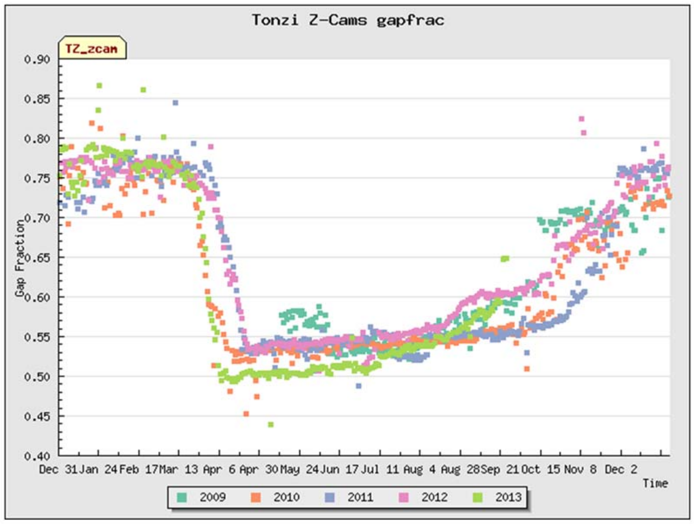
Monitor Seasonality of Gap Fraction of Forests
with Upward Looking Camera

Evaluating Phenology by Measuring Fraction of Light Transmission
Oak Savanna, Ione, CA



Ryu et al RSE 2012

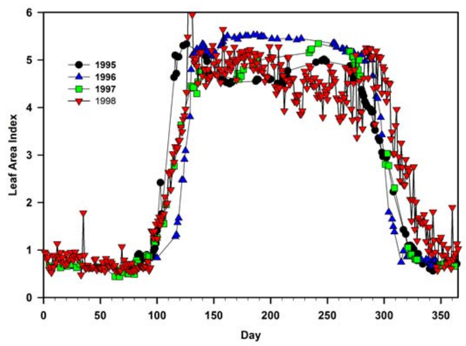
Gap Fraction Phenology with Upward Looking Cameras under Oak Savanna



Can Detect Start and End of Growing Season with Precision

Interannual Variability of Phenology, case I

Walker Branch Watershed, TN

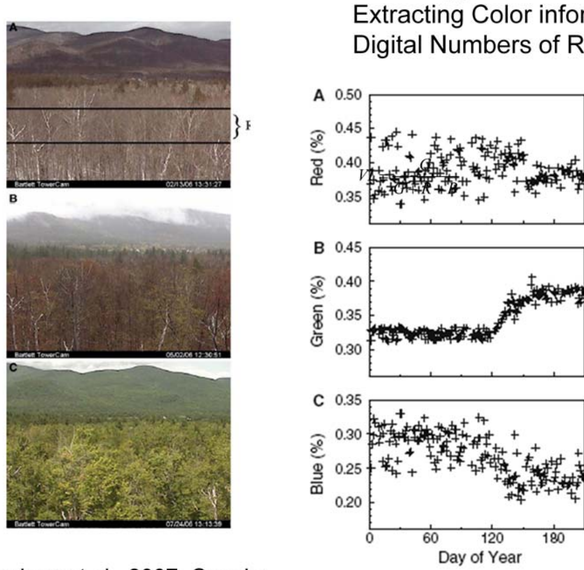


•Humid Climates, driven by Temperature and Day Length

•Start of Spring Can Vary by up to 30 days, on a year to year basis

•Years with Earlier Spring may Experience mid summer drought, shortening the physiological growing season

Phenology with WebCams by
Extracting Color information from
Digital Numbers of Red, Green and Blue

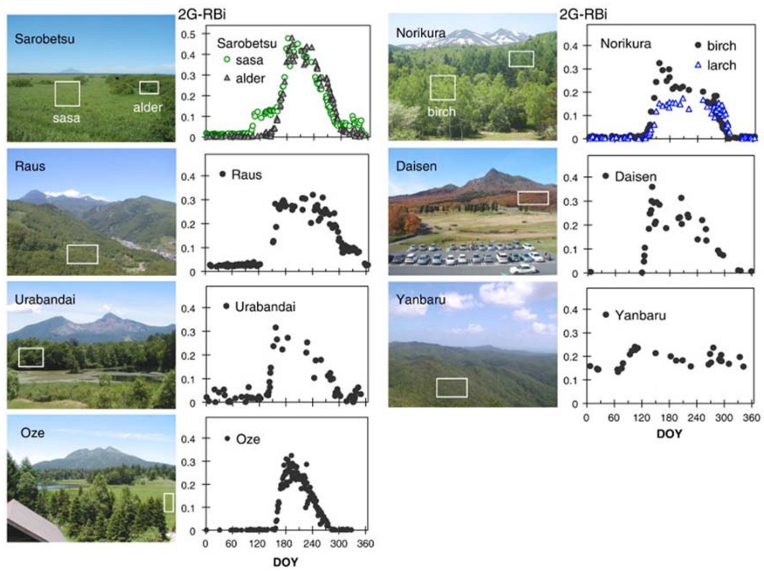


$$ExG = 2G - (R + B)$$

$$g_{cc} = \frac{G}{G + R + B}$$

Richardson et al., 2007, Oecologia

Phenology from Digital Cameras



Ide 2010 Ecological Informatics

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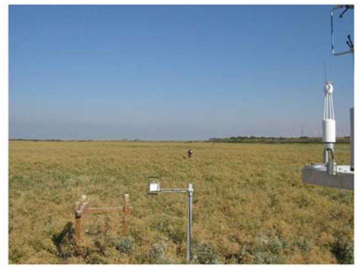
Digital cameras are producing quantitative and qualitative measures of phenology. Digital information from the Red, Green Blue bands can be manipulated to produce a greeness index. Here are data from Japan by Ide et al.

Phenology of Flowering and Seeding Plants Complicates interpretation of Greenness Indices

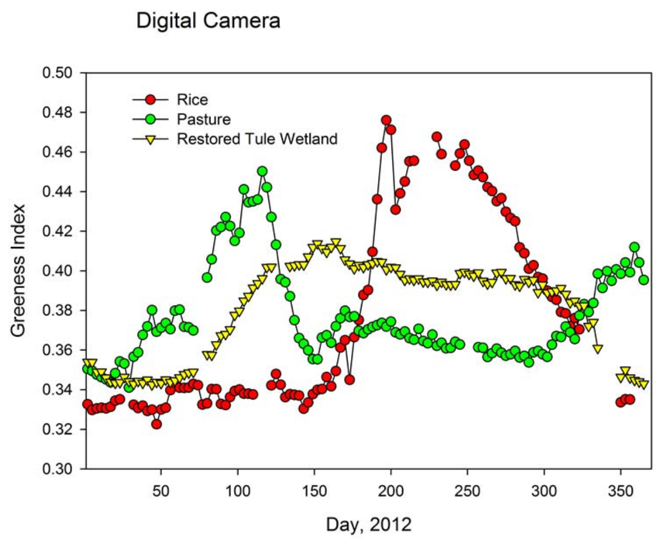
Purple Flowering Alfalfa



White and Yellow flowers on Pepperweed

Rice in Seed Stage

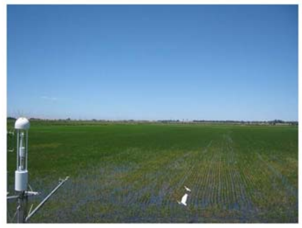
Greenness Index over Crop, Wetland and Pasture



Saenz, Knox, Sturtevant, Koteen, Verfaillie, Baldocchi, unpublished

Cameras Monitor Management and Phenology of Crops, Rice 2013

Disced, pre-planting



Flooding, seedlings

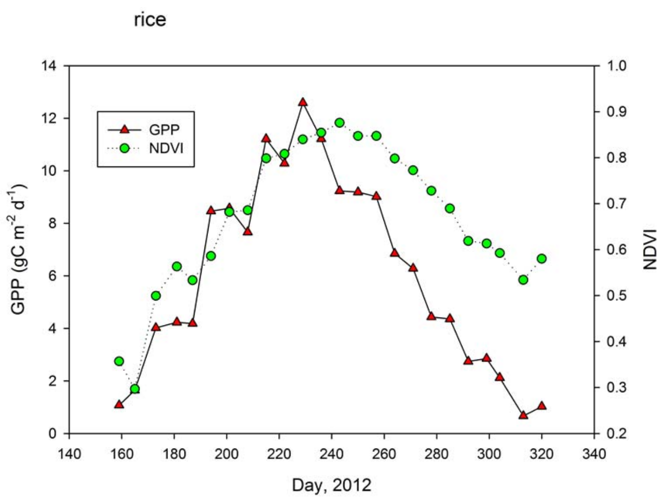
Full canopy, vegetated

Seed Filling

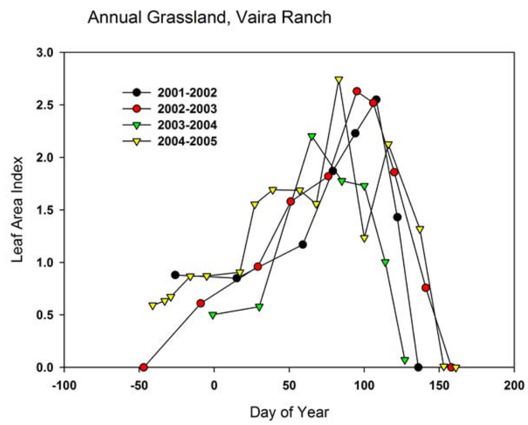
Harvesting

Chopped Straw

Canopy Photosynthesis vs Vegetation Index, Rice



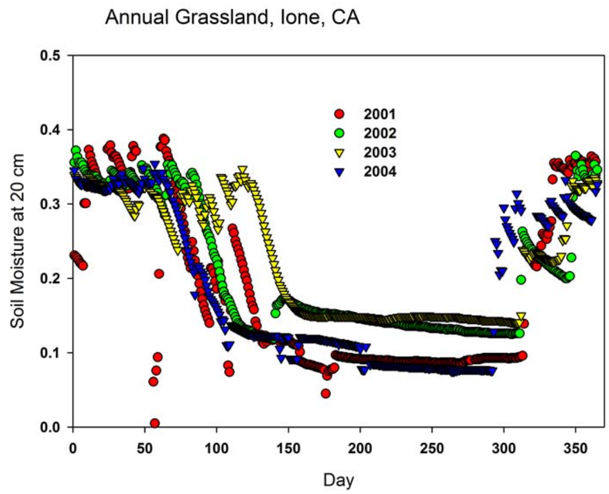
Interannual Variability of Phenology, case II



•Semi-Arid Climates Phenology is driven by timing of Rainfall and Rain fall amount

•Growing season Length can vary by 30 days year to year

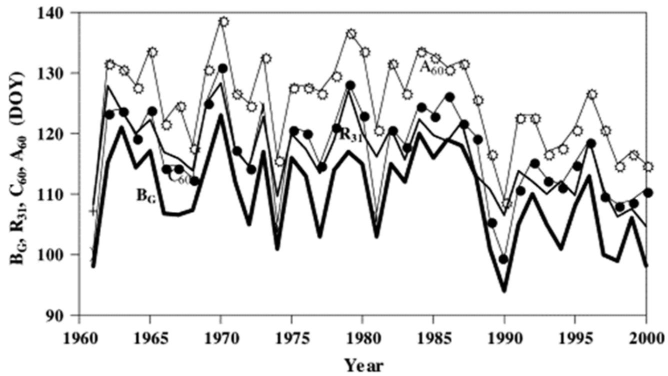
Length of Rain Period affects Phenology of Annual Grassland



Interannual variation of Wet season can vary by > 50 days


Global
Change
Biology

Warming in Spring, by 1 C, advances the growing season by 7 days.

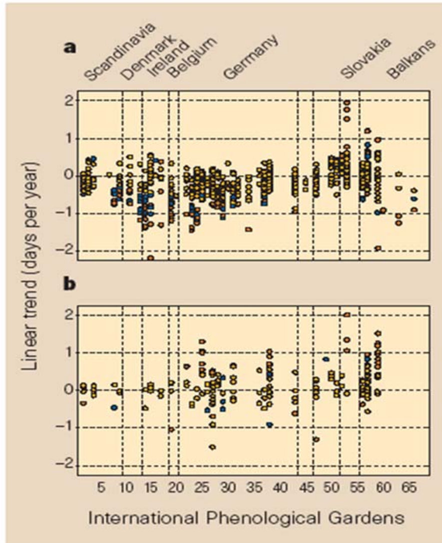


Average dates of the beginning of growing season (*B*G), beginning of stem elongation for winter rye (*R*31), beginning of cherry tree blossom (*C*60) and beginning of apple tree blossom (*A*60) in Germany, 1961–2000.

Chmielewski et al (2004), AgForMet

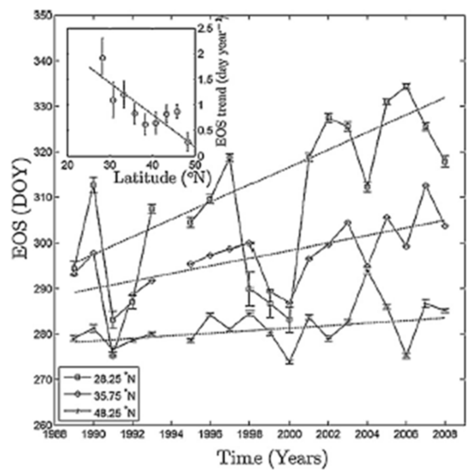
Many long term measures of spring are showing earlier and earlier appearance

Mean annual growing season in Europe increases by 10.8 days from 1981 to 1991.



Menzel and Fabian, Nature 1999

Positive Trends in the Date of the End of the Growing Season



Dragoni and Rahman, 2012

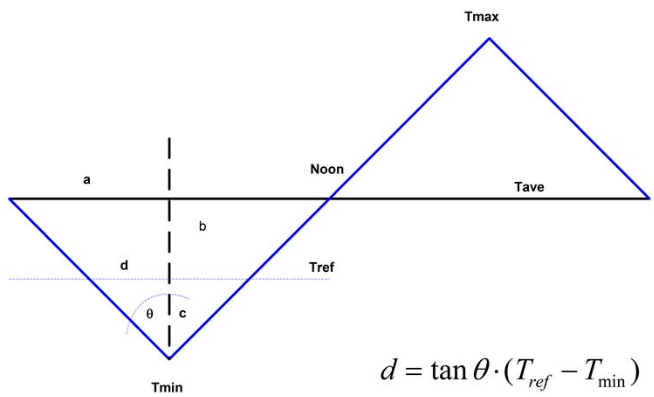
And the end of the growing season is getting later.

Summary

- The distribution of plant functional types is associated with climatic thresholds such as minimum temperature, occurrence of frost or freezing, and water balance
- New biogeographical theories and remote sensing measurements are able to help us map the global distribution of potential and existing vegetation with greater accuracy
- Phenology concerns us with the timing of plant activities. The timing of leaf out is one of the most distinct phenological events and can cause dramatic switches in atmospheric humidity, surface energy balance and carbon uptake
- Phenology is often estimated using growing degree days
- Many new studies are showing that global warming is causing length of growing season to lengthen, hence a feedback of temperature on phenology, besides kinetics
- Timing of phenology also has a major impact of the warming and the humidification of the atmosphere and the growth of the planetary boundary layer

$$\mathrm{Utah}_t = \sum_{i=1}^{t} T_{\mathrm{U}}, \quad \text{with } T_{\mathrm{U}} = \begin{cases} T \leq 1.4\,^{\circ}\mathrm{C} & : 0 \\ 1.4\,^{\circ}\mathrm{C} < T \leq 2.4\,^{\circ}\mathrm{C} & : 0.5 \\ 2.4\,^{\circ}\mathrm{C} < T \leq 9.1\,^{\circ}\mathrm{C} & : 1 \\ 9.1\,^{\circ}\mathrm{C} < T \leq 12.4\,^{\circ}\mathrm{C} & : 0.5 \\ 12.4\,^{\circ}\mathrm{C} < T \leq 15.9\,^{\circ}\mathrm{C} & : 0 \\ 15.9\,^{\circ}\mathrm{C} < T \leq 18.0\,^{\circ}\mathrm{C} & : -0.5 \\ T \geq 18.0\,^{\circ}\mathrm{C} & : -1 \end{cases}$$

Estimate Degree Hours from max-min Temperatures

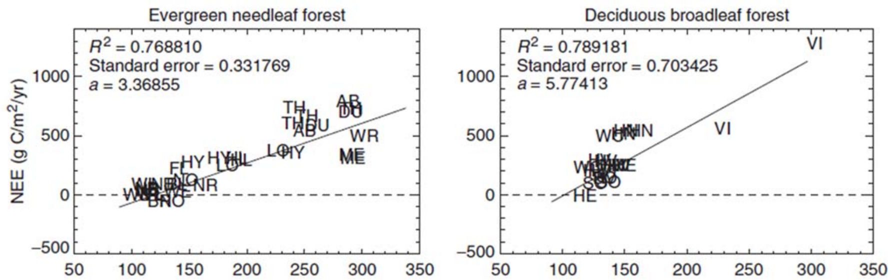


$$d = \tan\theta \cdot (T_{ref} - T_{min})$$

$$\tan\theta = \frac{a}{b} = \frac{6hr}{T_{ave} - T_{min}} = \frac{d}{c} = \frac{d}{T_{ref} - T_{min}}$$

Chill Hours = 2 d

Net Carbon Exchange Scales with Length of Carbon Uptake Period



Carbon Uptake Period

Churkina et al. 2005 Global Change Biology

Environmental and Ecological Drivers and Signals

Temperature

Is it warm enough to avoid frost damage?

Photoperiod

Are the days long enough to sustain a positive carbon balance?

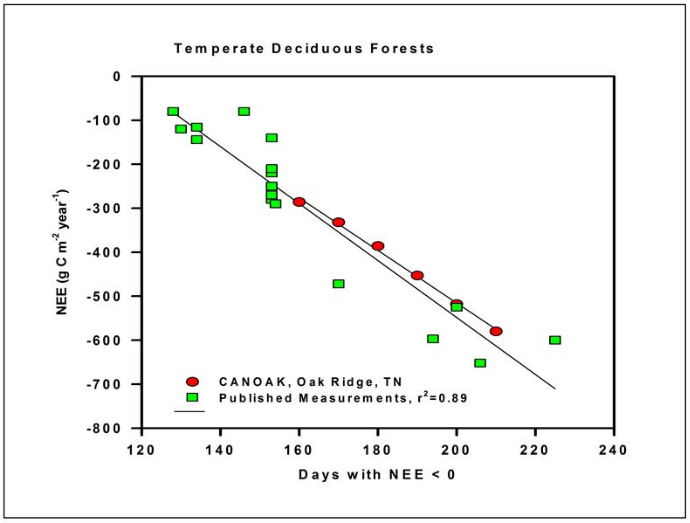
Rain/Soil Moisture

Is there Enough Soil Moisture to sustain growth?

Species, Plant Functional Group, Canopy Position (understory/overstory) and Age

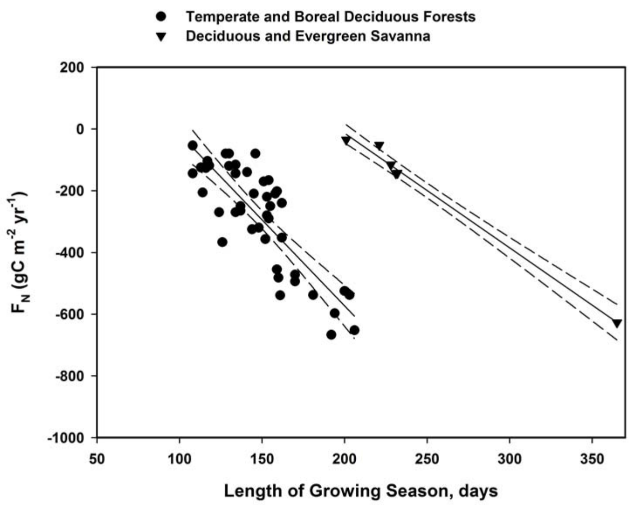
Which plants & species emerge early and late and why?

Year to Year differences in NEE across sites is due to differences in Growing Season Length



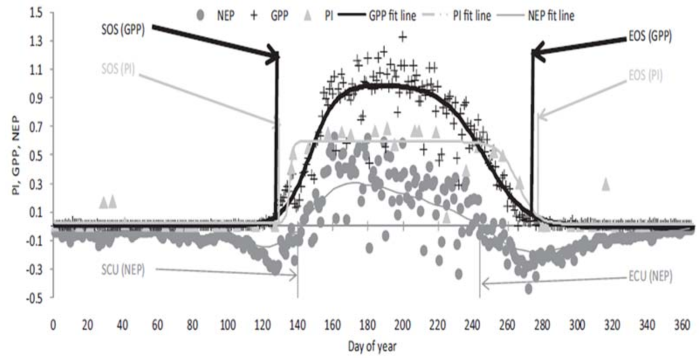
Baldocchi et al, 2001 Ecol Modelling

Net Ecosystem Carbon Exchange Scales with Length of Growing Season



Baldocchi, Austral J Botany, in press

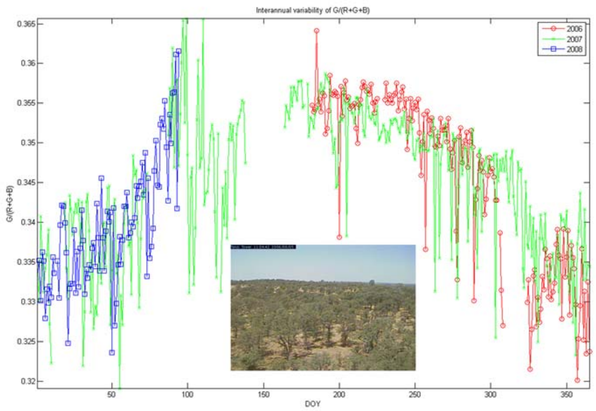
Gross Primary Production as a Measure of Phenology



Gonsamo et al 2012 AgForMeet

Seasonality of WebCam Vegetation Index: Oak Savanna

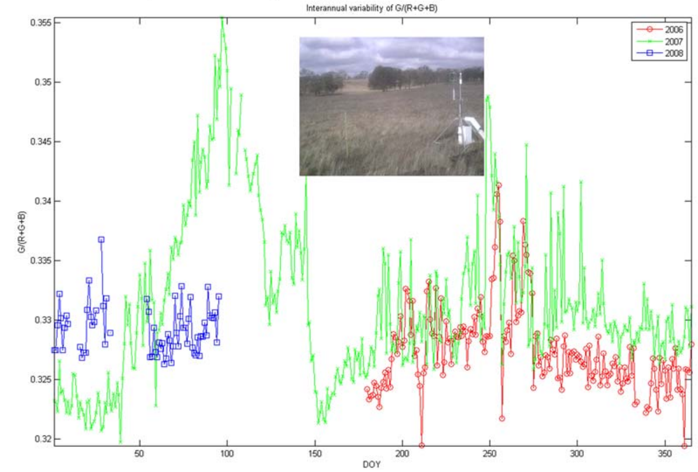
http://nature.berkeley.edu/~yryu/movie_tonzi_2007.wmv



Youngryel Ryu, analyst

Seasonality of WebCam Vegetation Index: annual grassland

http://nature.berkeley.edu/~yryu/movie_vaira_2007.wmv



Youngryel Ryu, analyst