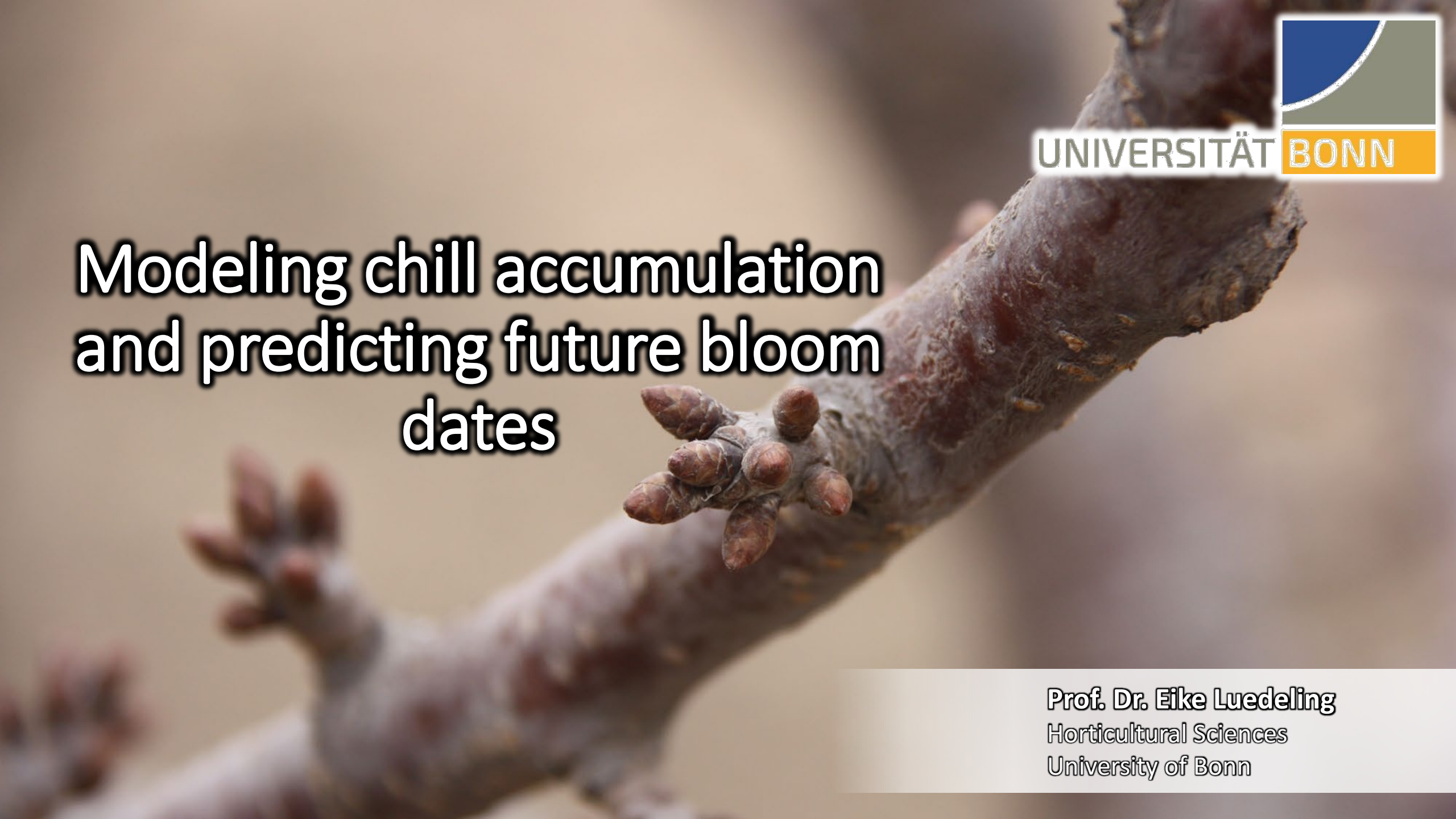


Modeling chill accumulation and predicting future bloom dates

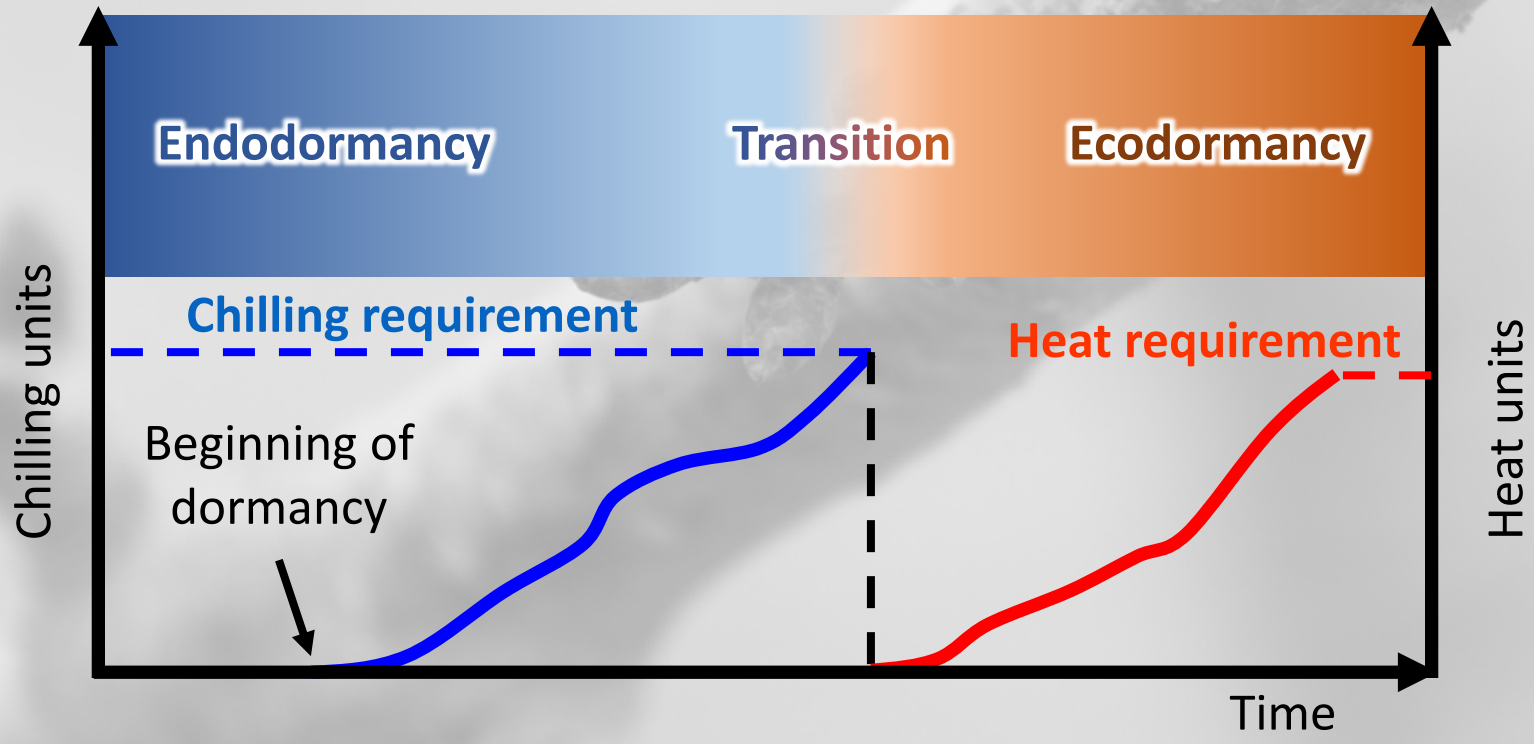
Prof. Dr. Eike Luedeling
Horticultural Sciences
University of Bonn

Outline

- Modeling tree dormancy
- Chill models
- Challenges with the Dynamic Model
- Model choice and comparison
- The PhenoFlex framework

Tree dormancy

- Temperate fruit trees are dormant in winter
- Require chill and heat to resume growth
- Complex process with lots of open questions

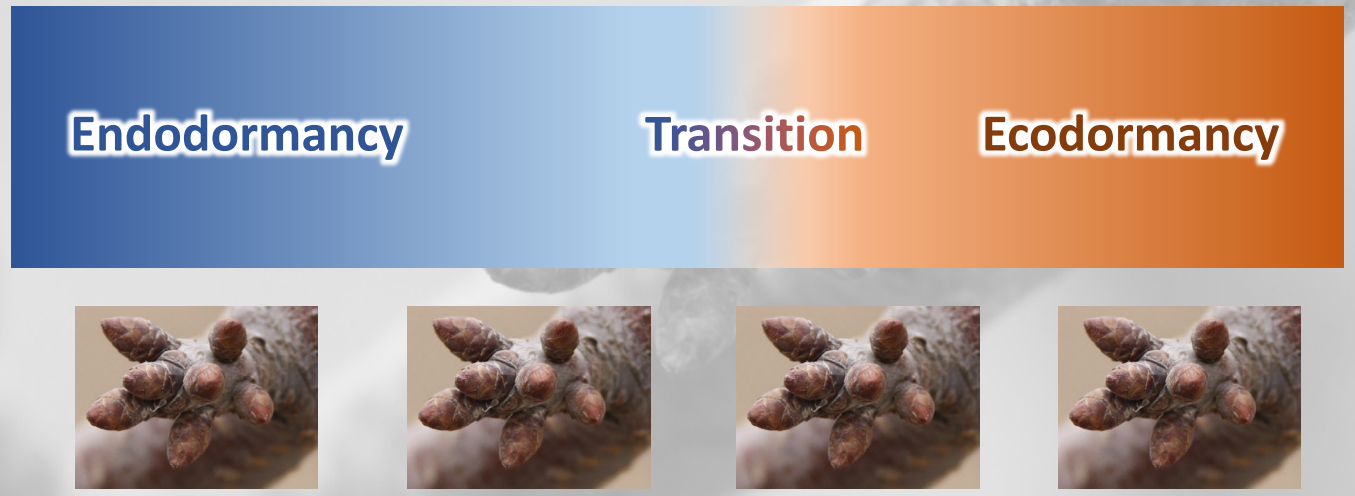


Luedeling et al. 2009. Agricultural and Forest Meteorology 149, 1854-1864.

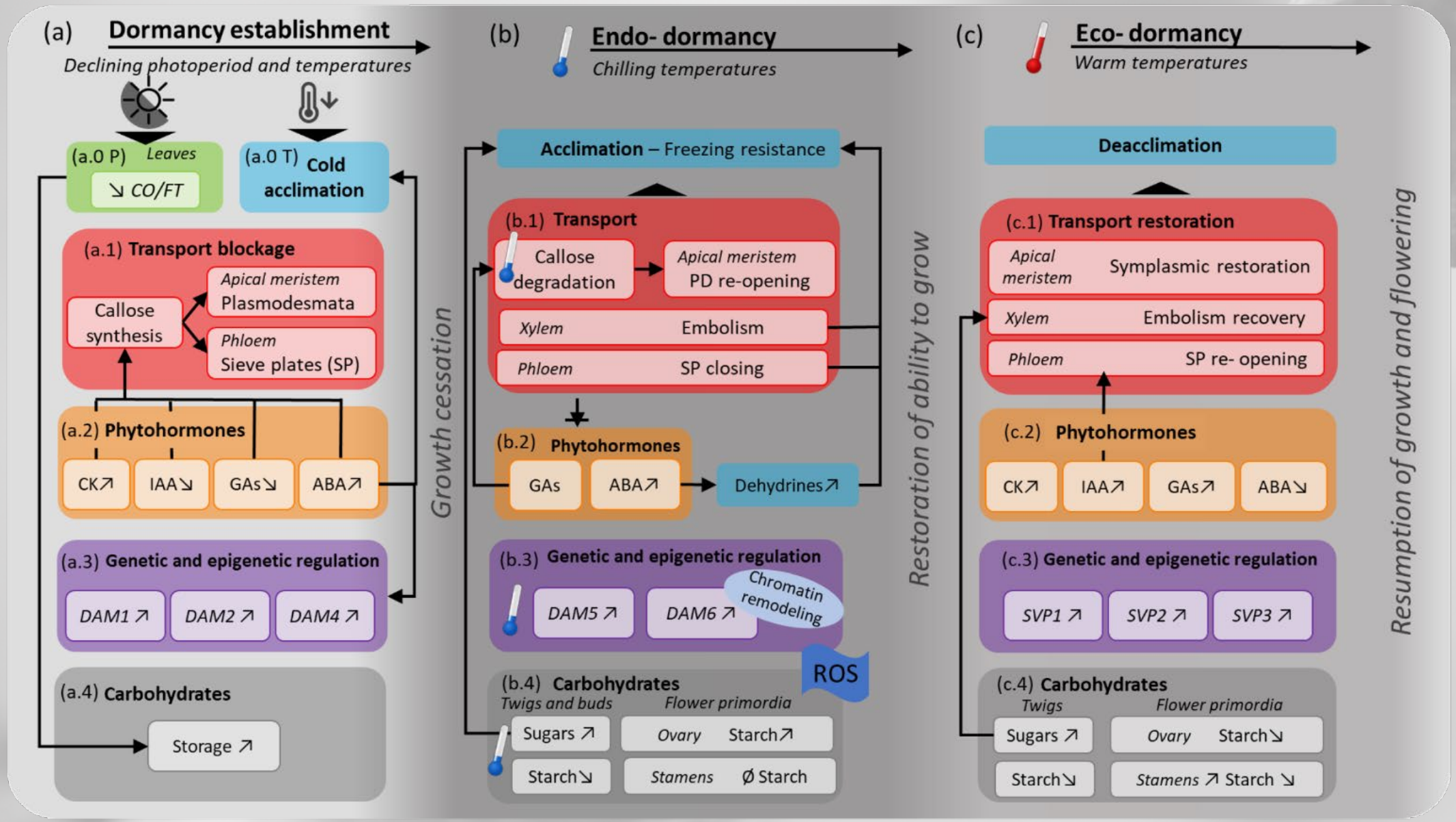
Modeling dormancy

UNIVERSITÄT BONN

- Modeling things we can’t really observe is pretty hard…
- We can only easily observe budburst in spring
- Some insights possible through forcing experiments



Can we measure any of this?



Fadón et al., 2020. Agronomy 10, 241.

Chill (and heat) models

- Since we can’t see much development, models involve major guesswork…
- Some models exist
  - Chilling Hours
  - Utah Model
  - Dynamic Model
  - A few others, mostly modified Utah models
- Modelers, researchers and growers have often gone for the easy models (mostly Chilling Hours)
- Does that matter?

Commonly used chill models

- Most models operate at an hourly time step

Hourly time step:

$$\text{Chilling} = \sum_{t_0}^{t} w$$

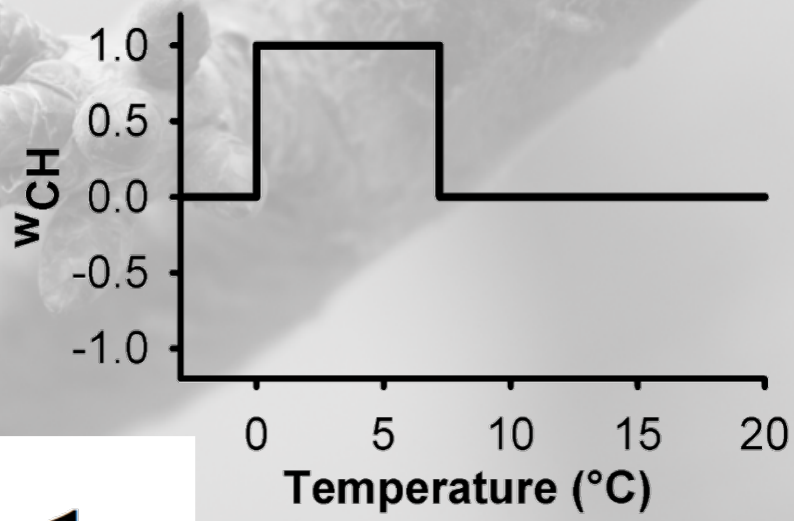
Commonly used chill models

- Most models operate at an hourly time step

The Chilling Hours Model

Hourly time step:

$$\text{Chilling} = \sum_{t_0}^{t} w$$



$$w = \begin{cases} 0\,^{\circ}\text{C} < T < 7.2\,^{\circ}\text{C} & : 1 \\ \text{else} & : 0 \end{cases}$$

We'll talk about the proper citation later

Commonly used chill models

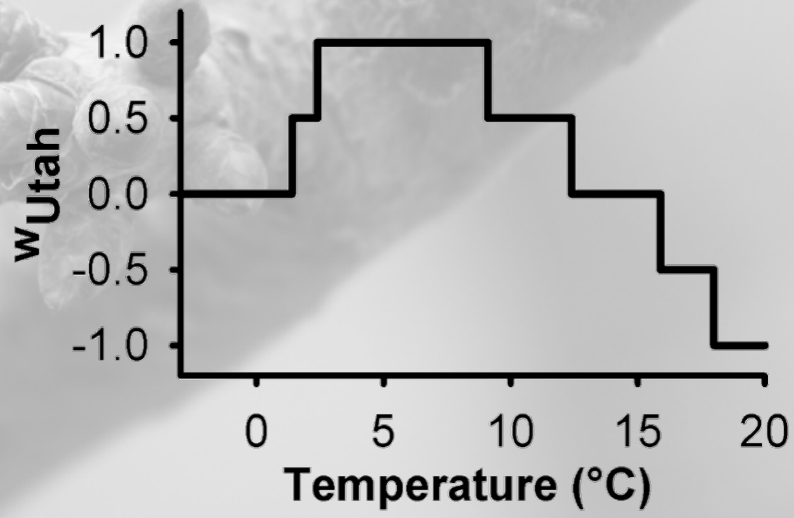
- Most models operate at an hourly time step

The Utah Model

Hourly time step:

$$\text{Chilling} = \sum_{t_0}^{t} w$$

$$W = \begin{cases} T \leq 1.4\,^{\circ}\text{C} & : 0 \\ 1.4\,^{\circ}\text{C} < T \leq 2.4\,^{\circ}\text{C} & : 0.5 \\ 2.4\,^{\circ}\text{C} < T \leq 9.1\,^{\circ}\text{C} & : 1 \\ 9.1\,^{\circ}\text{C} < T \leq 12.4\,^{\circ}\text{C} & : 0.5 \\ 12.4\,^{\circ}\text{C} < T \leq 15.9\,^{\circ}\text{C} & : 0 \\ 15.9\,^{\circ}\text{C} < T \leq 18.0\,^{\circ}\text{C} & : -0.5 \\ T \geq 18.0\,^{\circ}\text{C} & : -1 \end{cases}$$



Richardson et al. 1974. Hortscience 9, 331-332.

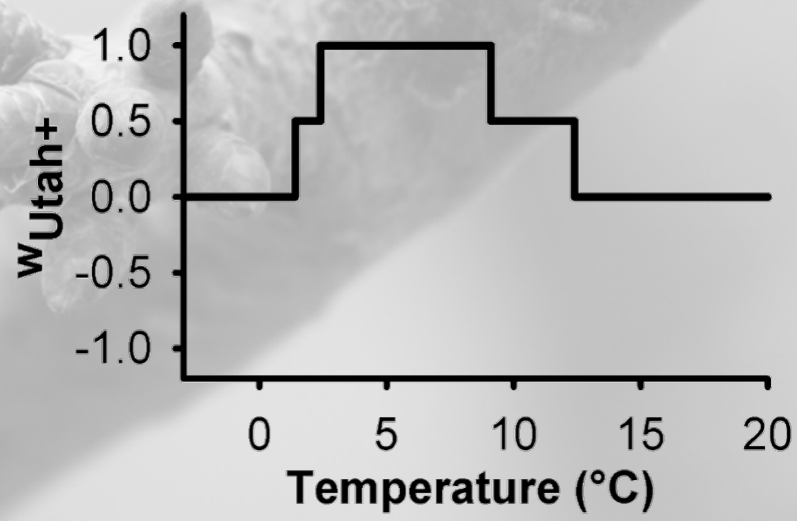
Commonly used chill models

- Most models operate at an hourly time step

The Positive Utah Model

Hourly time step:

$$\text{Chilling} = \sum_{t_0}^{t} w$$



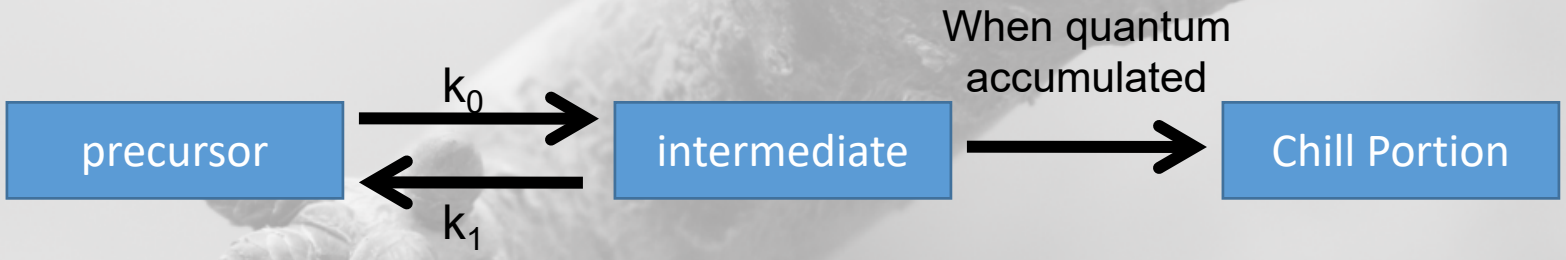
$$W = \begin{cases} T \leq 1.4\,^{\circ}\text{C} & : 0 \\ 1.4\,^{\circ}\text{C} < T \leq 2.4\,^{\circ}\text{C} & : 0.5 \\ 2.4\,^{\circ}\text{C} < T \leq 9.1\,^{\circ}\text{C} & : 1 \\ 9.1\,^{\circ}\text{C} < T \leq 12.4\,^{\circ}\text{C} & : 0.5 \\ T \geq 12.4\,^{\circ}\text{C} & : 0 \end{cases}$$

Linsley Noakes & Allan 1994. Scientia Horticulturae 59, 107-113.

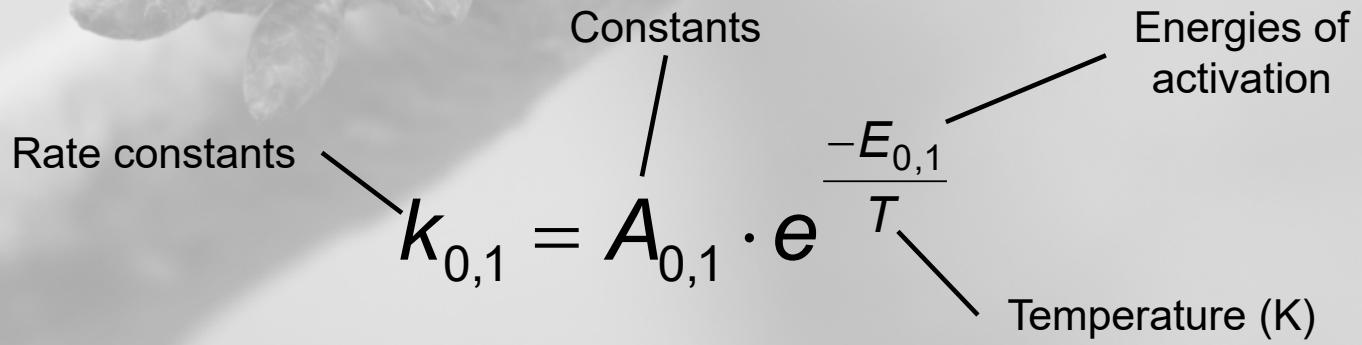
Commonly used chill models

- Most models operate at an hourly time step

The Dynamic Model



- 2-step process
- Intermediate product formed first
- Intermediate can be destroyed
- Gets fixed as a Chill Portion if enough of it accumulates

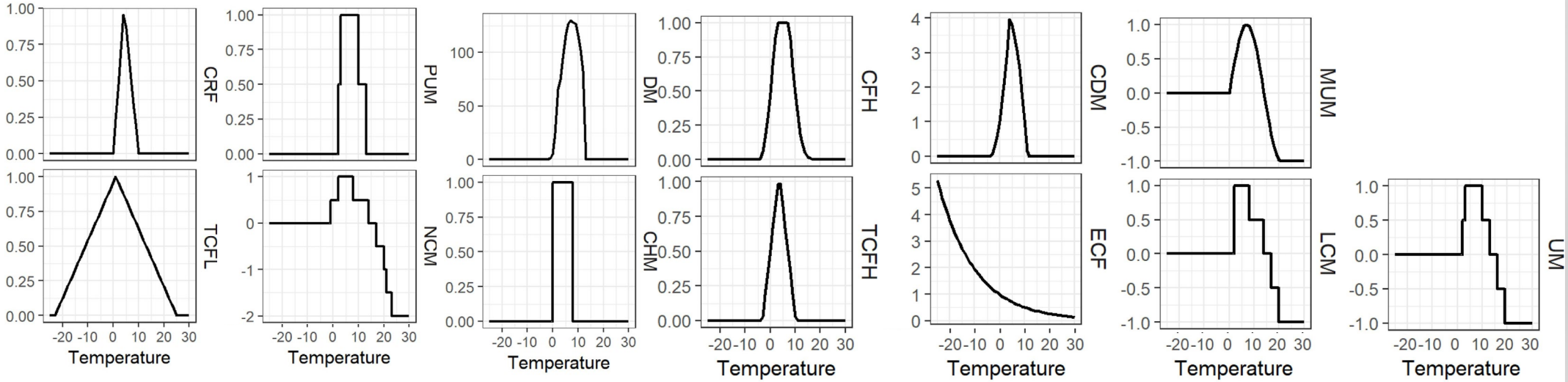


Fishman et al. 1987. Journal of Theoretical Biology 124, 473-483 + 126, 309-321.

Common and uncommon chill models

Major differences between models!

Model name	Unit name	Disciplinary origin	Time step	Chill negation by heat	Author/reference
Dynamic model (DM)	Chill Portions (CP)	Horticulture	Hourly	Yes	Erez et al. (1990); Fishman et al. (1987a) and Fishman et al. (1987b)
Chilling Hours model (CHM)	Chilling Hours (CH)	Horticulture	Hourly	No	Bennett (1949) and Weinberger (1950)
Utah model (UM)	Chill Units (CU)	Horticulture	Hourly	Yes	Richardson et al. (1974)
Positive Utah model (PUM)	Chill Units (PCU)	Horticulture	Hourly	No	Linsley-Noakes et al. (1994)
North Carolina model (NCM)	Chill Units (CU)	Horticulture	Hourly	Yes	Shaltout and Unrath (1983)
Modified Utah model (MUM)	Chill Units (CU)	Horticulture	Hourly	Yes	Linvill (1990)
Low Chill model (LCM)	Chill Units (CU)	Horticulture	Hourly	Yes	Gilreath and Buchanan (1981)
Chill Days model (CDM)	Chill Days (CD)	Horticulture and Forestry	Daily	No	Cesaraccio et al. (2004)
Chilling Rate function (CRF)	Rate of Chilling (RC)	Horticulture	Daily	No	Chmielewski et al. (2011)
Triangular Chill function (TCFL)	Chill Function (CF)	Horticulture	Daily	No	Legave et al. (2013)
Exponential Chill function (ECF)	Chill Function (CF)	Horticulture	Daily	No	Legave et al. (2013)
Chilling function (CFH)	Chilling Units (Cu)	Forestry	Hourly	No	Harrington et al. (2010)
Triangular Chill function (TCFH)	Rate of Chill (Rc)	Forestry	Daily	No	Hänninen (1990)



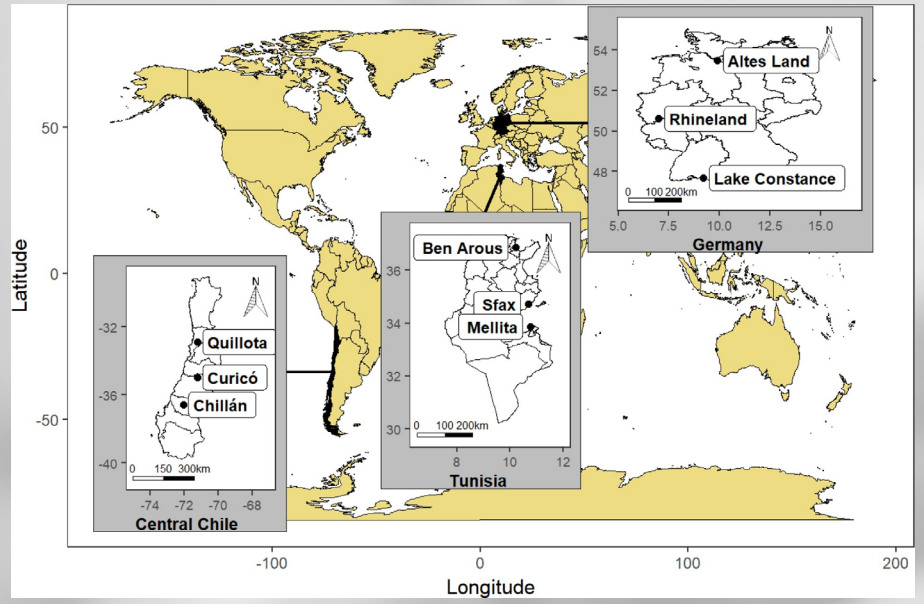
Fernandez et al. 2020. European Journal of Agronomy 119, 126103.

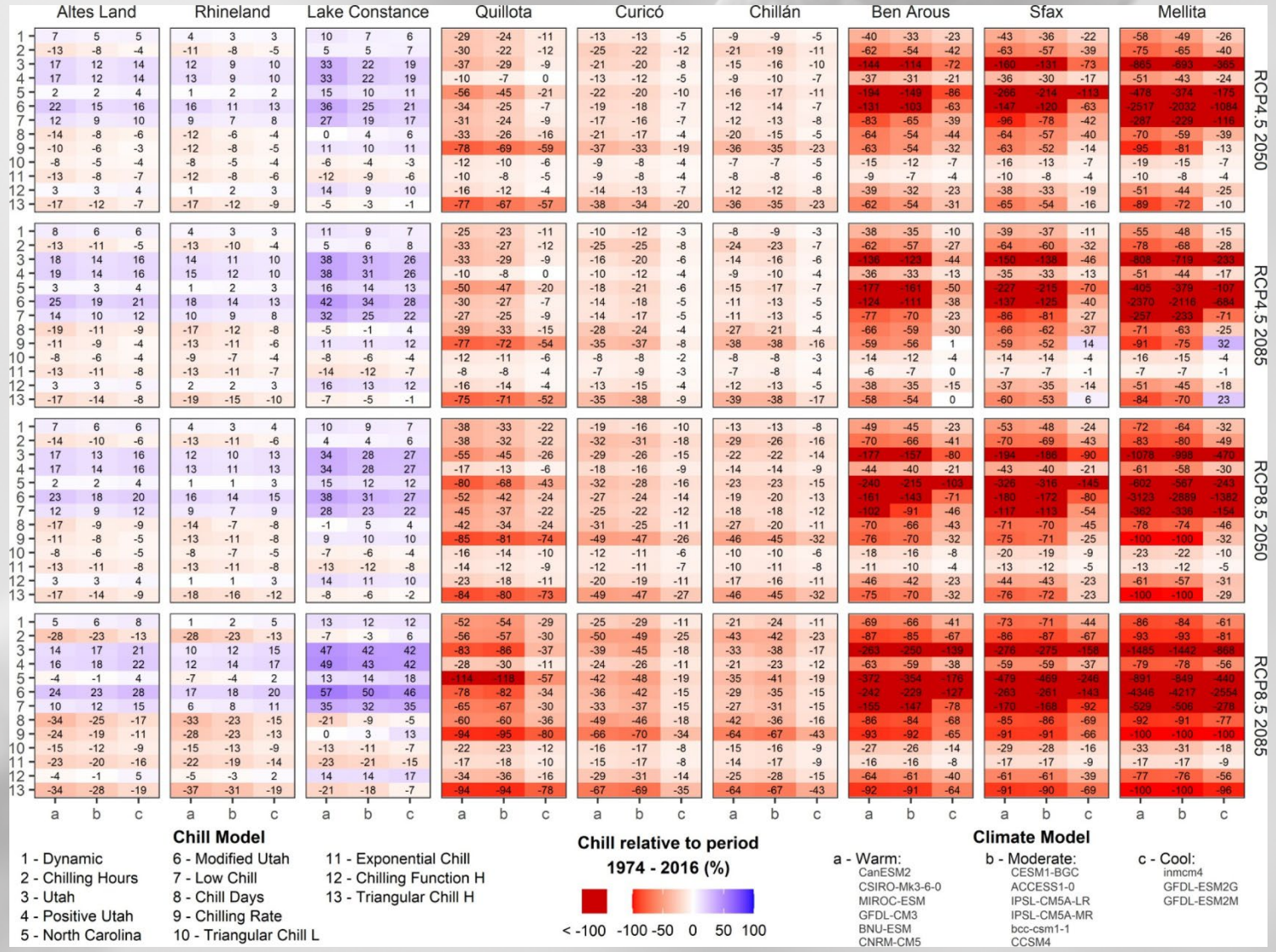
How to choose models

- Having many models is great
- Many people have chosen the easiest one: Chilling Hours (me too in the beginning…)
- Is that a good idea? How can we know?
- Does it even matter?

Model sensitivity

- Model responses in different places and to different climate scenarios
- Considerable spread of responses
- Model choice matters a lot!



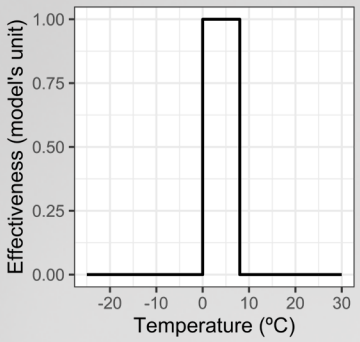


Fernandez et al. 2020. European Journal of Agronomy 119, 126103.

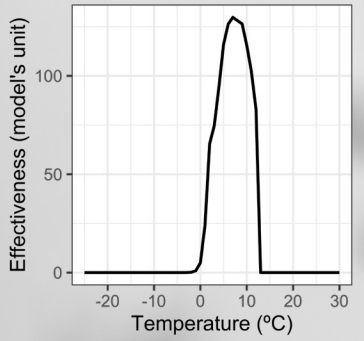
Model equivalence

- Chill models are not interchangeable

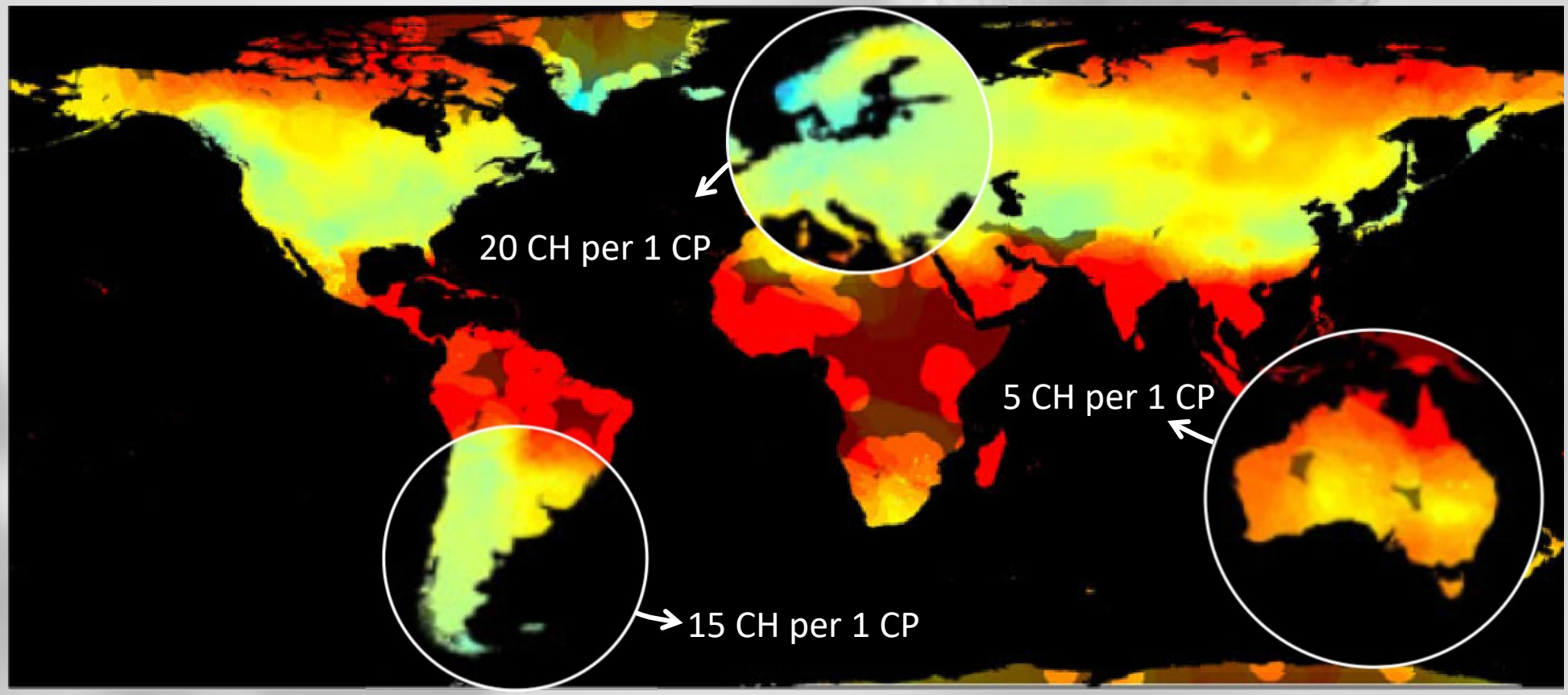
Chilling hours model



VS



Dynamic model



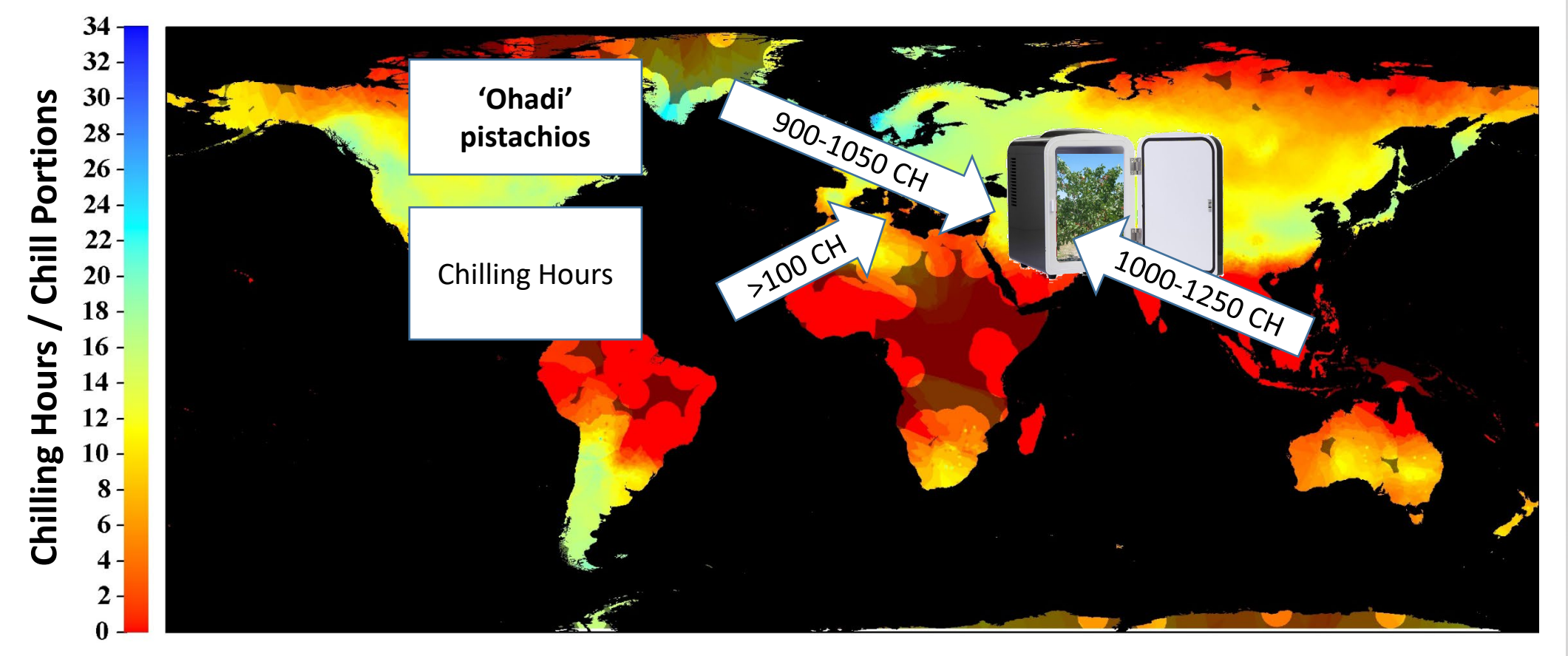
Model choice matters!

Illustration by Dr. Eduardo Fernandez

Luedeling, E., and Brown, P. 2011. Int. J. Biometeorol. 55, 411-421

Model equivalence

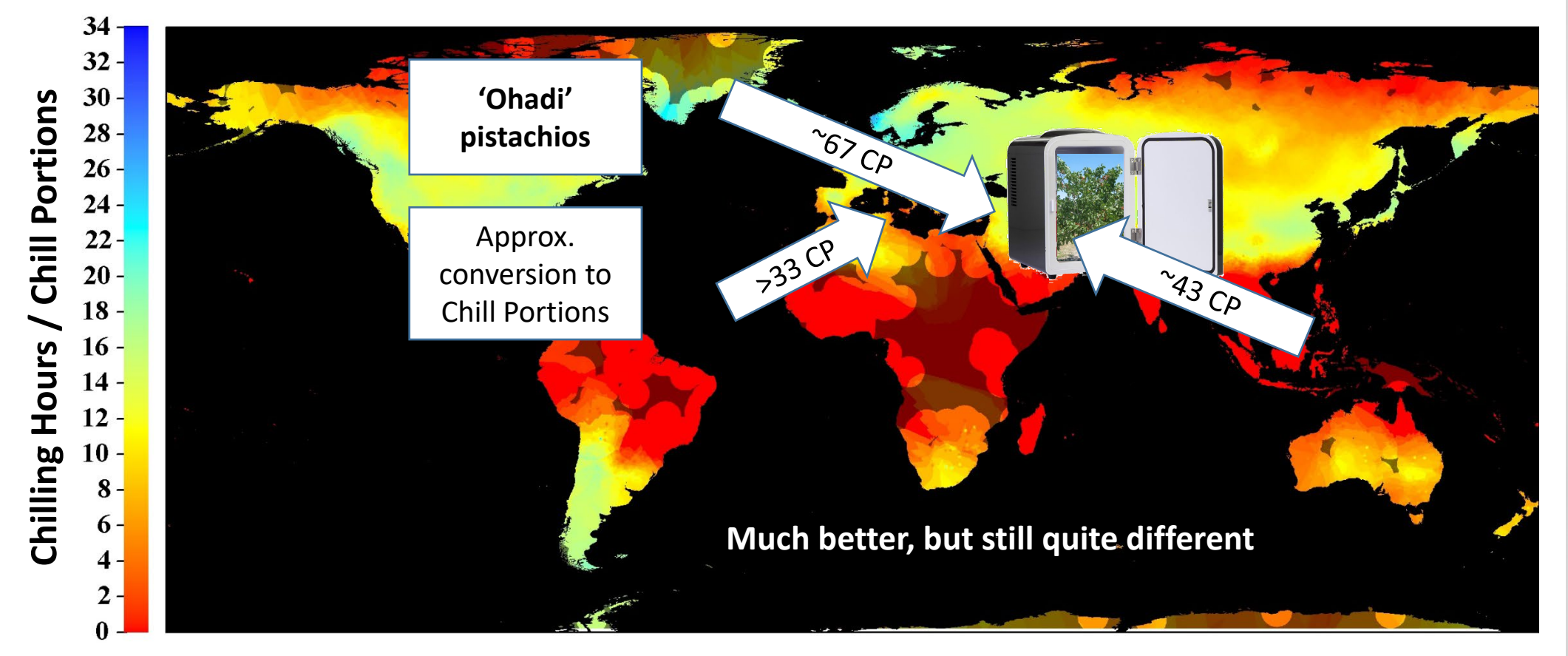
- Inconsistent estimates



Luedeling, E., and Brown, P. 2011. Int. J. Biometeorol. 55, 411-421

Model equivalence

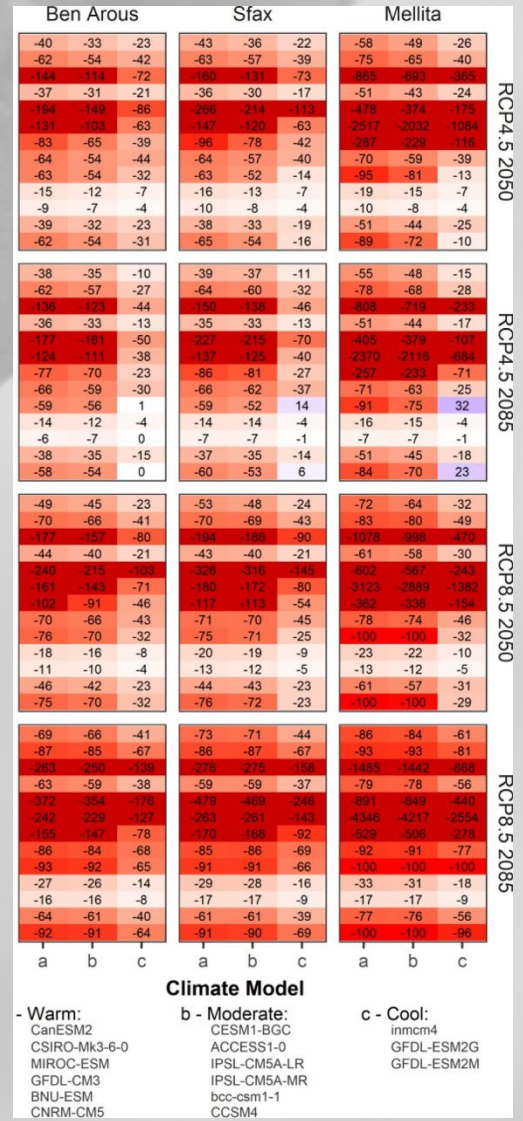
- Inconsistent estimates



Luedeling, E., and Brown, P. 2011. Int. J. Biometeorol. 55, 411-421

Model ensembles?

- Some people (me too at some point) use many models in their research to deal with model uncertainty
- Best example: Coupled Model Intercomparison Project (CMIP) of the climate science community
- Should we use all 13 models in our research?



Fernandez et al. 2020. European Journal of Agronomy 119, 126103.

Model quality matters!

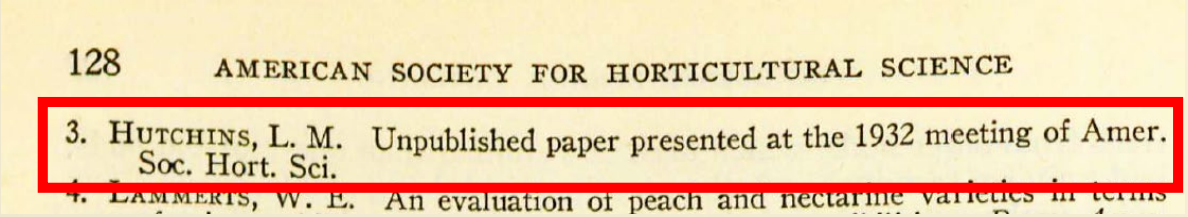
- All members of an ensemble need to be credible
- Models need to meet quality standards to qualify
- For instance, CMIP includes very rigorous testing procedures
- Including “bad apples” in an ensemble contaminates the analysis, rather than enriching it!

https://www.mnn.com/lifestyle/arts-culture/blogs/we-believe-conspiracy-theories-psychological-roots

Comparing models

- Not so easy for a process you can't easily observe
- To test chill models, we can try to assess whether they make consistent predictions of the end of endodormancy
  - Natural chill → controlled forcing conditions
  - Fully temperature-controlled chilling/forcing studies are rare (and expensive)
- Many less straightforward arguments indicate that the Dynamic Model is the front-runner so far
- But we can also take a closer look at models and get some quality indications

Comparing models

	“Chilling Hours”	“Dynamic Model”
Origin	 128 AMERICAN SOCIETY FOR HORTICULTURAL SCIENCE 3. HUTCHINS, L. M. Unpublished paper presented at the 1932 meeting of Amer. Soc. Hort. Sci. 4. LAMMERTS, W. E. An evaluation of peach and nectarine varieties in terms	$dL/d\pi = k_1(2)(1-\eta)\{\exp[k_1(1)\eta\pi] + 1\}$ $f_2 = k_1(1)\eta\{1 - \exp[-k_1(2)(1-\eta)\pi]\}$ $\Theta_c = (E_1 - E_0)\ln(A_1/A_0)$
	Citation in: Weinberger, 1950. Proceedings of the American Society for Horticultural Science 56, 122-28.	Fishman et al., 1987. Journal of Theoretical Biology 124, 473–483.
Evidence base	None or at best anecdotal (as far as I know)	Decades of published controlled-temperature experiments in Israel led by Amnon Erez and others
Performance in model comparisons	Usually poor performance	Always among the best performing models

Examples:

- Zhang & Taylor, 2011. HortScience 46, 420-425.
- Ruiz et al., 2007. Environ. Exp. Bot. 61, 254-263.
- Luedeling et al., 2009. Agric. For. Meteorol. 149, 1854-1864.

Comparing models

UNIVERSITÄT BONN

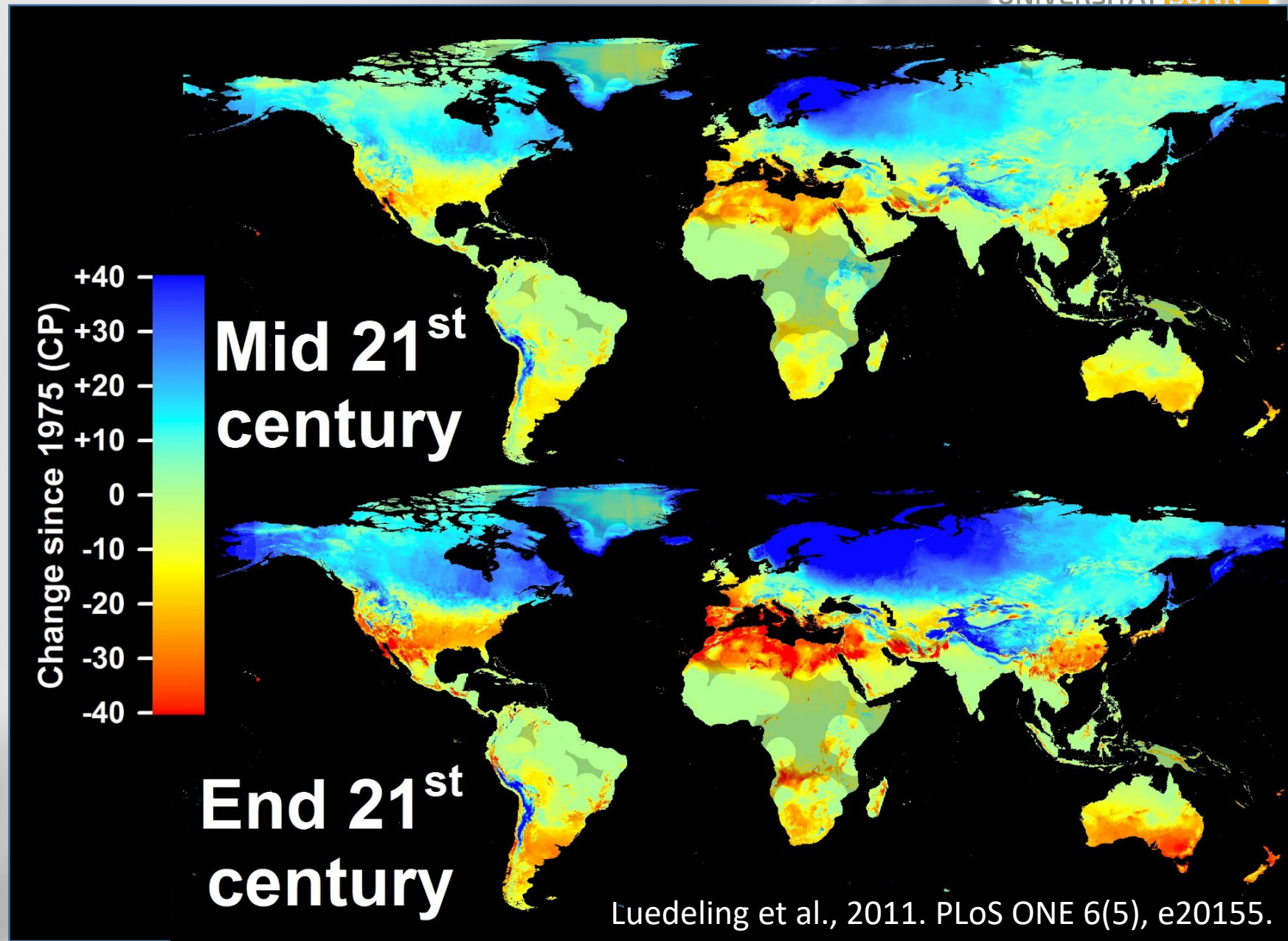
- Do models consider known phenomena?

Information from controlled experiments	Chilling Hours	Utah	Utah+	Dynamic Model	Phenology models in ecology / forestry
Depends on temperature	+	+	+	+	+
Daily temperature cycle	+	+	+	+	-
Weighted temperatures	-	+	+	+	±
Continuous weights	-	-	-	+	±
Warm temperatures -	-	+	-	+	-
Moderate temperatures +	-	-	-	+	-
Two-phase process	-	-	-	+	-

Luedeling et al. 2009. Erwerbs-Obstbau 51, 81-94.

The Dynamic Model

- Good reasons to consider using this model
- Appears (to me) by far the most credible!



Luedeling et al., 2011. PLoS ONE 6(5), e20155.

The Dynamic Model

- Slowly becoming the standard in the scientific horticultural literature
- Performance still not always convincing
- Challenges with using it “properly”
- Model is complicated and difficult to use
- For a long time only accessible (to most people) via an ancient Excel table…
- Improved with the chillR package

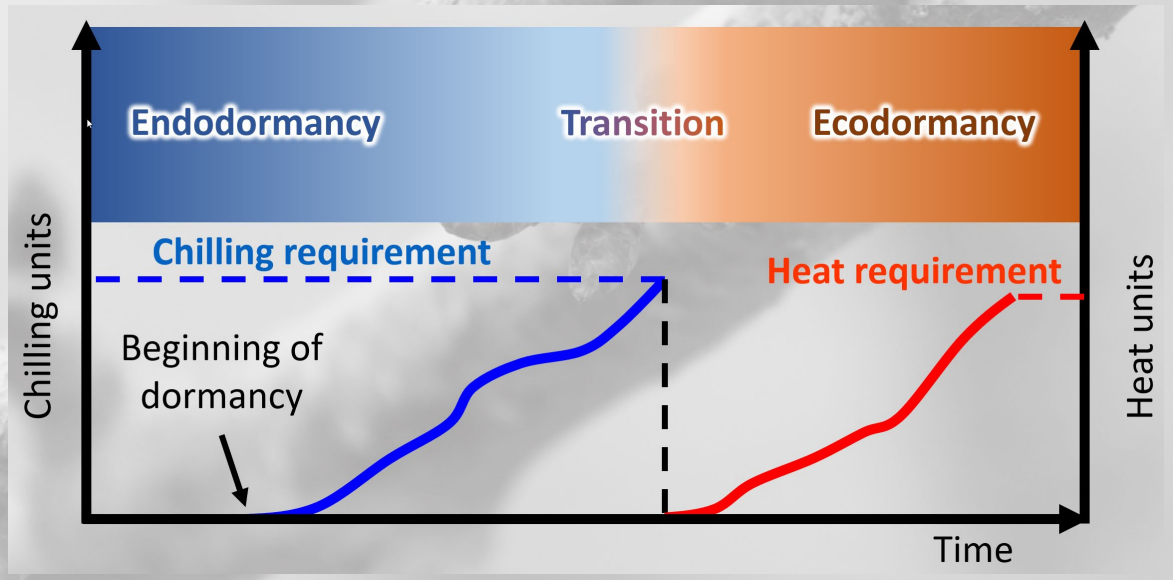
C	D	E	F	G	H	I	J	K	L	M	N	O
	e0	4.15E+03										
	e1	1.29E+04		DYNAMIC MODEL CHILLING PORTIONS - EREZ, A. and FISHMAN, S.								
	a0	1.40E+05		The Volcani Center, Bet Dagan, ISRAEL								
	a1	2.57E+18										
	slp	1.6		Add hourly data in column B from row 13 down. **Do not erase rows 11, 12.**								
	tetmlt	277		copy data from row12 colums C to L till the last entry in column B.								
	aa=a0/a1	5.43E-14		total cumulative chiling portions will appear in column L.								
	ee=e1-e0	8.74E+03										
date	Temp(C)	Temp (K)	ftmprt	sr	xi	xs	ak1	Inter-S	Inter-E	delt	**Portions**	
12/4/1999 16:45	15	288.00	####	22471935.51	1.00	0.81	0.09	0.00	0.07	0.00	0	
12/4/1999 17:45	12	285.00	####	252887.94	1.00	1.11	0.06	0.072604	0.13	0.00	0	

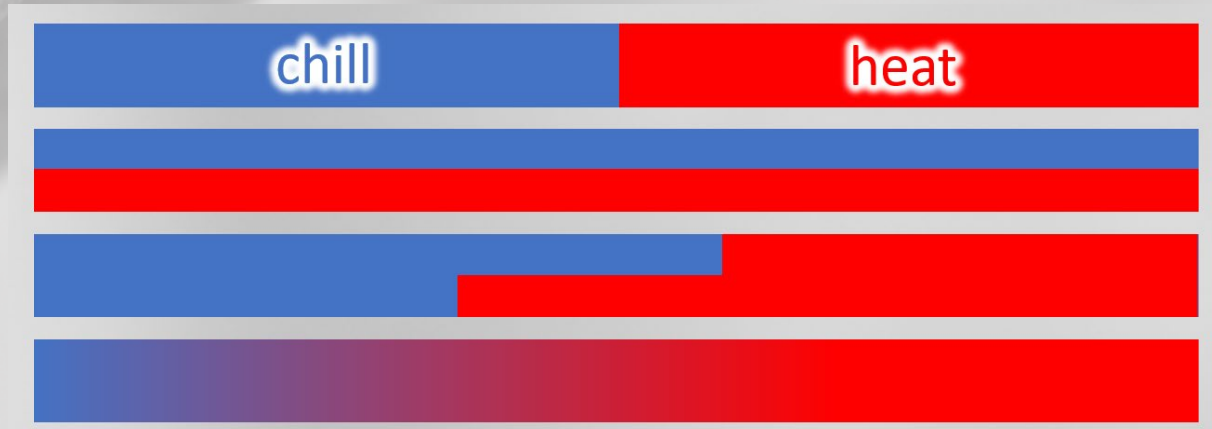
The Dynamic Model

- Original publications clearly stated the need to adjust model parameters for each species or even cultivar
- This has very rarely been done!
- We treat all our trees as if they were peaches (grown under experimental conditions in Israel)
- No clear instructions on how to parameterize the model (as far as I know)
- Important: all other models have the same problem – the authors just didn’t point it out…

Modeling the whole dormancy process

- Requires coupling a chill with a heat model
- Can be coupled in various ways
  - Sequential accumulation
  - Parallel accumulation
  - Overlapping accumulation
  - Chill-dependent heat effectiveness?
- All concepts have been used…
- Strictly parallel or sequential seems unlikely





The PhenoFlex framework

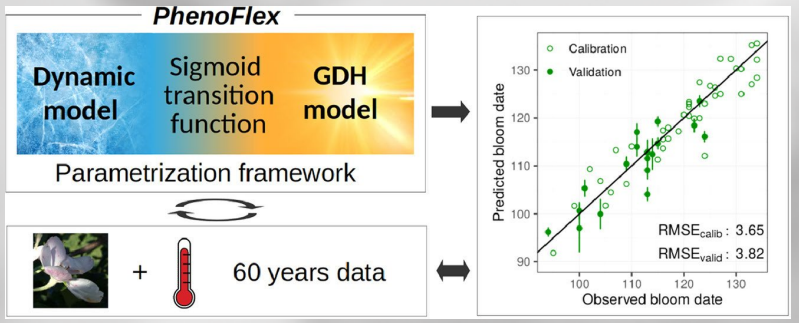
- Problem so far has been that the heat and chill models have been taken ‚as is' without parameterization for specific conditions
- Possible interaction between chill and heat has been neglected
- We've developed a framework that overcomes these constraints

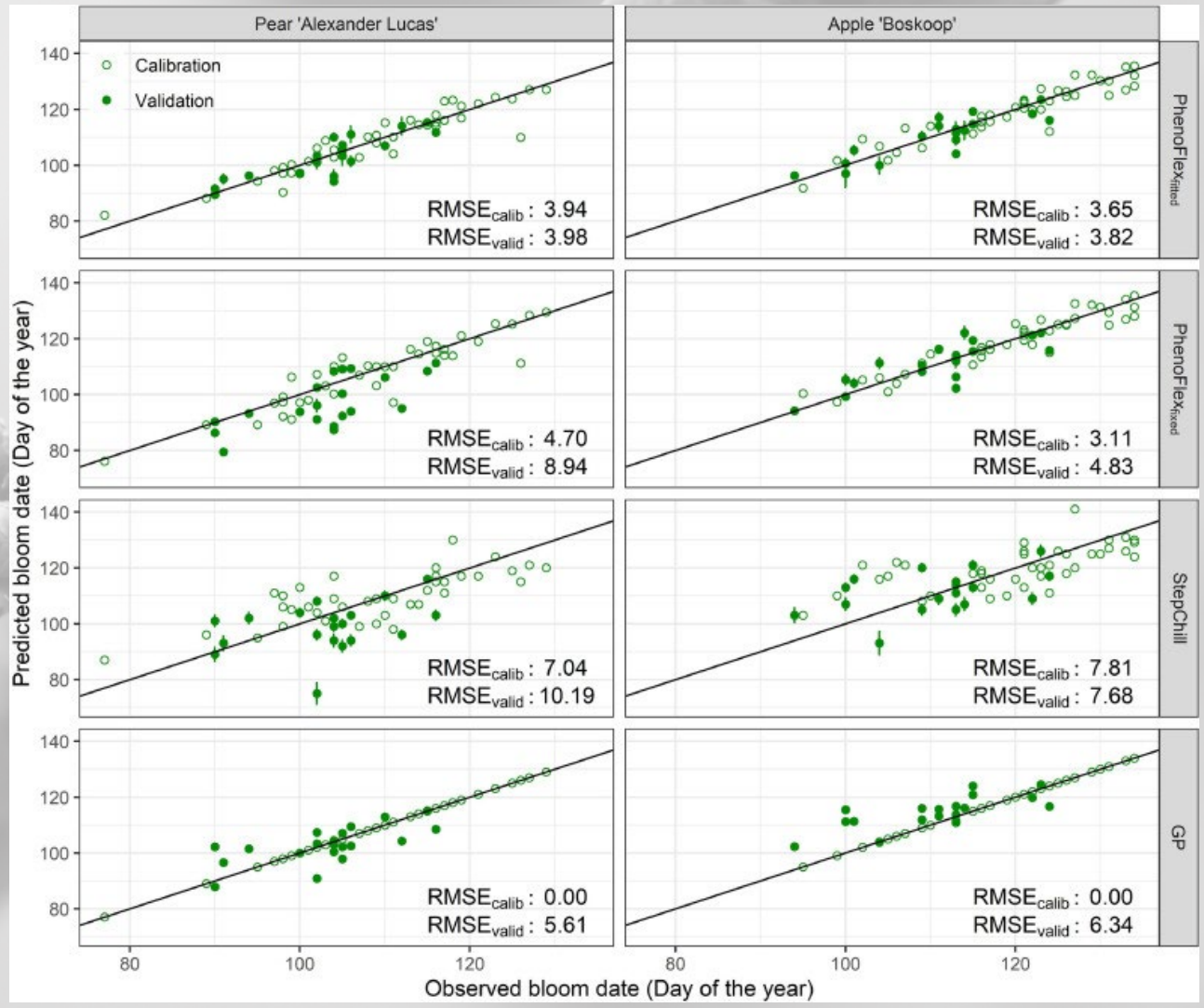
- All parts are fully parameterizable

Luedeling et al., 2021. Agricultural and Forest Meteorology 307, article 108491.

The PhenoFlex framework

- Allows determining model parameters from long-term phenology data
- Cultivar-specific chill and heat responses
- Promising results so far, but still some open questions



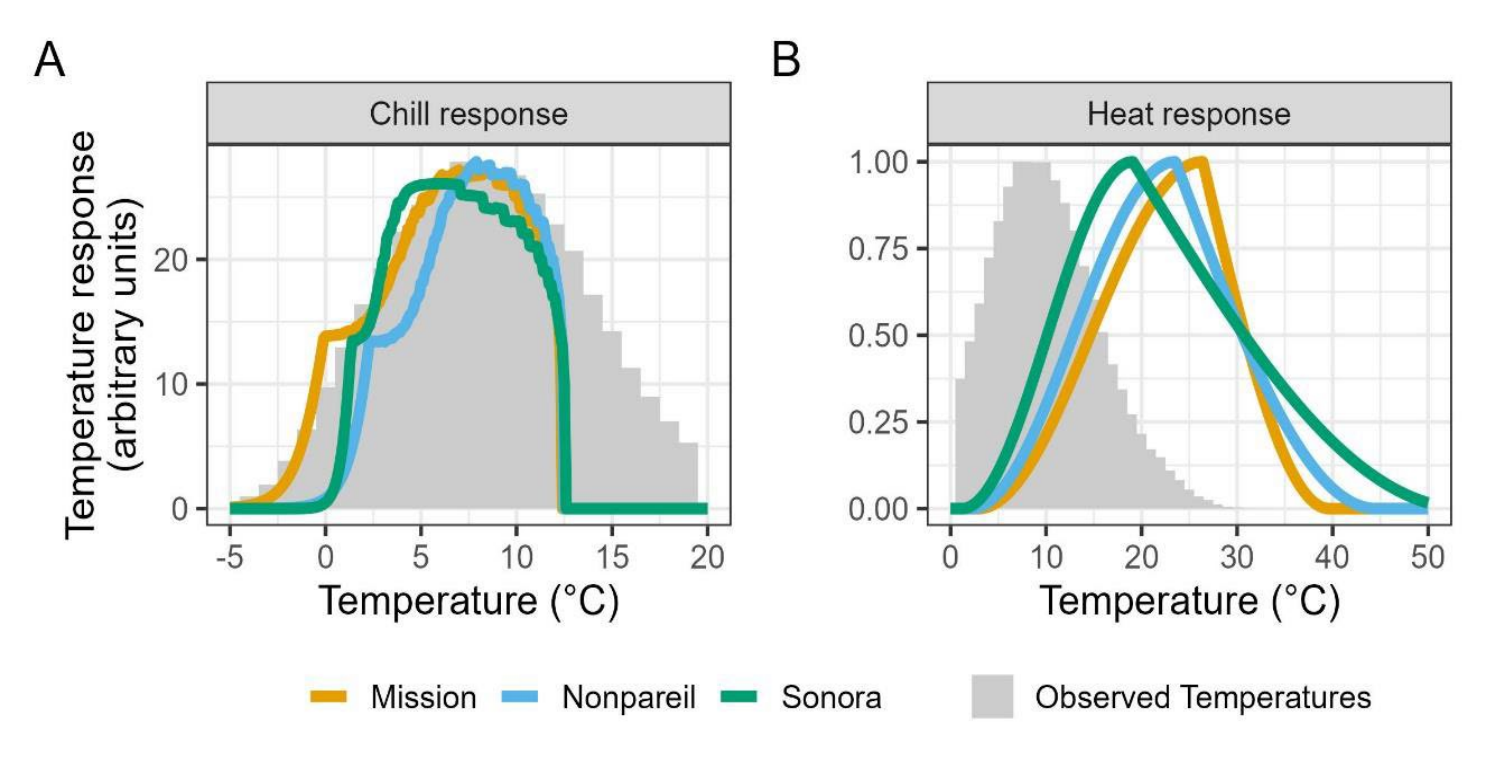


Luedeling et al., 2021. Agricultural and Forest Meteorology 307, article 108491.

Fitted temperature responses

- Fitted temperature responses often differ from commonly assumed effective temperature ranges

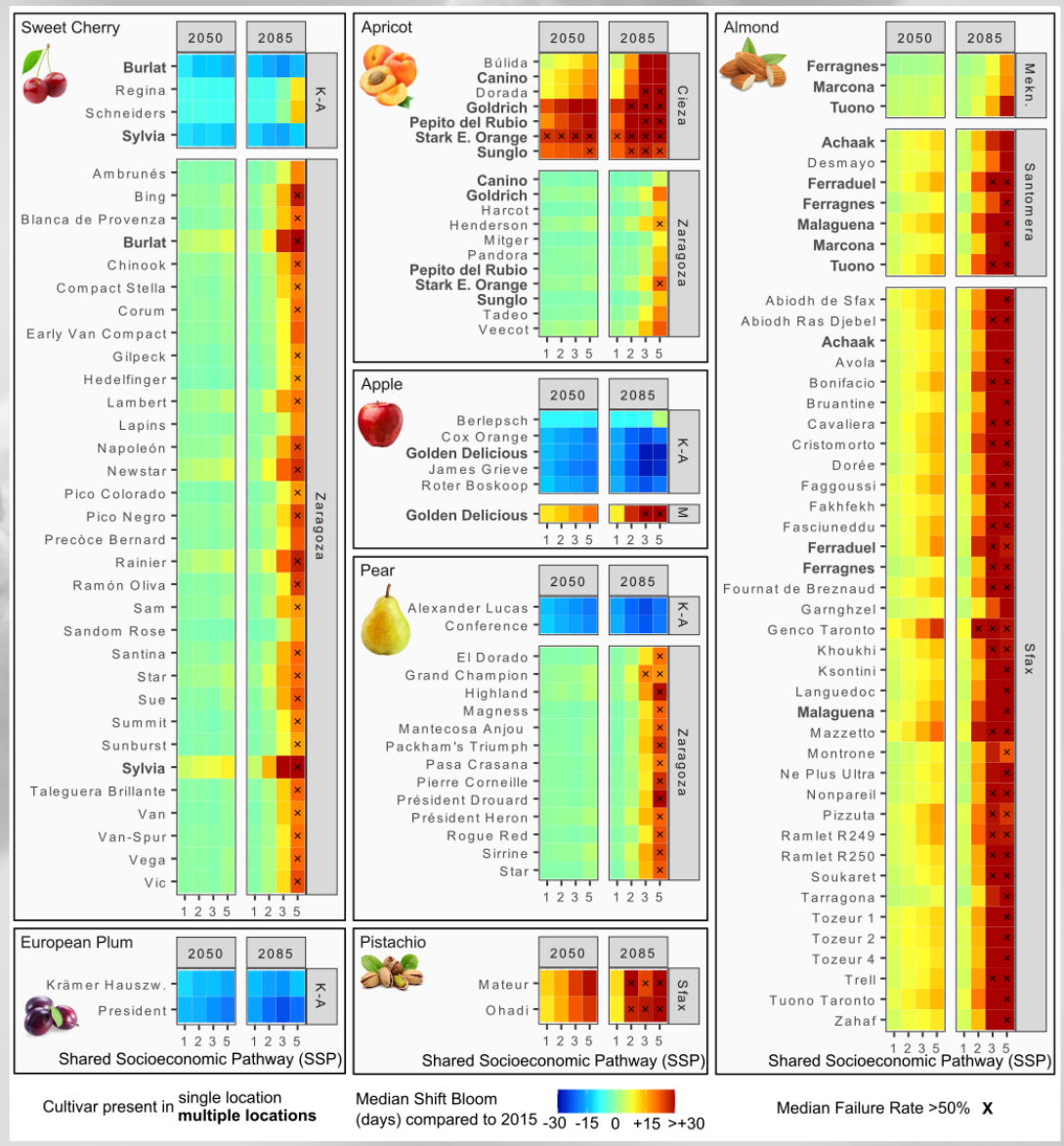
Chill and heat responses of almond cultivars in California



Caspersen et al., in press. Acta Horticulturae.

Deploying PhenoFlex

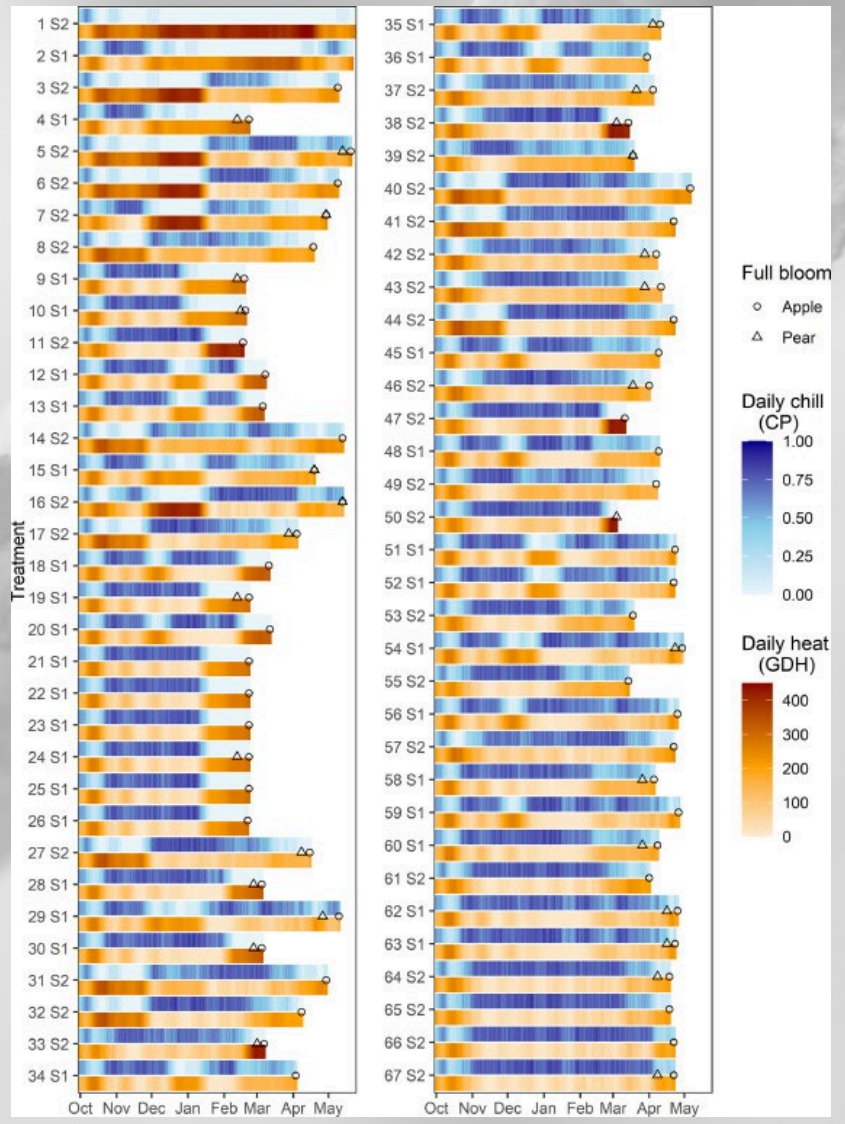
- R functions (relatively) easy to integrate into workflows
- Recently applied for >100 cultivars from the Mediterranean region
- Several ongoing studies on cherries, apples and olives – MSc and PhD projects



Caspersen et al., under review.

Experimental enhancement

- Observations on apples and pears grown under semi-controlled conditions
- 67 treatments generated by frequently transferring potted trees between three environments
- Mostly worked well, but exposed model limitations under extreme conditions



Fernandez et al., 2022. Agricultural and Forest Meteorology 322, 109020.

The chillR package

- The chillR package for R contains functions to support (almost) all analyses shown today
- Open-source contributed package (on CRAN, R's official server)
- Successively added functions since 2013
- Tutorial at https://hortibonn.github.io/Tree-Phenology/
- Automates many data processing and analysis steps in phenology analysis
  - Dynamic Model
  - Climate change impact projection framework
  - Phenology data analysis
  - PhenoFlex

Luedeling et al., 2013-2024. chillR package for R - https://CRAN.R-project.org/package=chillR.

Tree phenology analysis with R

UNIVERSITÄT BONN

- MSc-level module offered at the University of Bonn
- Often attended by external participants
- Started last week, so not much happened yet
- Tuesdays 8:30-10:00; Thursdays 10:15-11:45 (until end of January)
- Materials are here: https://hortibonn.github.io/Tree-Phenology/
- Possible to participate remotely – let me know quickly if you're interested

Luedeling et al., 2013-2024. chillR package for R - https://CRAN.R-project.org/package=chillR.

Thanks for staying awake (if that's the case)

Questions, comments?

Eike Luedeling

luedeling@uni-bonn.de