Models for Honeybee Arrival and Blossom Phenology

MISG2020 SA Study Group Problem

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Phenology

- Phenology refers to the timing of annually recurrent biological events
- In plants, these include leaf unfolding, blossoming, fruit development, leaf colouration and fall
- In animals these events are more diverse and relate to the species in question, but can include the timing of hibernation, migration, breeding, molting, animal calls, growth of antlers, etc.
- The study of phenology tracks the timing of these recurrent biological events, and considers their biotic and abiotic forces
- This scientific field emerged in the 1960s, and forms one of the subdisciplines of *Biometeorology*

Phenology

- The greatest abiotic force affecting the timing of phenological events is the climate
- These can include:
  - Onset of rainfall
  - Threshold number of sunshine hours
  - Temperatures above a certain threshold
  - Accumulation of heat through the dormant period (growing degree days)
  - Accumulation of cold through the dormant period (chilling days)
- As the climate changes, the timing of these trigger events is changing. To many (but not all) species, ‘spring’ is now occurring in late winter, and ‘autumn’ in early winter

Phenology

- Each species has a unique set of biotic and abiotic factors which determine the timing of a given phenological event
- As a consequence, the rate of phenological shift is highly species and location specific

Eg. Granny Smith Apples in are flowering earlier at a rate of 4.2d/°C in South Africa, and only 2.4d/°C in Poland

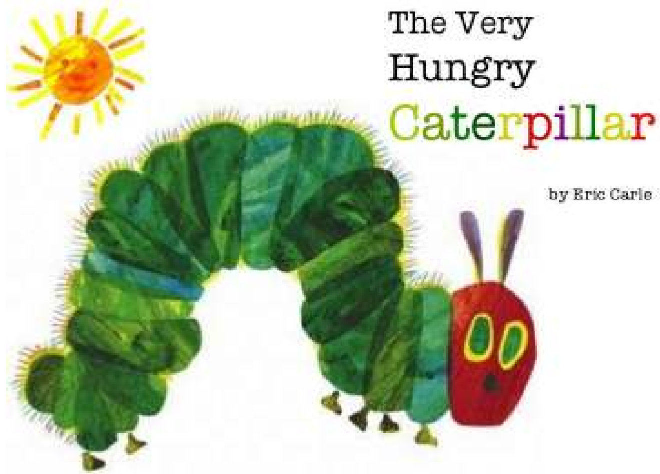
Eg. In China, cotton is flowering earlier by 0.66d/°C, while wheat is advancing at a rate of 3.4d/°C

Phenological Mismatches

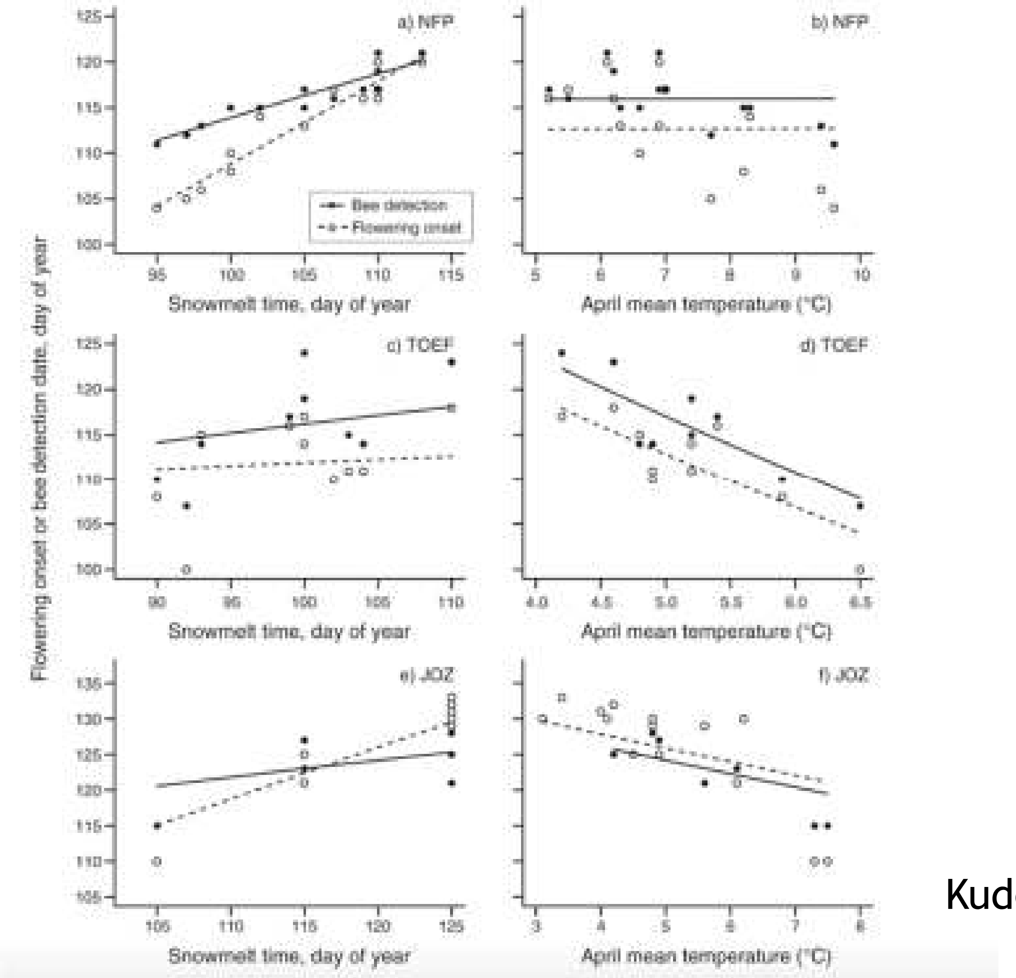
- This species specificity in phenological shifts results in an increasing incidence of ‘mismatch’ between predators and prey, and flowers and their pollinators
- These mismatches occur when two species that would have previously coincided in their spring phenophases have differing forcings
- If the forcing for the one species is attained before the forcing of the other, their triggers for spring will progressively occur out of sync

Phenological Mismatches

Eg. An oak tree may have had leaf unfolding occur in the first week of September, coinciding with the hatching of caterpillars. The caterpillars are responding to temperatures above 22 degrees Celsius, while the oak tree is responding to the first rain. Over the past century temperatures have increased, and the 22 degrees Celsius threshold is now reached in the last week of August. The wet season is occurring later due to the expansion of the Hadley Cell, and first rains are now occurring in mid-September. The caterpillars are now hatching three weeks before any food supply is available

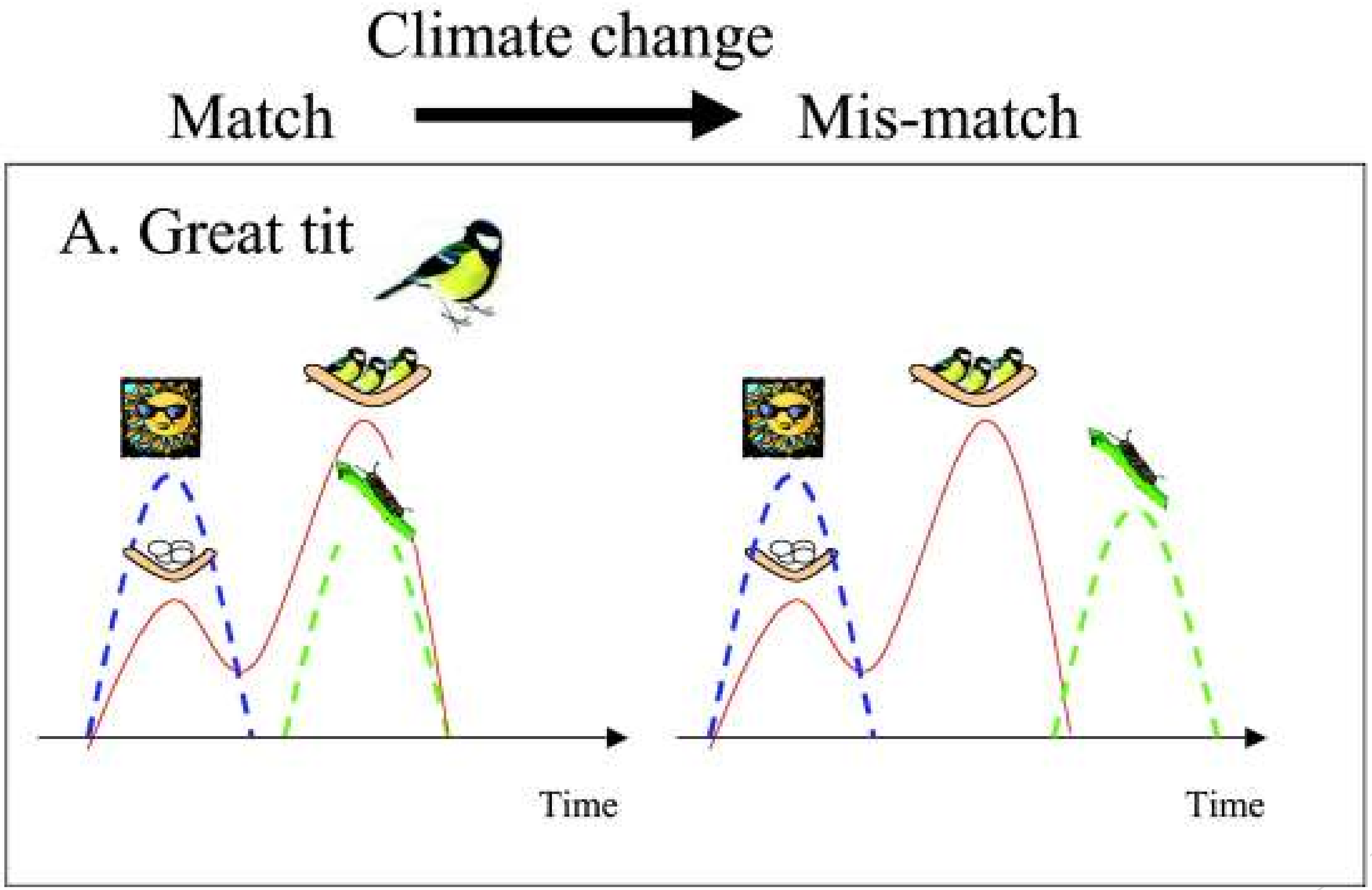


Phenological Mismatches

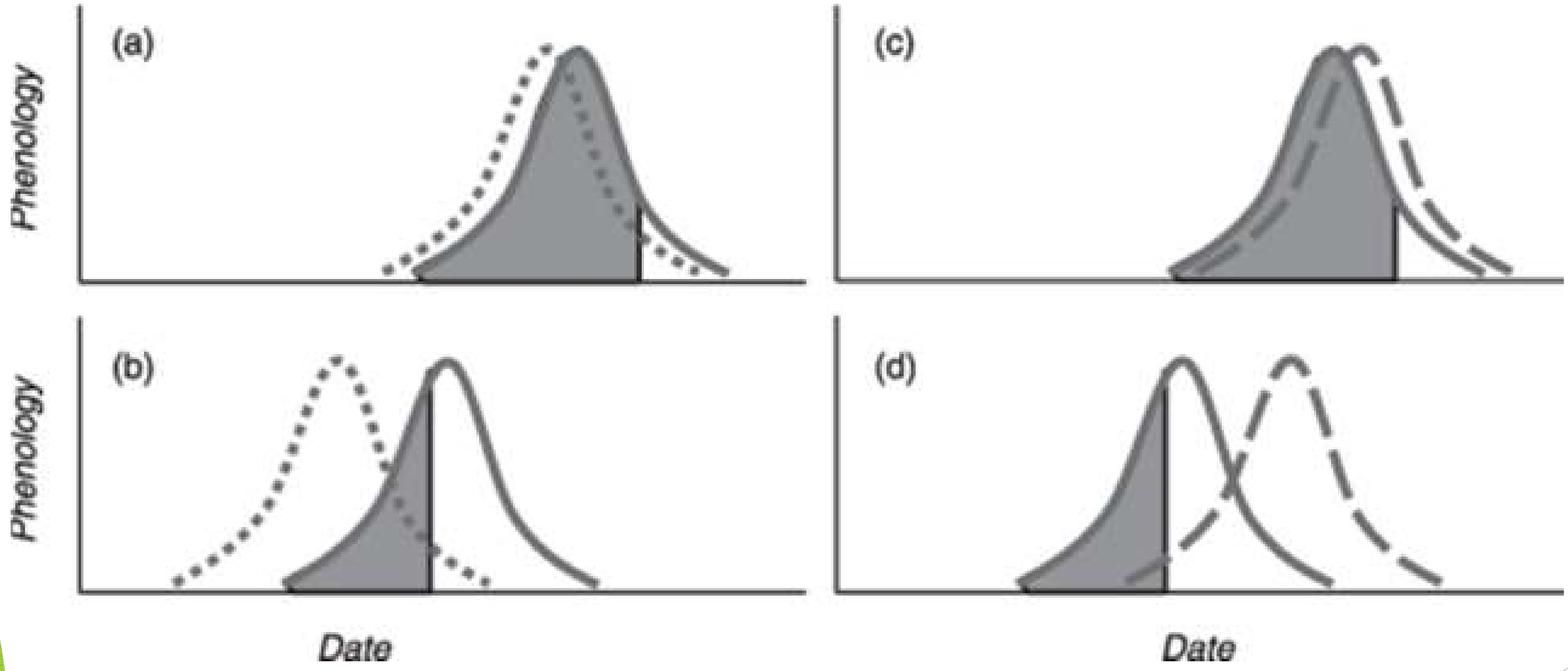


Kudo & Ida 2013

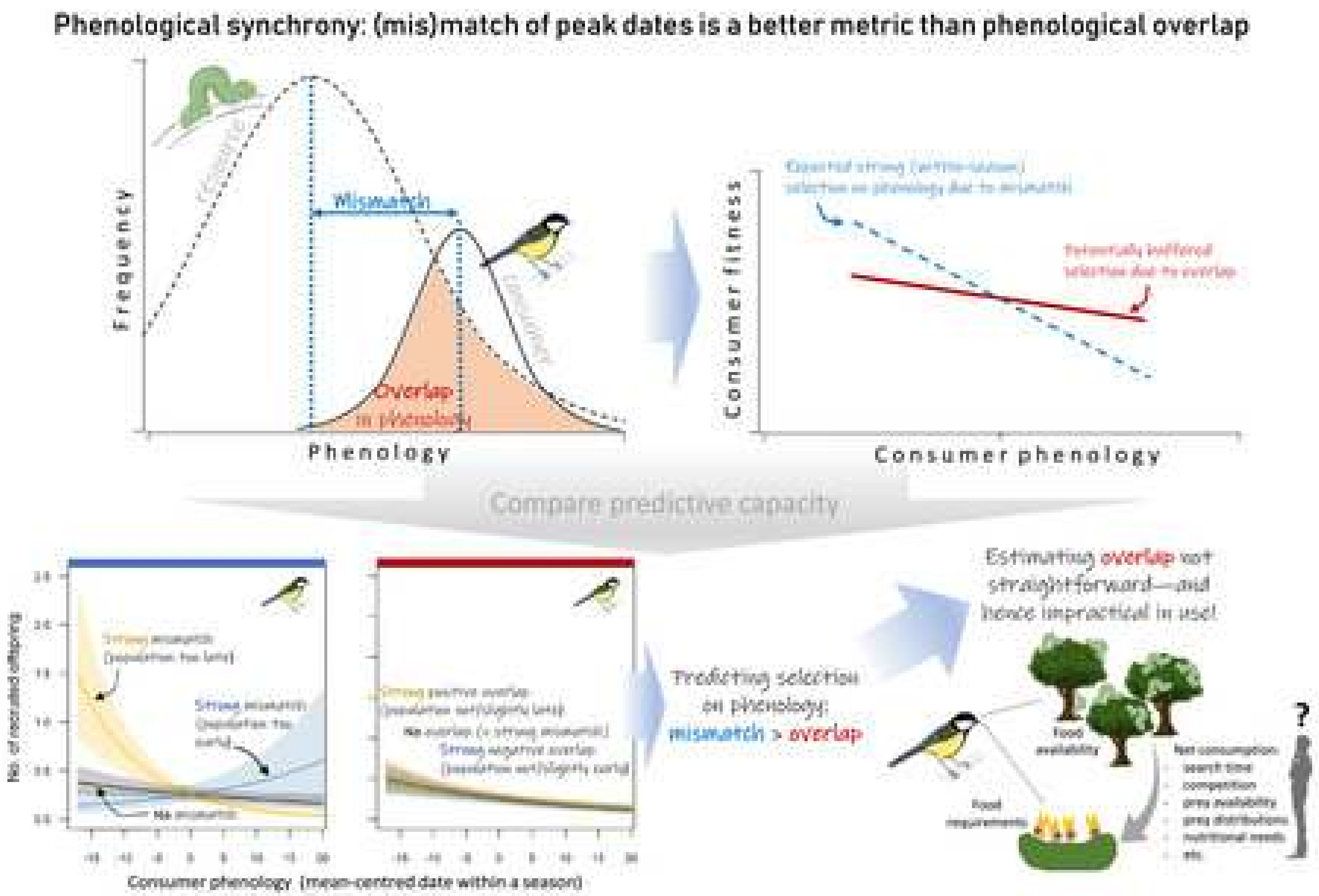
Phenological Mismatches



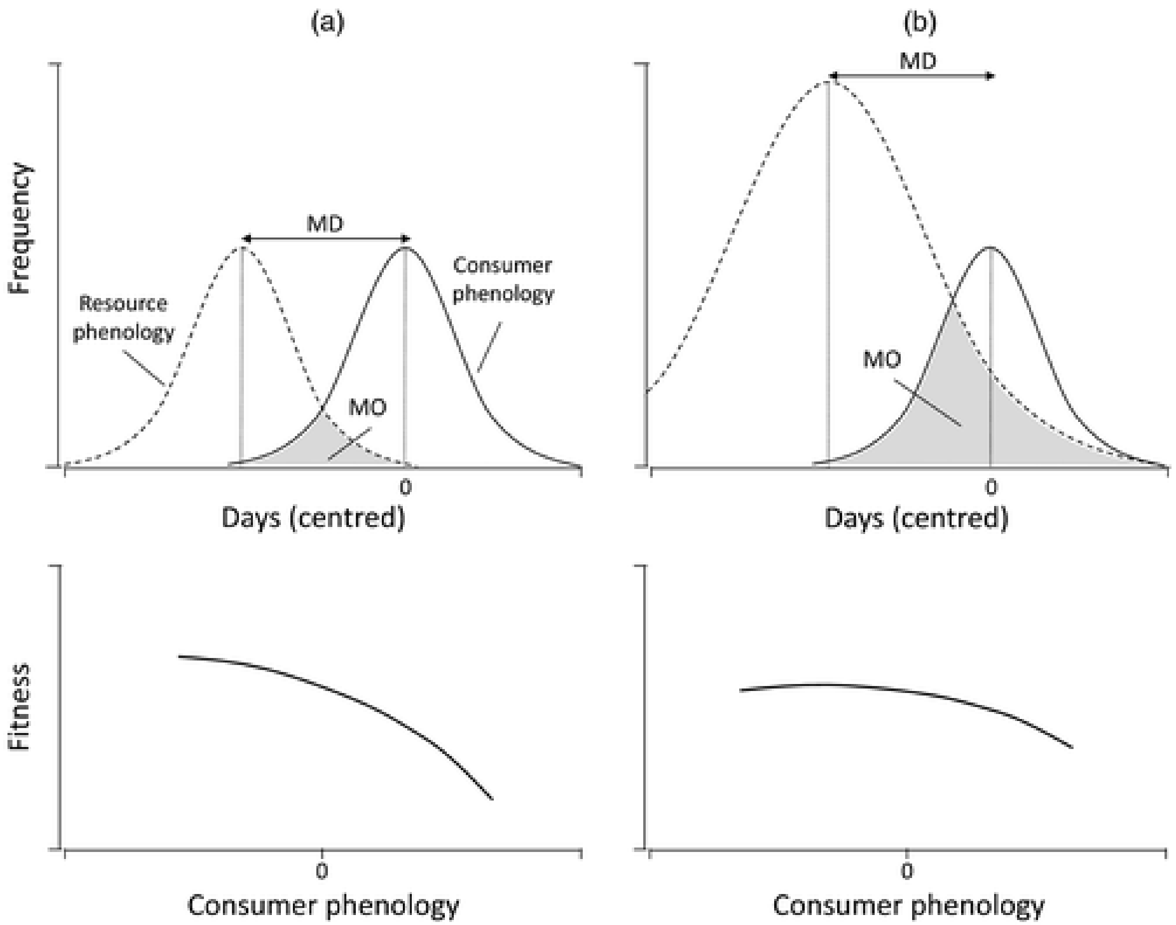
Phenological Mismatches



Phenological Mismatches



Phenological Mismatches



$$\mathrm{MO}_p = \frac{\int_a^b f_I(t)\mathrm{d}t}{\int_c^d f_F(t)\mathrm{d}t},$$

Phenology

- Scientists track the timing of phenological events via:
  - Ground-based observations
  - Documentary records
  - Digital repeat photography
  - Remote sensing
- Extensive records have been captured for the global North, and the phenological responses are understood at high resolution
- These are then related to climate datasets, which allow for the triggers to be well-understood, and for future models to be developed
- For the global South, the phenological and climate records are far more sparse
- This is where phenological models become valuable

Phenological models

- Allow for the timing of phenological events, and shifts thereof, to be determined for locations and time periods for which phenological records are not available.
- Use climate variables – which are the abiotic forces of these phenological events – to mathematically model the phenology of a particular species
- South Africa has 200 registered weather stations – so this allows for far greater coverage than the existing phenological studies
- By understanding the covariance in phenological shifts between species elsewhere, this also allows for a range of species phenophase shifts to be modelled in South Africa
- Can be integrated into climate models to allow for changes in carbon storage to be more accurately projected and the impacts on climate forecasted

Phenological models

- Statistical studies of phenology and climate usually rely on aggregated mean monthly temperature and rainfall, with reasonably successful results
- More complex studies additionally explore factors such as first and last frost date, number of frost days rainfall date, first dates above specific threshold temperatures, and a larger range of climatic variables including sunshine hours, humidity, wind, drought and synoptic events such as mid-latitude cyclone passage.
- None of these, however, are the direct triggers for a phenological events
- Phenology models usually work with these direct forcings – accumulation of moisture, heat or chilling units OR can use machine learning to build accurate predictions from existing data used as training sets

Phenological models

"Forcing" describes, very vaguely, the accumulation of heat stimuli for a plant following the period of dormancy. When sufficient heat portions are accumulated the plant will start flowering. A very well-known and widely used forcing model for the beginning of blossom of many plant species is the Spring-Warming model. It has the form

$$F^* = \sum_{i=t_1}^{t_2} R_f(T_i)\Delta t \qquad (1)$$

$R_f(T_i)$ is a function of the daily mean temperature T_i on day i and is called the forcing rate function. Δt is the time step, usually 1 day (1 d). The smallest summation index t_2, for which the sum on the right side approaches or exceeds the prescribed plant-specific forcing requirement F^* is the date (day of year = DOY) of the beginning of blossom in the year under consideration. The starting day t_1 of the summation is prescribed as a fixed value (e.g., 1 January) or has to be determined by optimization. In a forcing model which is supposed to be a mechanistic model and not a pure fitting model, t_1 should lie before the first forcing days but after the "release of dormancy". If one applies Eq. (1) to spring temperatures T_i of several, subsequent years, one obtains a prediction for the beginning of blossom $t_2(pred, j)$ for each year j.

Blümel & Chmielewski, 2012

The Problem

Use coupled phenological models to assess the risk of mismatch between blossoming and bee arrival in South Africa

- What is the degree of temporal mismatch between blossoming (generalized or specific) and bee arrival?
- What is the risk to the bees, as relates to population size?
- When will the critical period of mis-match occur, beyond which population decline is irreparable?

The Problem

What do you have at your disposal?

- Bee phenology
- We do not have any bee phenology data for South Africa
- We do not have any bee population size data for South Africa
- You will need to work from existing models in the literature to estimate this

- Blossom phenology
- Jacaranda flowering dates from documentary data
- Machine learning constructed jacaranda flowering model developed in the study group
- Apple and pear blossom advance dates in Cape Town from the literature
- A range of existing phenology models from the literature

The Problem

Table 1. Bee phenology models: The best models for each bee species analyzed

Species	Sample size	R^2	Predictor	Estimate ± SE	P
C. inaequalis	217	0.20	Year	−0.14 ± 0.04	**<0.001**
			Latitude	3.48 ± 0.98	**<0.01**
			Longitude	−1.31 ± 0.67	**0.05**
			Sex	−15.53 ± 2.76	**<0.001**
A. miserabilis	450	0.23	Year	−0.05 ± 0.03	0.051
			Latitude	3.55 ± 0.67	**<0.001**
			Long	0.74 ± 0.43	0.08
			Sex	−15.03 ± 1.75	**<0.001**
A. crataegi	549	0.26	Year	−0.003 ± 0.03	0.92
			Latitude	3.52 ± 0.71	**<0.001**
			Sex	−17.43 ± 1.43	**<0.001**
A. carlini	413	0.31	Year	−0.07 ± 0.03	**0.005**
			Latitude	7.56 ± 0.80	**<0.001**
			Sex	−14.01 ± 1.95	**<0.001**
Osmia pumila	648	0.30	Year	−0.12 ± 0.05	**0.007**
			Latitude	5.46 ± 0.98	**<0.001**
			Long	1.40 ± 0.59	**0.02**
			Sex	−20.25 ± 1.87	**<0.001**
O. bucephala	189	0.65	Year	−0.07 ± 0.06	0.23
			Latitude	6.13 ± 0.93	**<0.001**
			Sex	−25.44 ± 2.46	**<0.001**
O. lignaria	223	0.23	Year	−0.12 ± 0.04	**<0.001**
			Latitude	2.26 ± 0.93	**0.02**
			Sex	−12.45 ± 2.45	**<0.001**
O. atriventris	305	0.47	Year	−0.07 ± 0.04	0.09
			Latitude	7.61 ± 1.00	**<0.001**
			Sex	−23.82 ± 2.77	**<0.001**
B. impatiens	279	0.16	Year	−0.05 ± 0.36	0.11
			Latitude	3.04 ± 0.82	**<0.001**
			Longitude	−1.72 ± 0.03	**<0.001**
B. bimaculatus	174	0.07	Year	−0.07 ± 0.04	0.09
			Latitude	2.09 ± 0.77	**<0.001**

Year estimate is given in $d \cdot y^{-1}$, longitude and latitude in $d \cdot degree^{-1}$, and sex in days. Significant P values are in bold.

Bartomeus et al. 2011

ForcSar Flowering Model

y	date of flowering
x_t	daily mean temperature (°C)
$R_f(x_t)$	forcing rate function
F^*	critical value of state of forcing for the transition from quiescence to flowering
t_0	1 January
T_b	base temperature

Model ForcSar

y such as $f_c(y) = F^*$

$$f_c(t) = \sum_{t_0}^{t} R_f(x_t)$$

$$R_f(x_t) = \frac{28{\cdot}4}{1 + e^{-0{\cdot}185\,(x_t - 18{\cdot}4)}} \qquad x_t > 0\,°\mathrm{C} \text{ (from Sarvas 1974 in Hänninen 1990)}$$

Model ForcTT

y such as $f_c(y) = F^*$

$$f_c(t) = \sum_{t_0}^{t} R_f(x_t)$$

$$R_f(x_t) = \begin{cases} 0 & \text{if } x_t < T_b \\ x_t - T_b & \text{if } x_t \geq T_b \end{cases}$$

Chuine et al., 1999

Questions?