A QTL-based Phenology Model of the Common Bean With Non-linear Genetic x Environment Effects

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Crops *in silico* Symposium

University of Illinois at Urban Champaign

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Population growth & food security

”Global population of 9.7 billion by 2050.” – UN, 2015

”Global arable land stagnated at 10.9%.” – World Bank, 2016

Plant Breeding

Crop Growth Models

”Agriculture accounts for 60% of fresh water withdrawal.” – World Bank, 2016

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Plant Breeding — Crop Growth Models

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Gene-based modeling: Linear regression models

Plant Breeding

Crop Growth Models

Linear mixed-effect Model with G x E

$$\hat{y}_{gl} = \mu + \sum_{e=1}^{E} \beta_{E_e} \Delta E_{gle} + \sum_{q=1}^{Q} \beta_{QTL_q} QTL_{gq} + \sum_{e=1}^{E} \sum_{q=1}^{Q} \beta_{QTL_q x E_e} QTL_{gq} \Delta E_{gle}$$

$$\Delta E_{gle} = \left(E_{gle} - \overline{E}_{gle}\right)$$

- Predicts static traits
- Predicts complex traits
- Limited application in training locations
  - Linear response to environmental factors

Boer et al. 2007

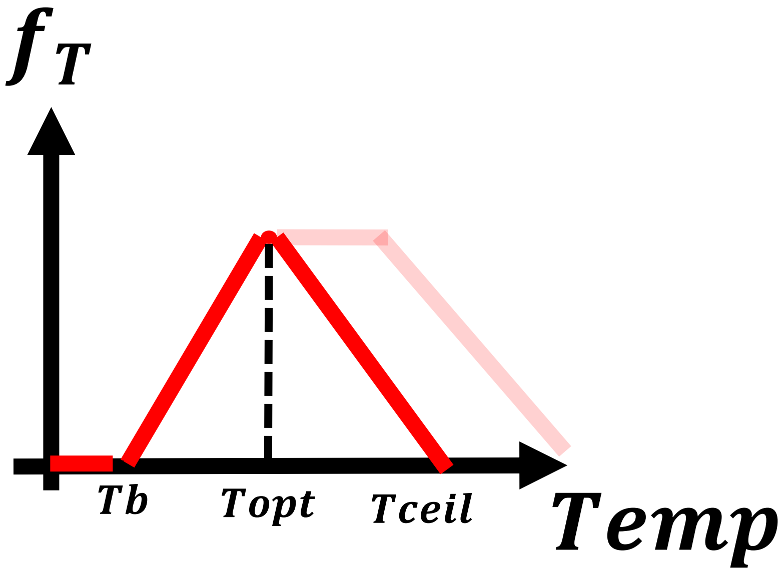
Gene-based modeling: Crop growth models

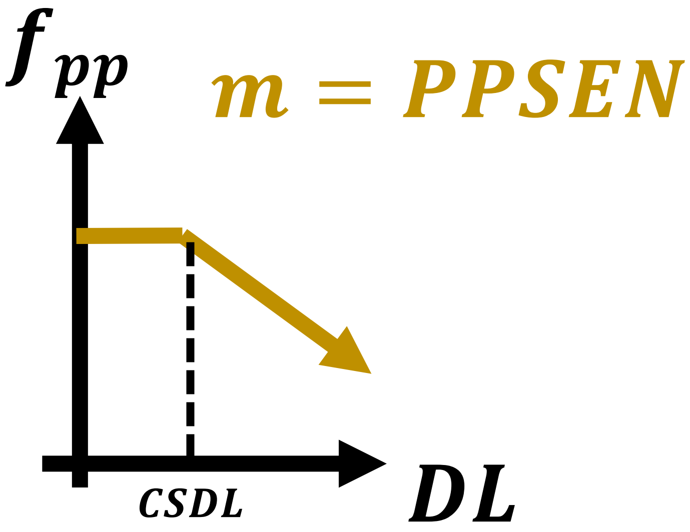
Plant Breeding

Crop Growth Models

Photothermal accumulation functions

$$\text{phys\_days}(t) = \sum_{t=1}^{\text{phys\_days}(t) \leq \textit{Threshold}} \left[f_T(\text{Temp}, Tb, Topt, \ldots) * f_{pp}(CSDL, PPSEN)\Delta t \right]$$





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Gene-based modeling: Modifying breeding models

Plant Breeding

- Predicts static traits
- Predicts complex traits
- Limited application in training locations
  - Linear response to environmental factors

Crop Growth Models

- Dynamic simulations
- Simulate component traits
- Non-linear environmental response

Non-linear, dynamic breeding models

Data

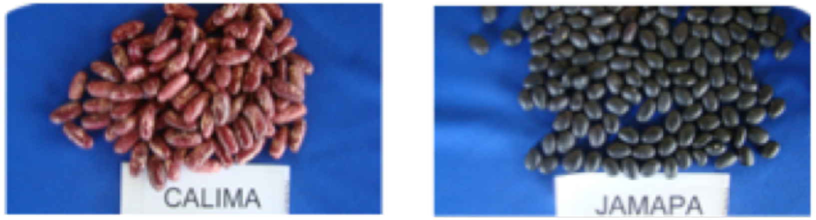
Data: Crop information

I. Common bean (*Phaseolus vulgaris L.*)

C a. *Calima* (Parent A)
   - I. Determinate, Andean
   - II. Sensitive to photoperiod

J b. *Jamapa* (Parent B)
   - I. Indeterminate, Mesoamerican
   - II. Insensitive to photoperiod

c. Recombinant Inbred Lines (RILs)
   - I. 184 individuals (F11: 14)

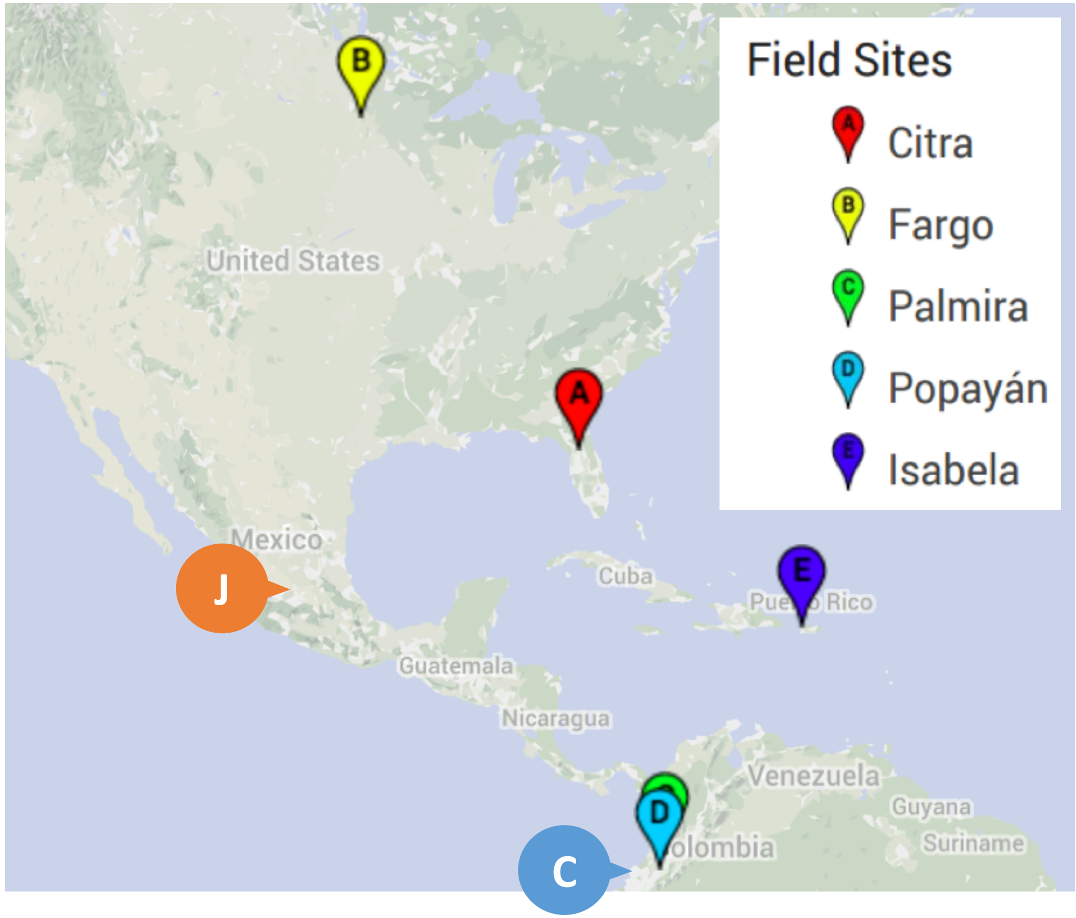


Seed Diversity within RILs

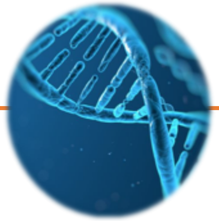
Source: Clavijo Jose, NSF Presentation, 2014

Data: Site information

Location	Day length (h)	Year	Temp [°C]
Citra (CT)	12.5~13.5	10’~11’	30/15
Fargo (ND)	13.5~15.6	12’	23/14
Palmira (PA)	12.0~12.1	11’~12’	29/19
Popayan (PO)	12.1~12.2	12’	22/16
Isabella (PR)	11.5~12.4	12’	29/19



I. Environmental factors
   a. Temperature, °C
      I. Mean, max, min, day, night, day-night-difference
   b. Day length, hr

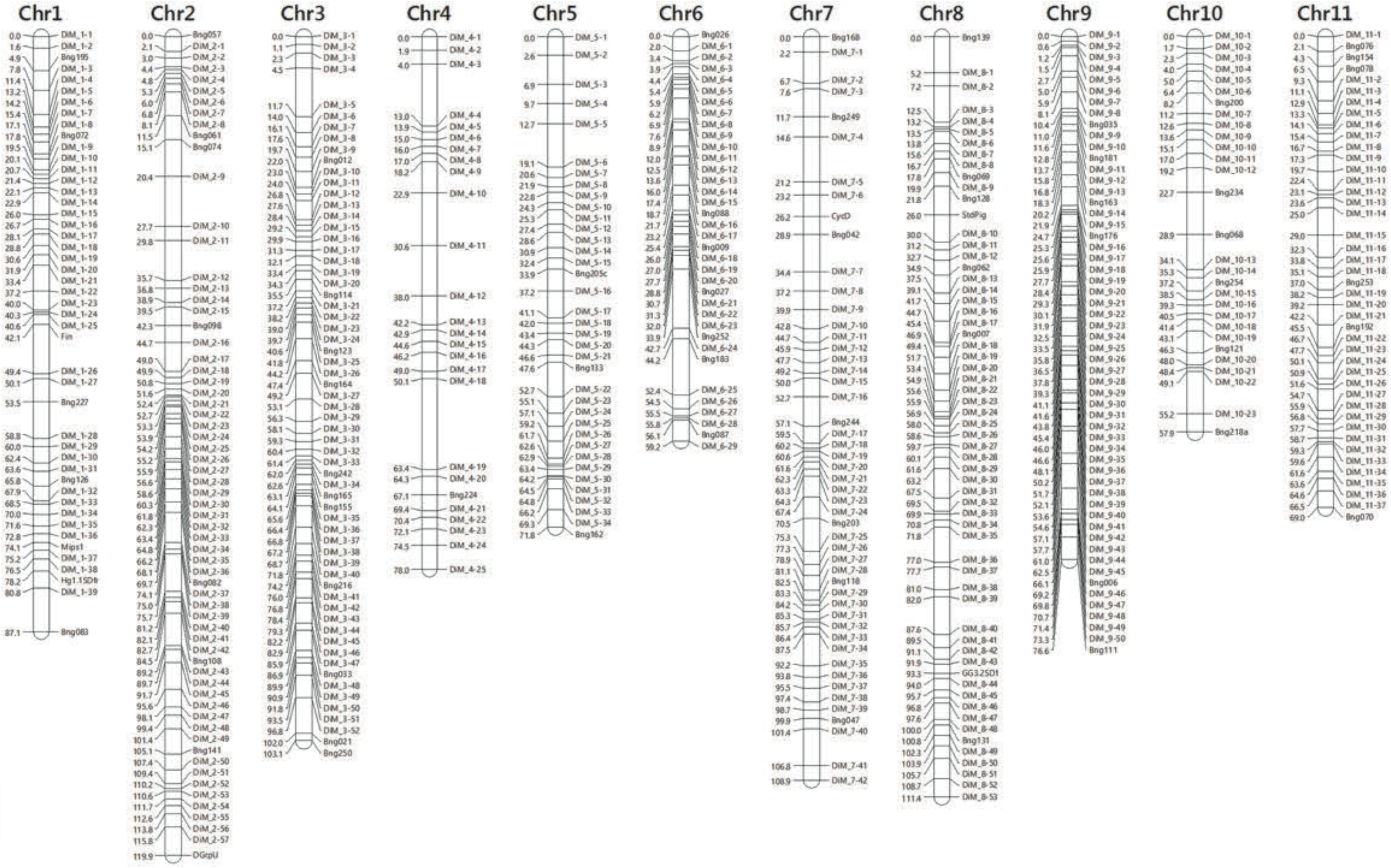


Data: Genetics

I. Linkage map (Bhakta et al. 2015)

a. **513** QTL markers

b. Average interlocus distance of 1.9 cM



QTL Marker$_i$

4	CAL	1
5	JAM	-1
6	RIJC001	-1
7	RIJC002	1
8	RIJC003	1
9	RIJC004	-1
10	RIJC005	1
11	RIJC006	1
12	RIJC007	1

Data: Model fitting & evaluation

I. Fitting
   a. 171 RILs grown across 5 sites
II. Evaluation
   a. 2 parents left out 16 RILs across 5 sites
   b. 2 parents 7 RILs planted in 2016 at Palmira, Colombia (PA16)
   c. 2 parents 106 RILs planted in 2016 at Citra, FL
      I. March sowing (CT16-1)
      II. May sowing (CT16-2)

Multi-stage phenology model

Phenology: Stages of bean development

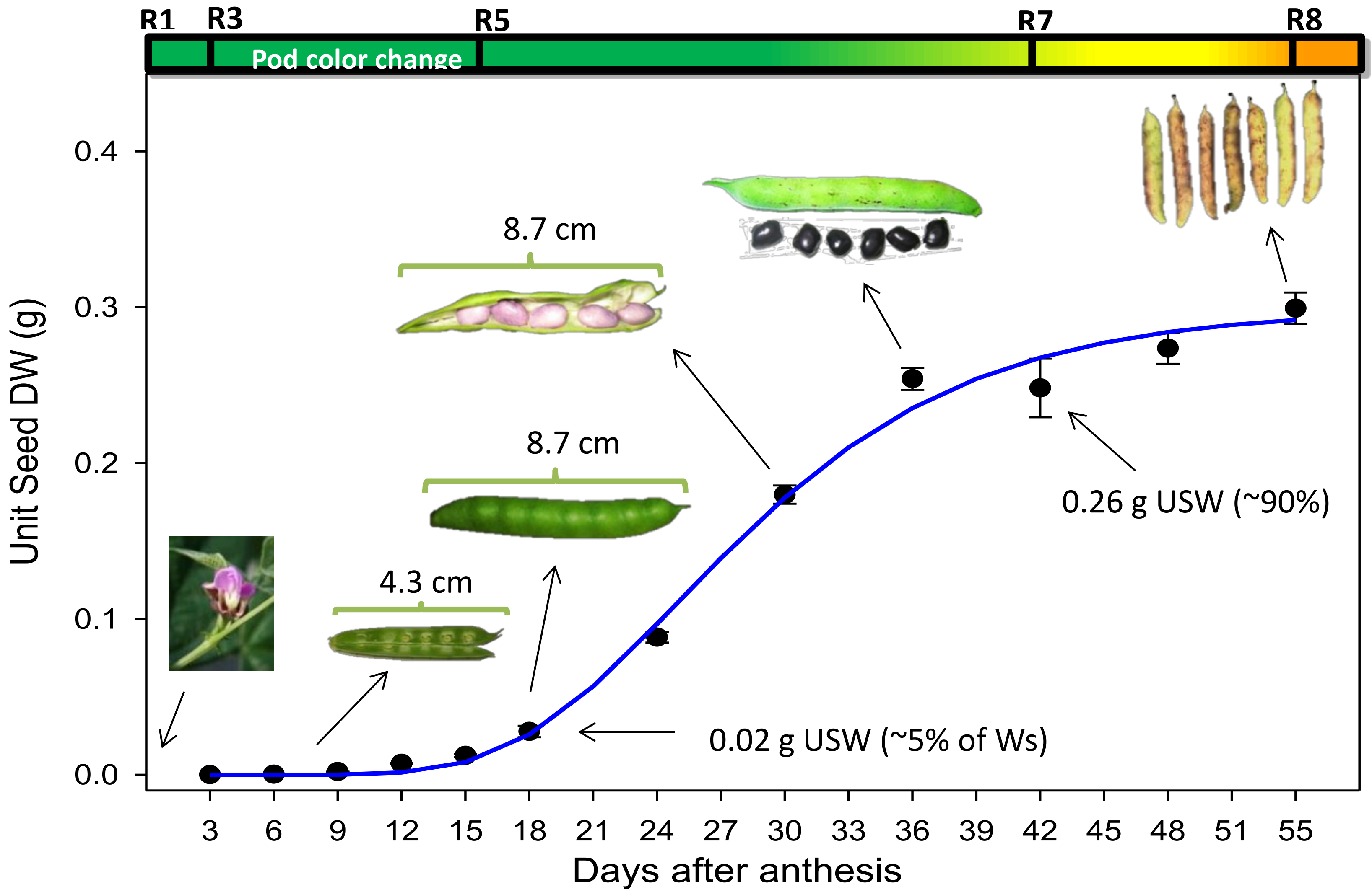
I. Planting

II. Emergence (VE)

III. Flowering (R1)

IV. Seed filling (R5)

V. Seed maturity (R7)



Clavijo Michelangeli et al. 2013

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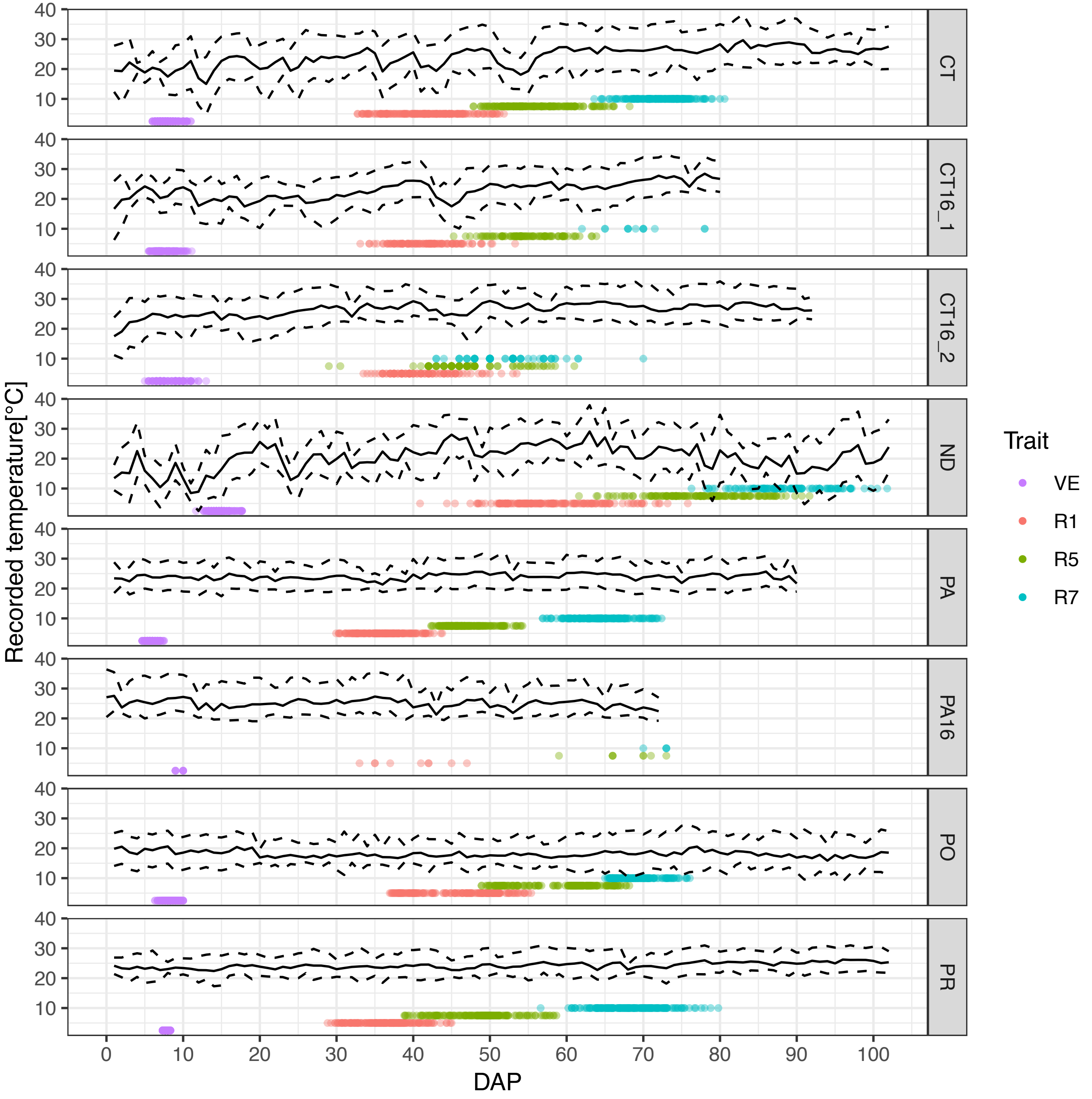

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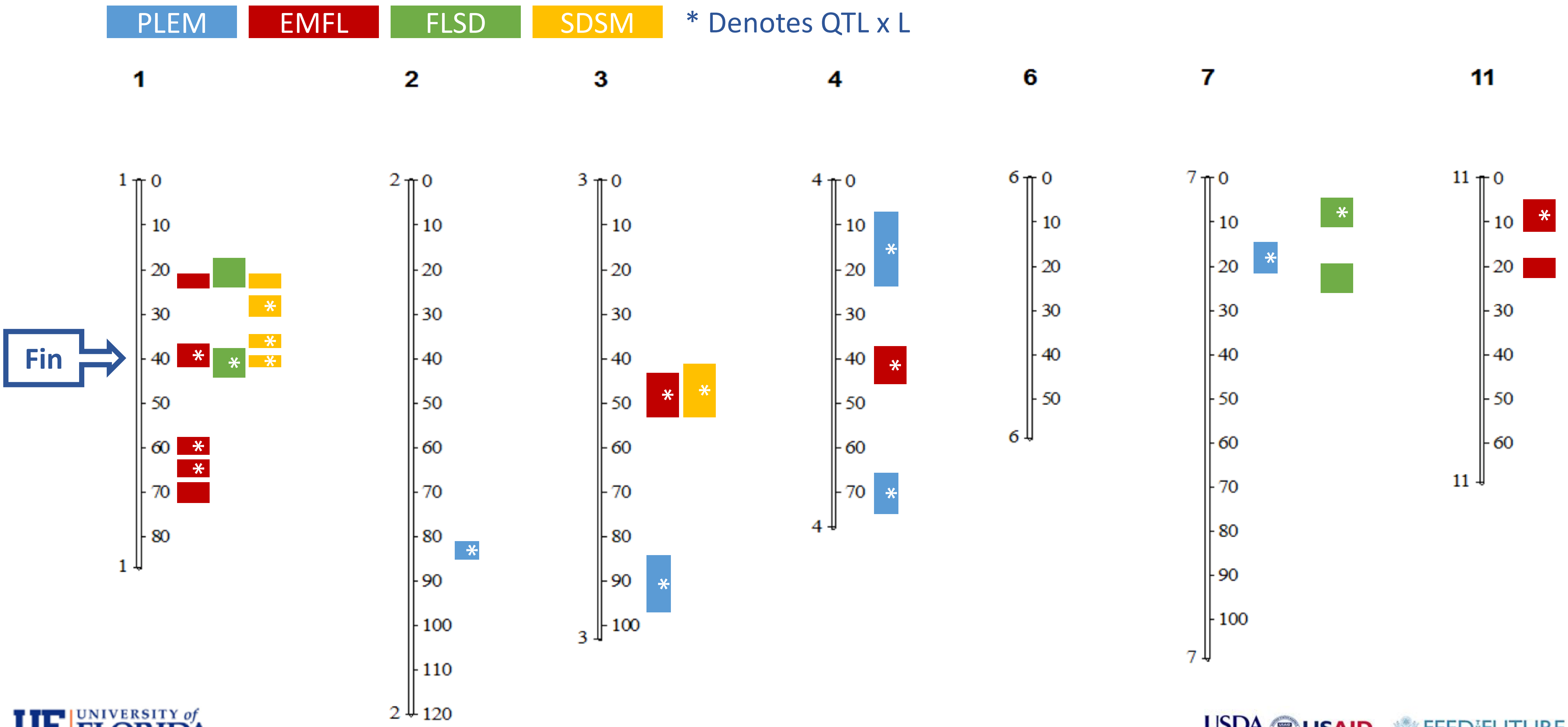
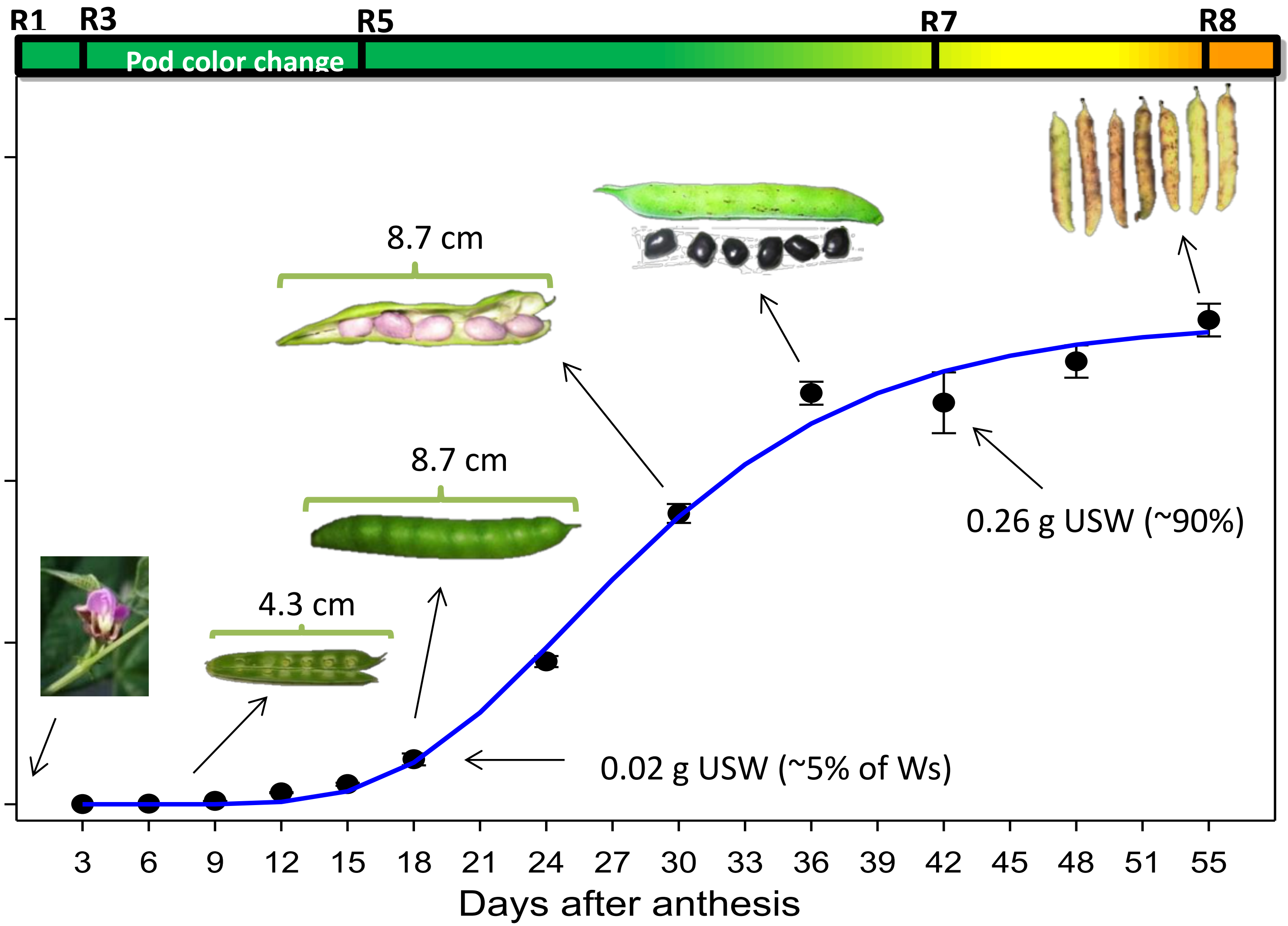
QTLs associated with phenological stages



Additive Nonlinear Rate Modules

Rate modules

I. Planting
   a. RPLEM = $(VEDAP)^{-1}$
II. Emergence (VE)
   a. REMFL = $(R1DAP - VEDAP)^{-1}$
III. Flowering (R1)
   a. RFLSD = $(R5DAP – R1DAP)^{-1}$
IV. Seed filling (R5)
   a. RSDSM = $(R7DAP – R5DAP)^{-1}$
V. Seed maturity (R7)



Clavijo Michelangeli et al. 2013

Rate modules

Accumulating daily rates of progress

$$\hat{Y}_{gls} = \sum_{d\,=\,DAP_{s-1}}^{\hat{Y}_{gls}\,\geq\,1} \max\left[0, rate_{gls}(d)\right]\Delta d$$

$$\begin{aligned} rate_{gls}(d) = \alpha_s + \textstyle\sum_h \left[TEmax_{s0} f_T\left(Temp_{lh},\ T_{peak_{s0}}\right)\Delta h\right] + PPSEN_{s0} f_{PP}(DL_{ld}, CSDL_s) + \\ \textstyle\sum_q \beta_{QTL_{sq}} QTL_{gq} + \\ \textstyle\sum_q \sum_h \left[TEmax_{sq} QTL_{gq} f_T\left(Temp_{lh},\ T_{peak_{sq}}\right)\Delta h\right] + \\ \textstyle\sum_q PPSEN_{sq} QTL_{gq} f_{PP}(DL_{ld}, CSDL_s) \end{aligned}$$

Rate modules

Computing daily rates of progress

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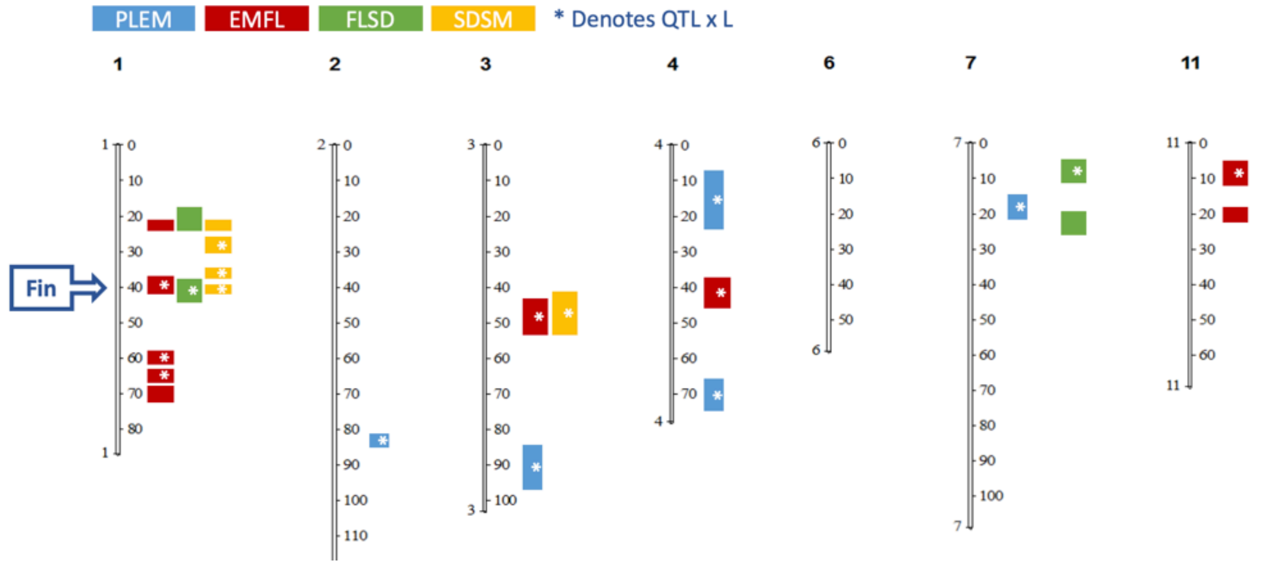

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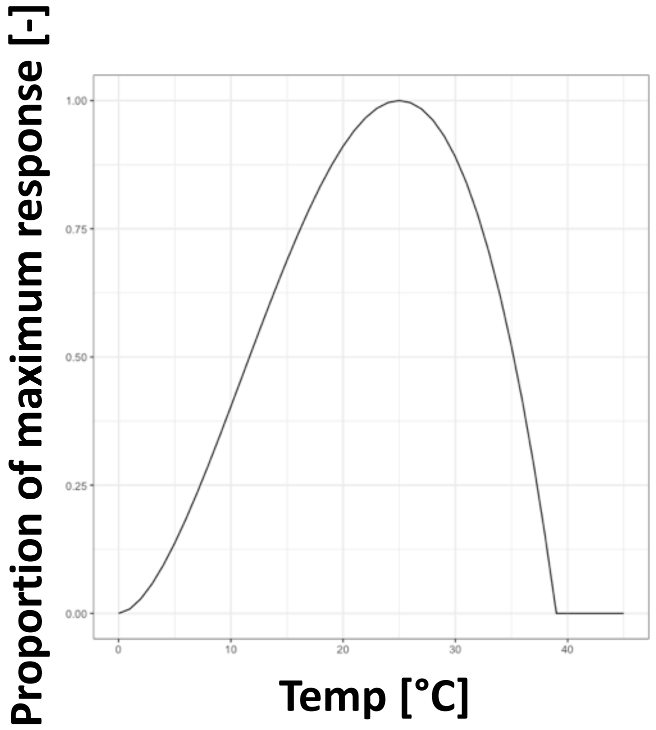

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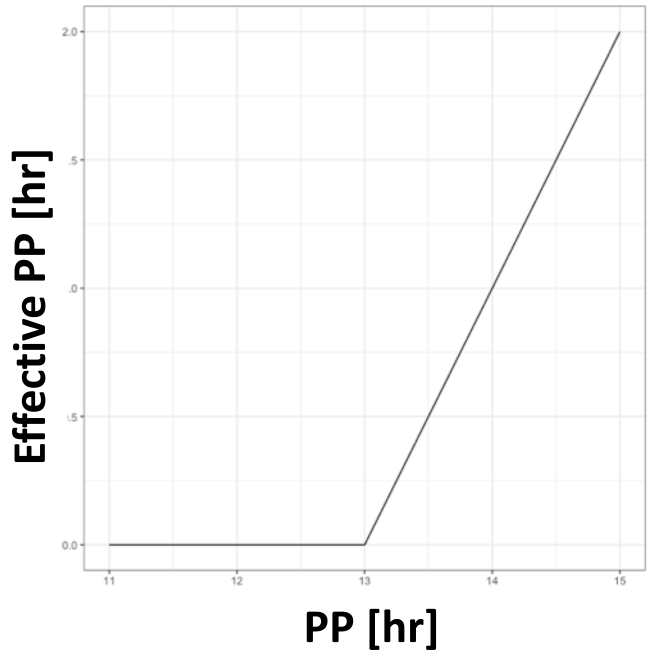
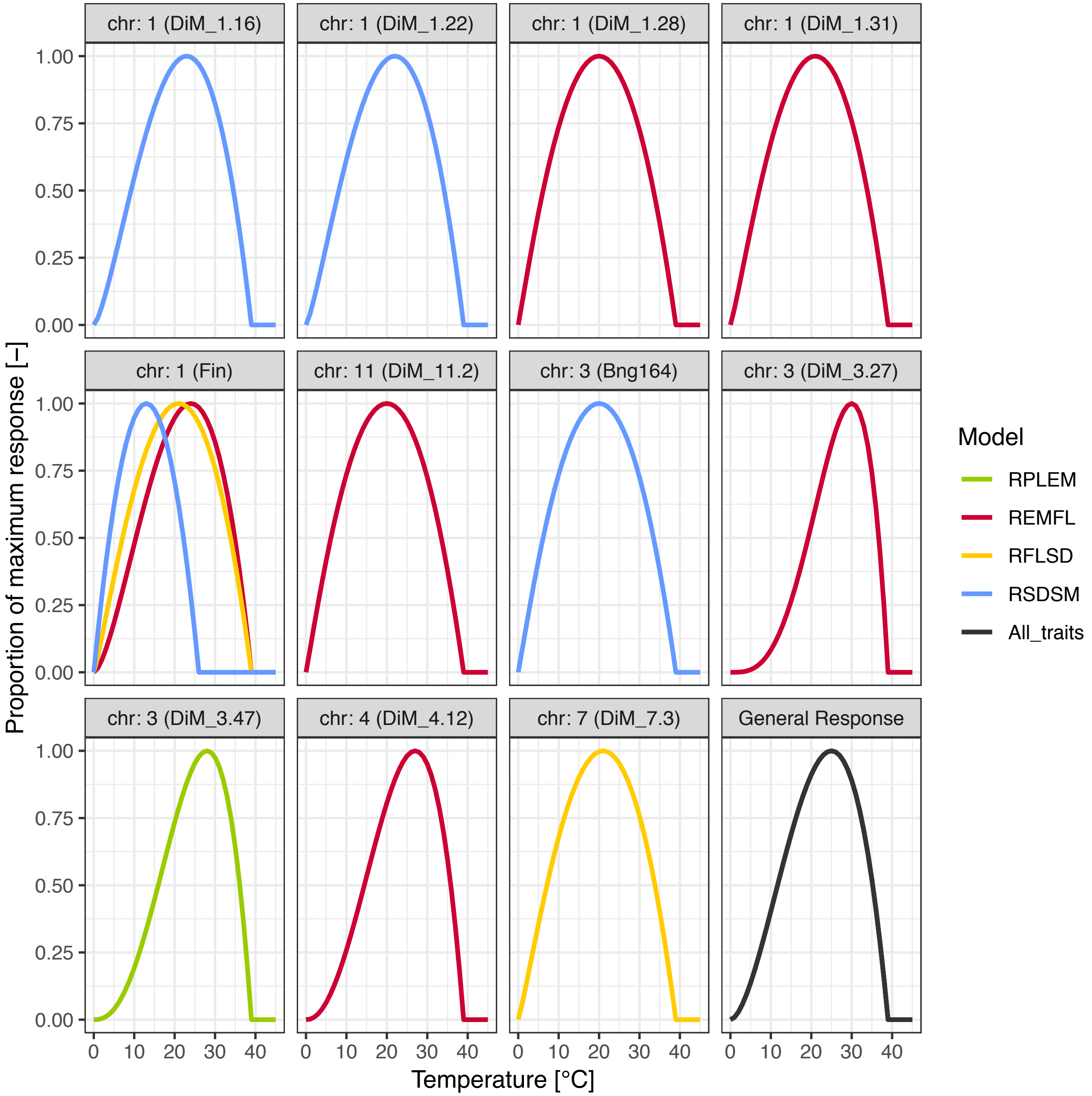
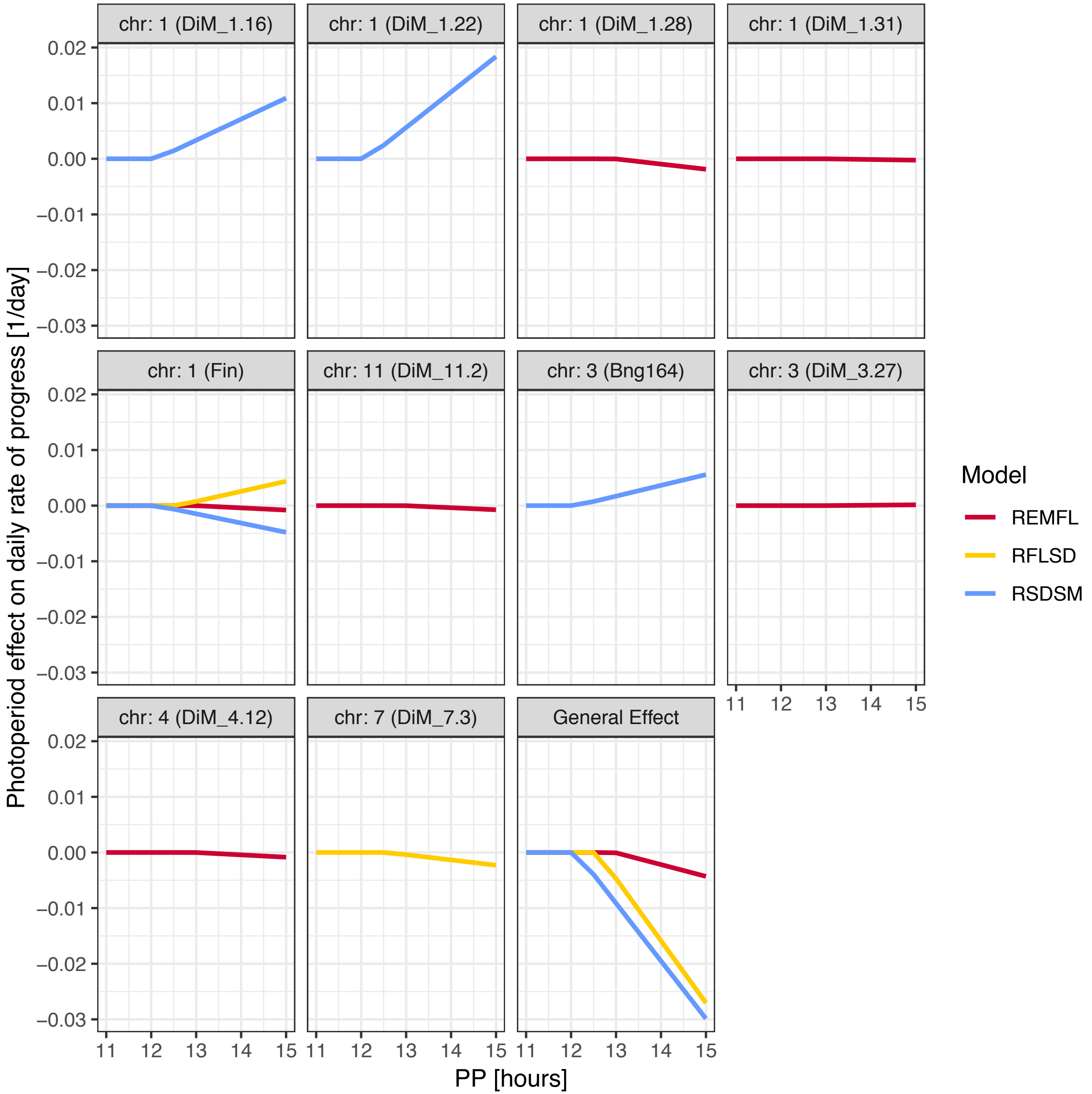


Temperature response profiles



PP effects for *Calima*



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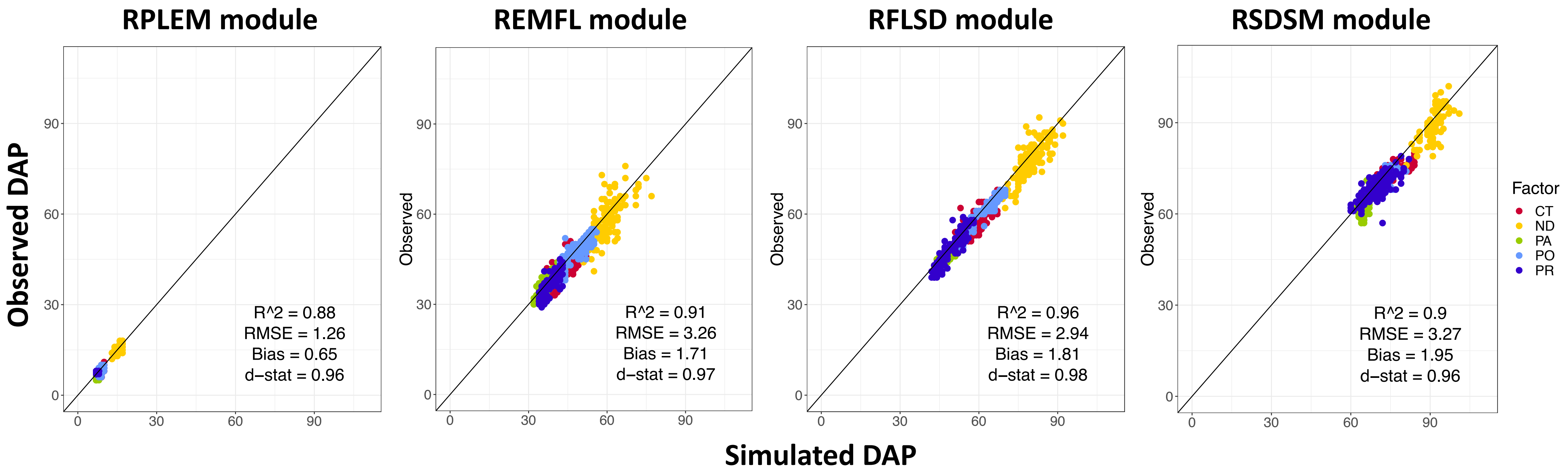
Fitted trait module performance

* Each module is initialize at observed DAP of previous stage

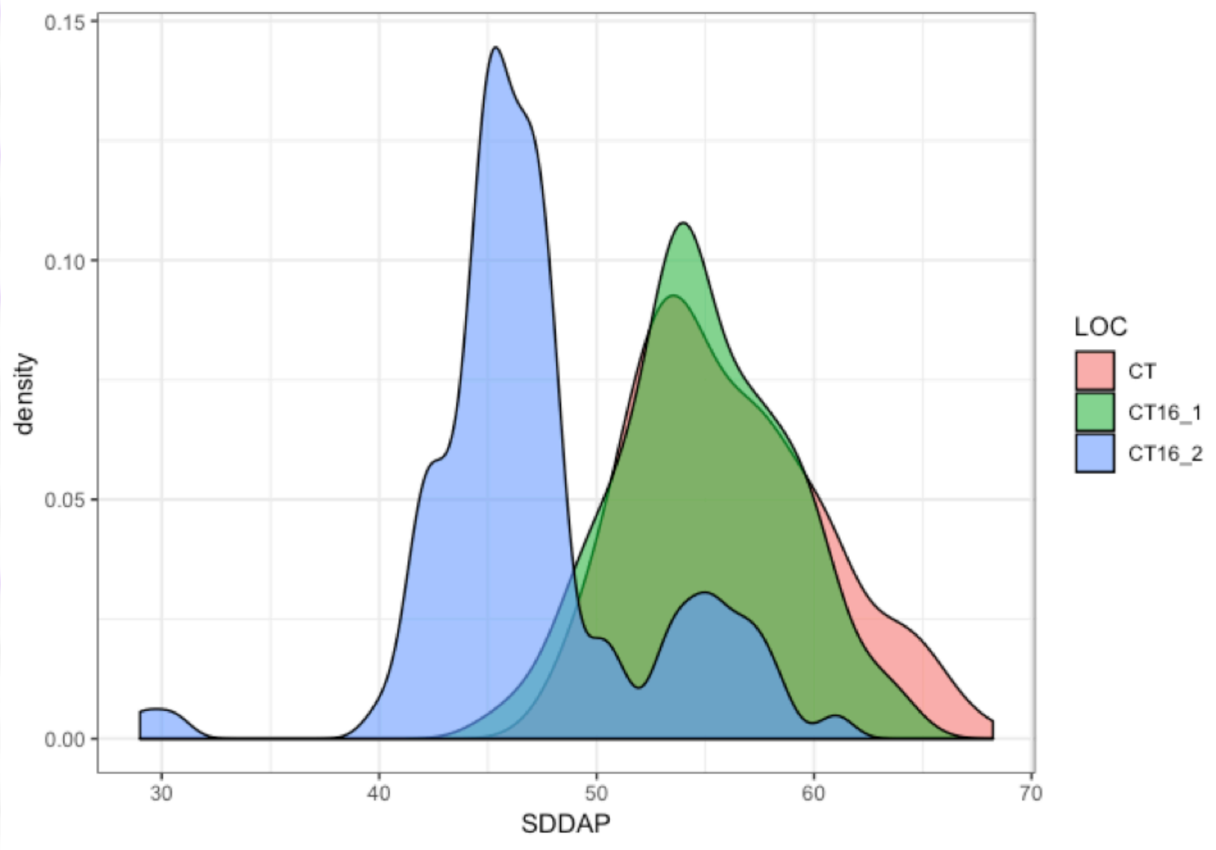


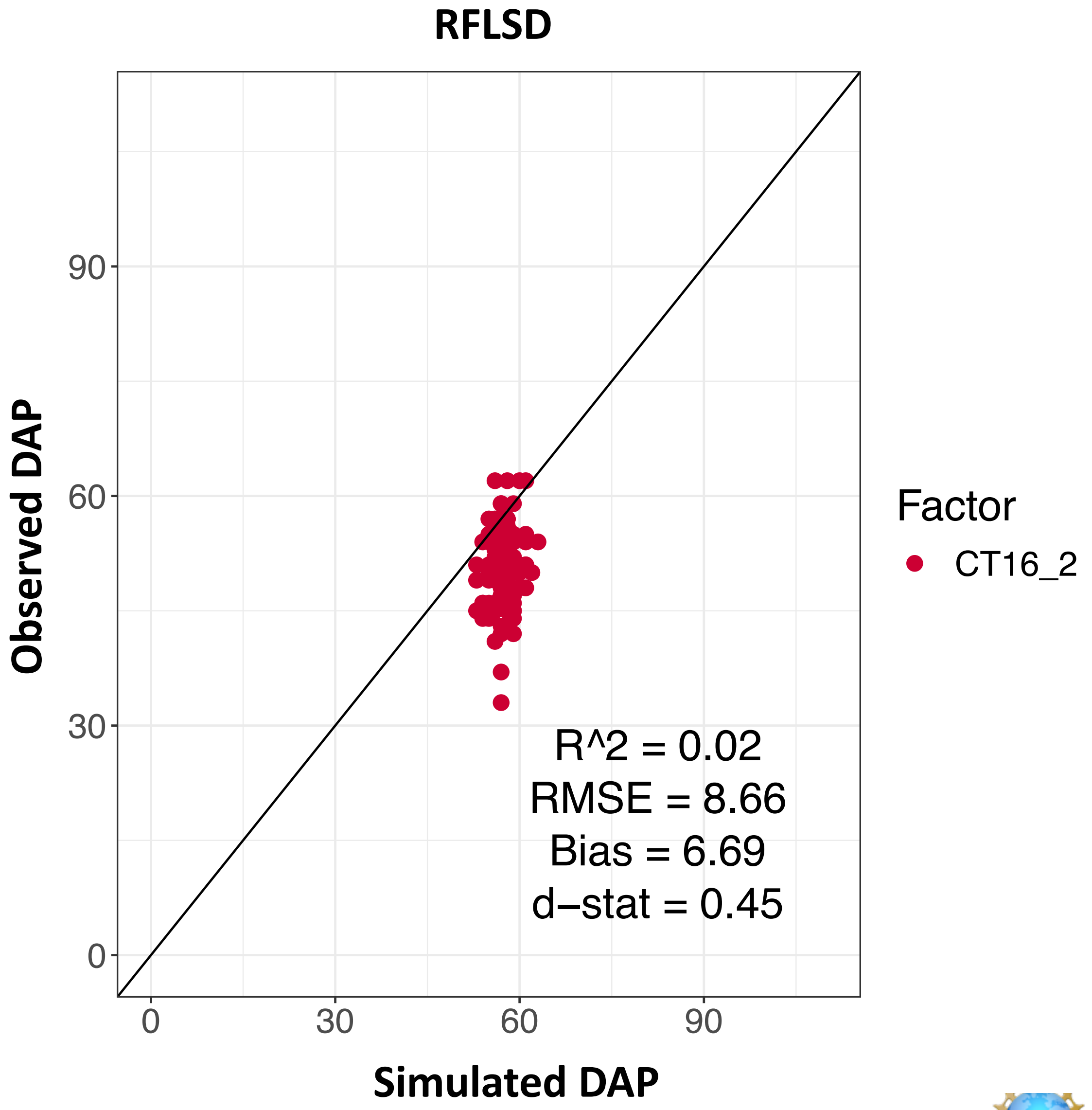
Phenology model evaluation

* Each module is initialize at simulated DAP of previous stage

Site	Stage	R^2	RMSE	Site	Stage	R^2	RMSE
NSF	VE	0.89	1.06	CT16-1	VE	0.01	1.46
	R1	0.89	3.32		R1	0.19	3.91
	R5	0.90	3.96		R5	0.02	5.02
	R7	0.85	4.19		R7	0.95	9.06
PA16	VE	0.10	1.8	CT16-2	VE	0.05	1.64
	R1	0.60	3.51		R1	0.33	3.46
	R5	--			R5	0.02	8.66
	R7	--			R7	0.01	15.45

Phenology model evaluation





Conclusions & What's next

I. Limitations
   a. Assumptions in temperature function (Tref & Toff)
      I. Limited G and G x E from training population and sites
   b. No soil-water-nutrient dynamics
   c. Not a mixed effect model (inflated SSE)

II. Improved breeding tool
   a. Dynamical simulation
   b. Non-linear G x E responses
   c. Simulate component traits

III. Next steps
   a. Implementation in DSSAT CROPGRO
   b. Extension to other reproductive development traits

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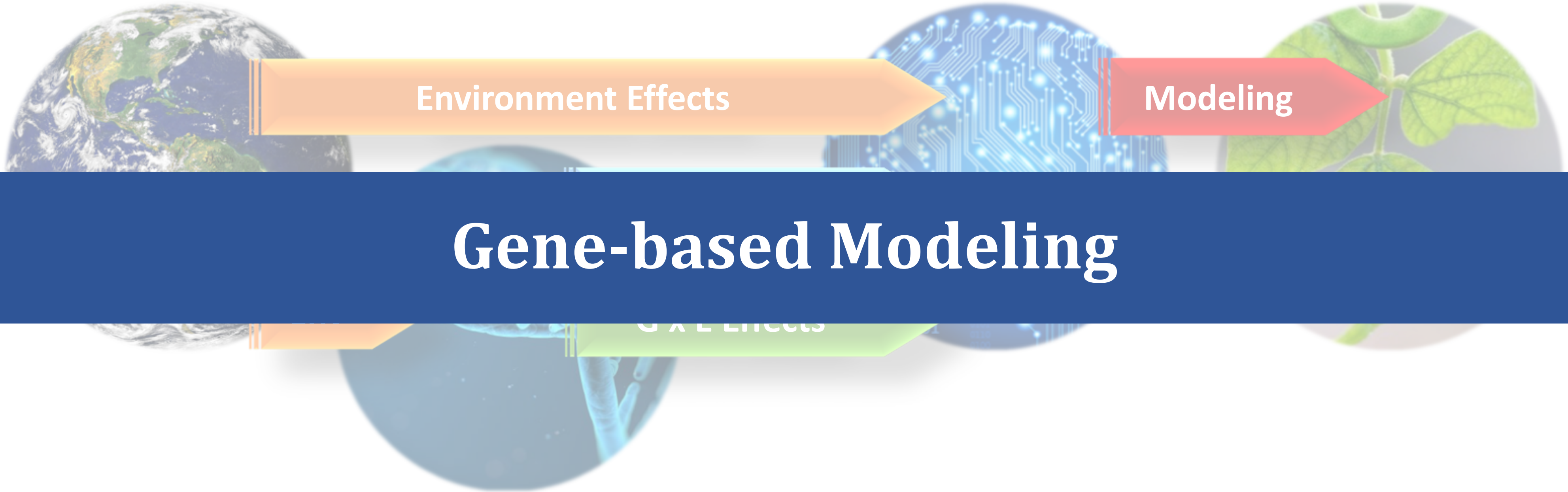
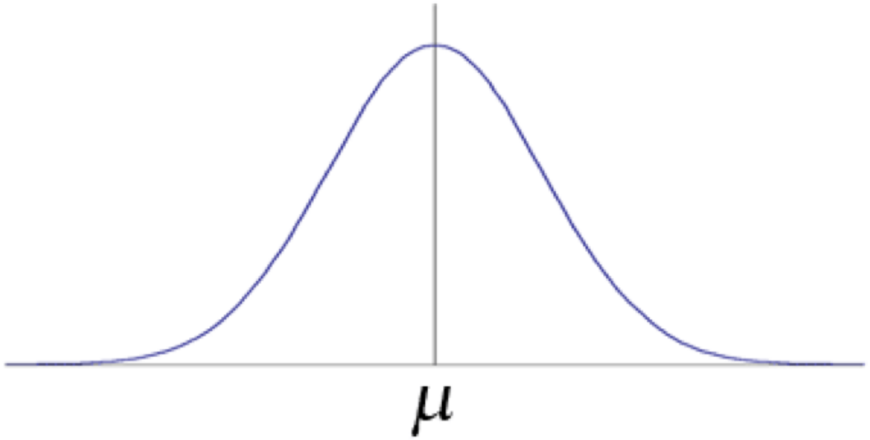
Questions & Suggestions

Gene-based Modeling



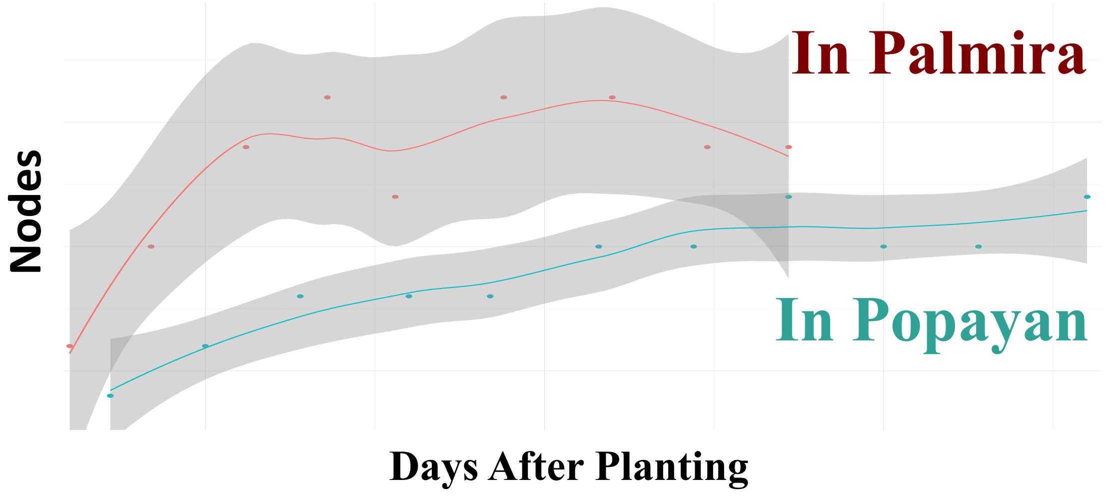
Gene-based modeling

Phenotype Distribution



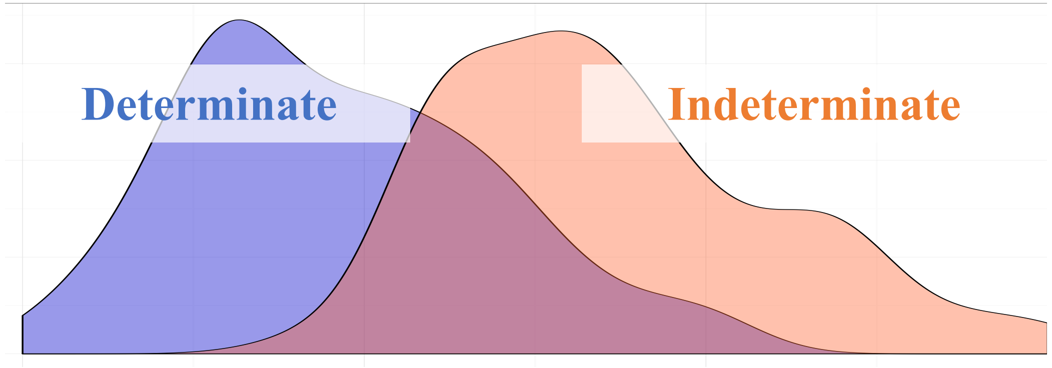
Gene-based modeling

Node number for a single variety (*Calima*)



Gene-based modeling

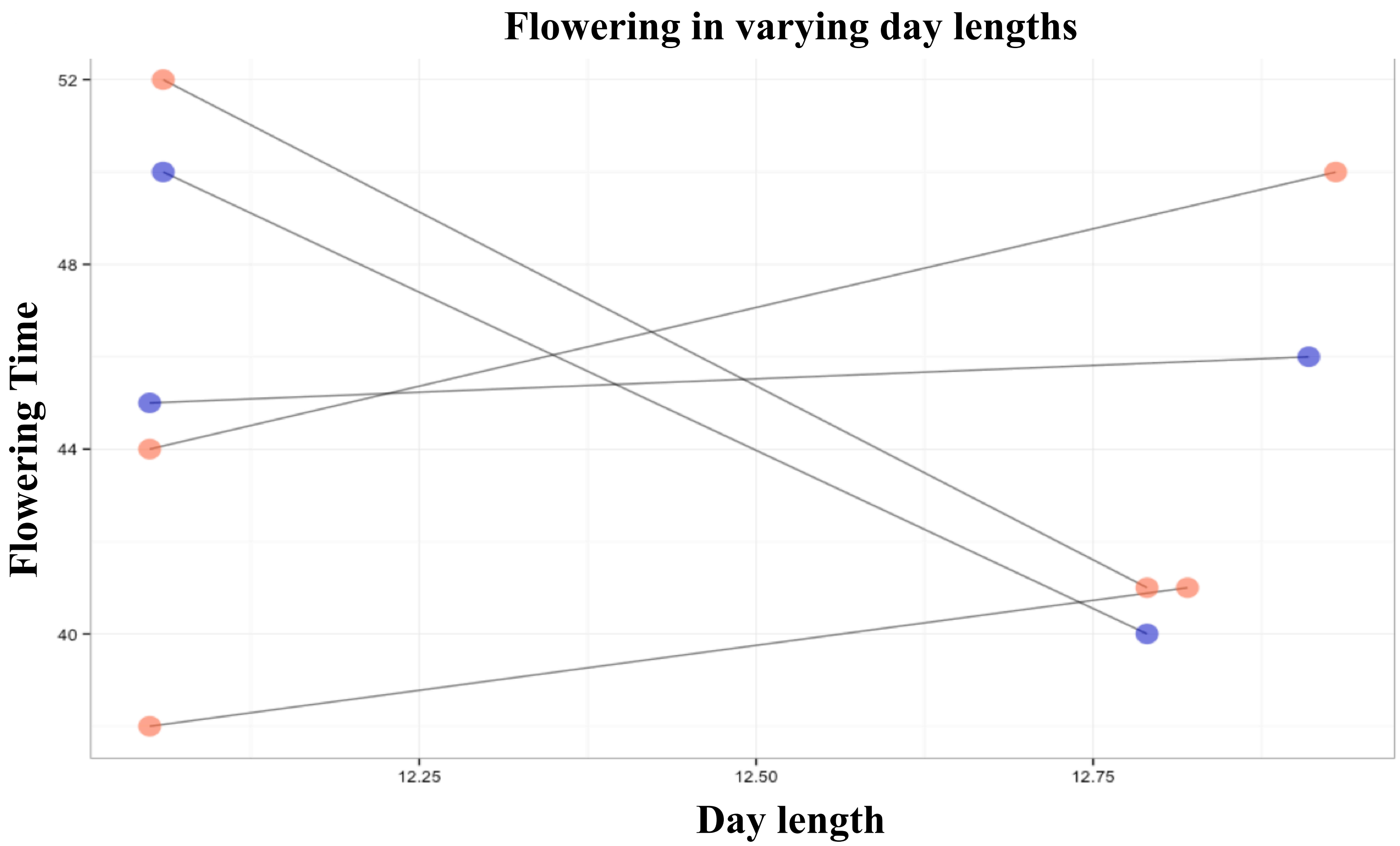
Flowering time in Palmira



Days After Planting

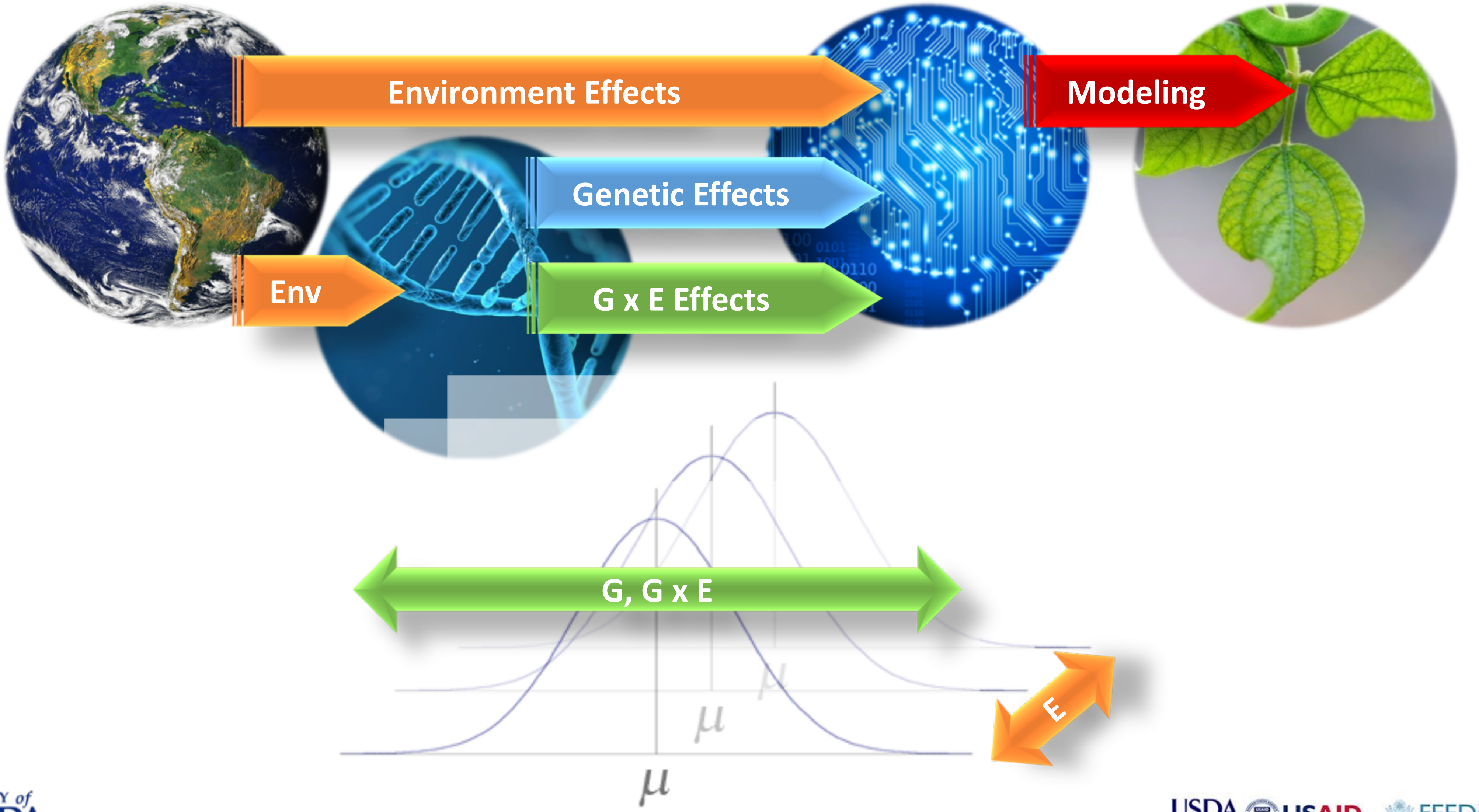
Gene-based modeling

Gene-based modeling



- Determinat
- Indeterminate

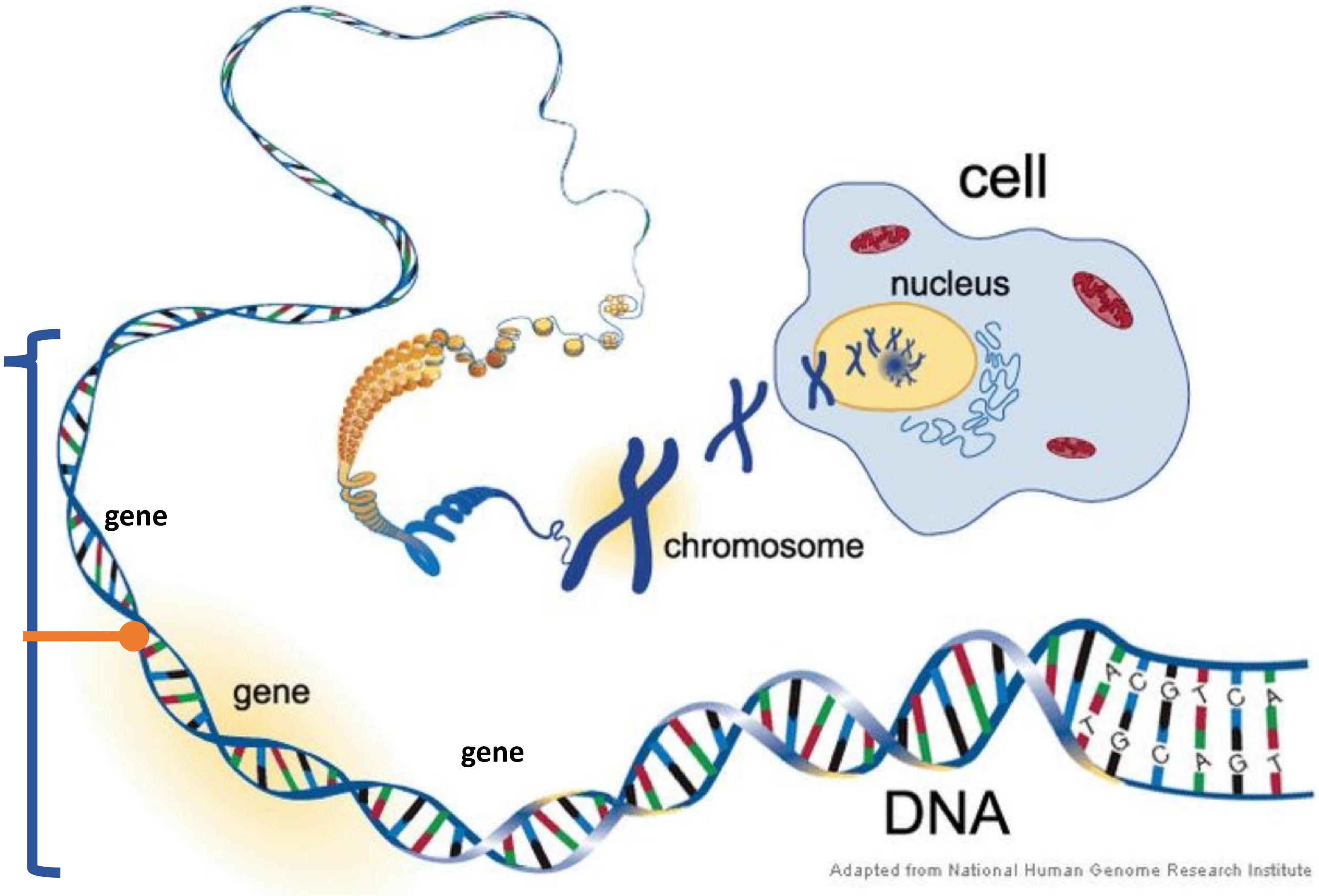
Gene-based modeling



Gene-based modeling: Genetic markers

Quantitative Trait Locus (QTL)

Single Nucleotide Polymorphism (SNP)



Gene-based modeling: Linear regression models

Plant Breeding

Crop Growth Models

Linear mixed-effect Model with G x S

$$\hat{y}_{ij} = \mu + \beta_S S_j + \sum_{q=1}^{Q} \beta_\alpha X_{iq} + \sum_{q=1}^{Q} \beta_{QTLxS} X_{iq} S_j$$

- Predicts static traits
- Predicts complex traits
- Limited application in training locations

Boer et al. 2007

Gene-based modeling: Crop growth models

Plant Breeding

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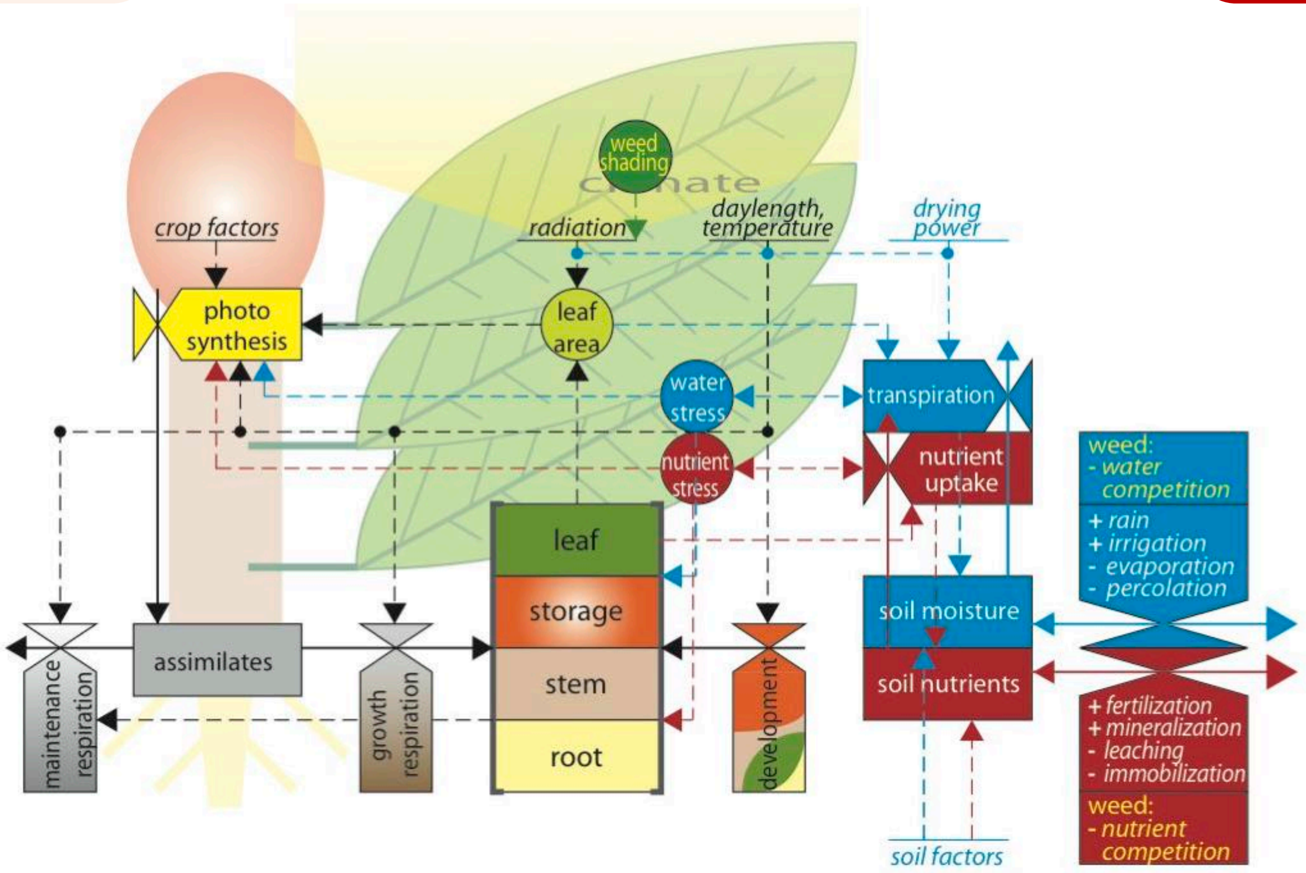

Source: M. van Ittersum

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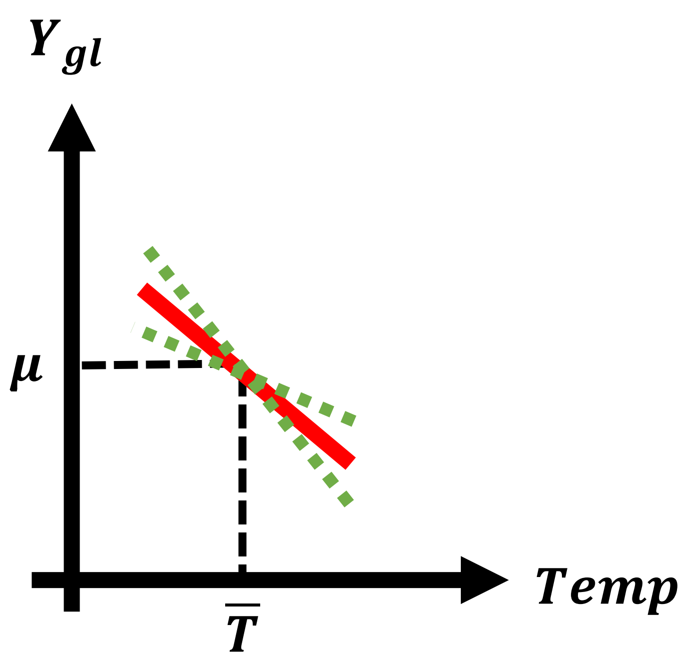
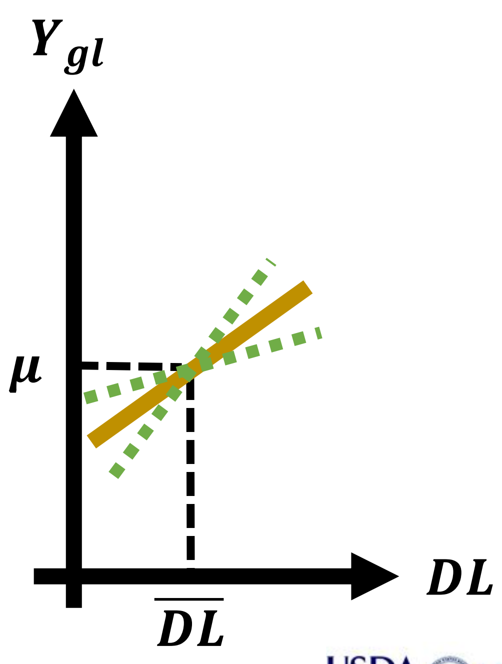
Model conversion

Base linear mixed effect model

$$\hat{Y}_{gl} = \mu + \beta_T \Delta T_{gl} + \beta_{DL} \Delta DL_{gl} + \sum_{q=1}^{Q} \beta_{QTL_q} QTL_{gq} + \sum_{q=1}^{Q} \left(\beta_{QTL_q xT} QTL_{gq} \Delta T_{gl} + \beta_{QTL_q xDL} QTL_{gq} \Delta DL_{gl} \right)$$

$$\Delta T_{gl} = \left(T_{gl} - \overline{T} \right) \quad \Delta DL_{gl} = \left(DL_{gl} - \overline{DL} \right)$$



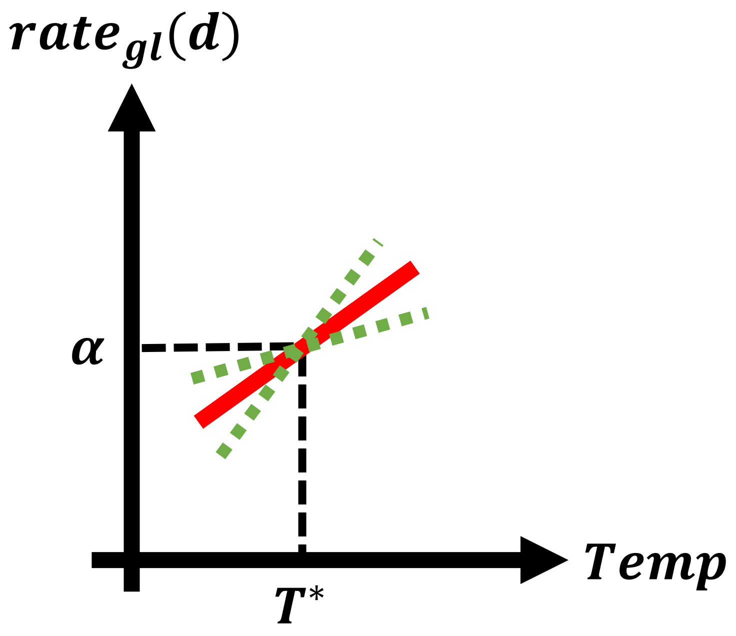


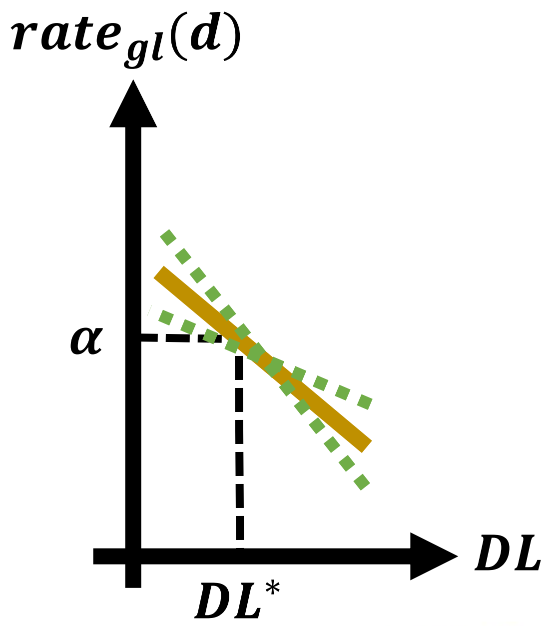
Model conversion

Convert to dynamic model

$$rate_{gl}(d) = \alpha + \beta_T \Delta T_{gl}(d) + \beta_{DL} \Delta DL_{gl}(d) + \sum_{q=1}^{Q} \beta_{QTL_q} QTL_{gq} + \sum_{q=1}^{Q} \left(\beta_{QTL_q xT} QTL_{gq} \Delta T_{gl}(d) + \beta_{QTL_q xDL} QTL_{gq} \Delta DL_{gl}(d) \right)$$

$$\Delta T_{gl}(d) = \left(T_{gl} - T^*\right) \quad \Delta DL_{gl}(d) = \left(DL_{gl} - DL^*\right)$$





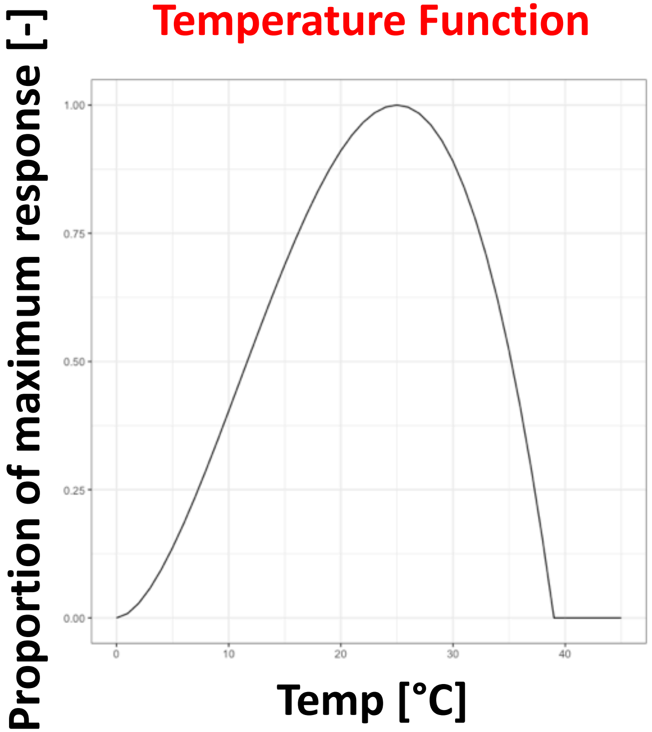
Model conversion

Non-linear E response functions

$$rate_{gl}(d) = \alpha + \beta_T \Delta T_{gl0}(d) + \beta_{DL} \Delta DL_{gl}(d) + \sum_{q=1}^{Q} \beta_{QTL_q} QTL_{gq} + \sum_{q=1}^{Q} \left(\beta_{QTL_q xT} QTL_{gq} \Delta T_{glq}(d) + \beta_{QTL_q xDL} QTL_{gq} \Delta DL_{gl}(d) \right)$$

$$\Delta T_{glq}(d) = \sum_{h=1}^{24} f_T\left(Temp_{d,h}, Tpeak_q\right) \quad \Delta DL_{gl}(d) = f_{pp}(d, CSDL)$$

Temperature Function



Photoperiod Function