Supplemental materials: How environmental tracking shapes communities in stationary & non-stationary systems

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1 Literature review

We systematically reviewed the literature for studies examining tracking and other traits. We searched ISI in August 2019 for:

1. Topic: 'phenolog* chang*' and Title: phenolog* AND trait*
2. Topic: 'warming shift*' AND trait* and Title: phenolog*
3. Topic: 'phenolog* track*' AND trait* and Title: phenolog*
4. Topic: 'phenolog* sensitiv*' AND trait* and Title: phenolog*

which resulted in 231 papers (83% of which were published in 2011 or later, see Fig. S1). From here we used the following criteria to determine from which papers we could not extract data: no phenology or phenological change measured (73 papers), no trait(s) measured or analyzed (49 papers), single-species studies focused on intra-specific variation (54 papers), modeling or theory studies without data (12 papers), or papers without new data presented (reviews, etc.: 4 papers), or miscellaneous reasons leading to no data relevant to our aims (7 papers). This left us with 30 papers including relevant data (Suzuki & Kudo, 1997; Post & Stenseth, 1999; Adrian *et al.*, 2006; Xu *et al.*, 2009; Goodenough *et al.*, 2010; Diamond *et al.*, 2011; Moussus *et al.*, 2011; Szilvia *et al.*, 2012; Dorji *et al.*, 2013; Ishioka *et al.*, 2013; Xia & Wan, 2013; Bock *et al.*, 2014; Kharouba *et al.*, 2014; Vegvari *et al.*, 2015; Bell *et al.*, 2015; Lasky *et al.*, 2016; McDermott & DeGroote, 2016; Zhu *et al.*, 2016; Brooks *et al.*, 2017; Du *et al.*, 2017; Munson & Long, 2017; Arfin Khan *et al.*, 2018; Zhang *et al.*, 2018; Ladwig *et al.*, 2019; Park *et al.*, 2019; Sharma & Upadhyaya, 2019; Xavier *et al.*, 2019; Zettlemoyer *et al.*, 2019), eight of which did not test for a relationship between tracking and the other studied traits (Suzuki & Kudo, 1997; Adrian *et al.*, 2006; Xu *et al.*, 2009; Bell *et al.*, 2015; McDermott & DeGroote, 2016; Sherwood *et al.*, 2017; Sharma & Upadhyaya, 2019; Xavier *et al.*, 2019). We present data from the remaining papers in Tables S2-S3. Most studies examined tracking as how a phenophase related to temperature (86% of all tracking metrics), followed by precipitation (10%, includes snow removal), followed by photoperiod (3%), followed by the climate mode NAO (1%) and water table depth (0.5%). Four of the 30 studies examined more than one major climate metric, though some measured many versions of temperature and/or precipitation metrics (e.g., 15 precipitation and/or temperature metrics considered in Munson & Long, 2017).

2 Model

Table S1: Table of parameter values, their definitions and lightweight version of their dimensions (i.e., not yet deemed 'grams' or such).

Parameter	Definition	Unit
N_i	seedbank of species i	seeds
s_i	survival of species i	unitless
δ (peak biomass)	total length of growing season	days
B_i	biomass of species i	biomass
R	resource	resource
c_i	conversion of R uptake to biomass of species i	$\frac{\text{biomass}}{\text{resource}}$
m_i	maintenance costs of species i	days^{-1}
a_i	uptake increase as R increases for species i	days^{-1}
u_i	max uptake for species i	$\frac{\text{(days)(biomass)}}{\text{resource}}$
ϕ_i	conversion of biomass to seedbank for species, includes overwintering of seeds i	biomass^{-1}, but conceptually $\frac{\text{seeds}}{\text{(biomass)(seeds)}}$
ϵ	abiotic loss of R	days^{-1}
$g_{max,i}$	max germination of species i	unitless
h_i	controls the rate at which germination declines as τ_p deviates from optimum for species i	days^{-2}
g_i	germination fraction	unitless
τ_p	timing of pulse	days
τ_i	timing of max germination of species i	days
α_i	phenological tracking of species i	unitless
θ_i	shape of uptake for species i	unitless
b_i	seedling biomass of species i	$\frac{\text{biomass}}{\text{seeds}}$
$f_i(R)$	R uptake $f(x)$ for species i	$\frac{\text{resource}}{\text{(days)(biomass)}}$
d_i	death rate of species i, used in calculations of lifespan	unitless
t	between year time (formerly T)	years
$0 \to \delta$	within season time (formerly τ)	days
b_0	initial biomass per germinant (seed)	biomass
ξ	$\frac{\text{final biomass}}{\text{initial biomass}}$	unitless

3 References

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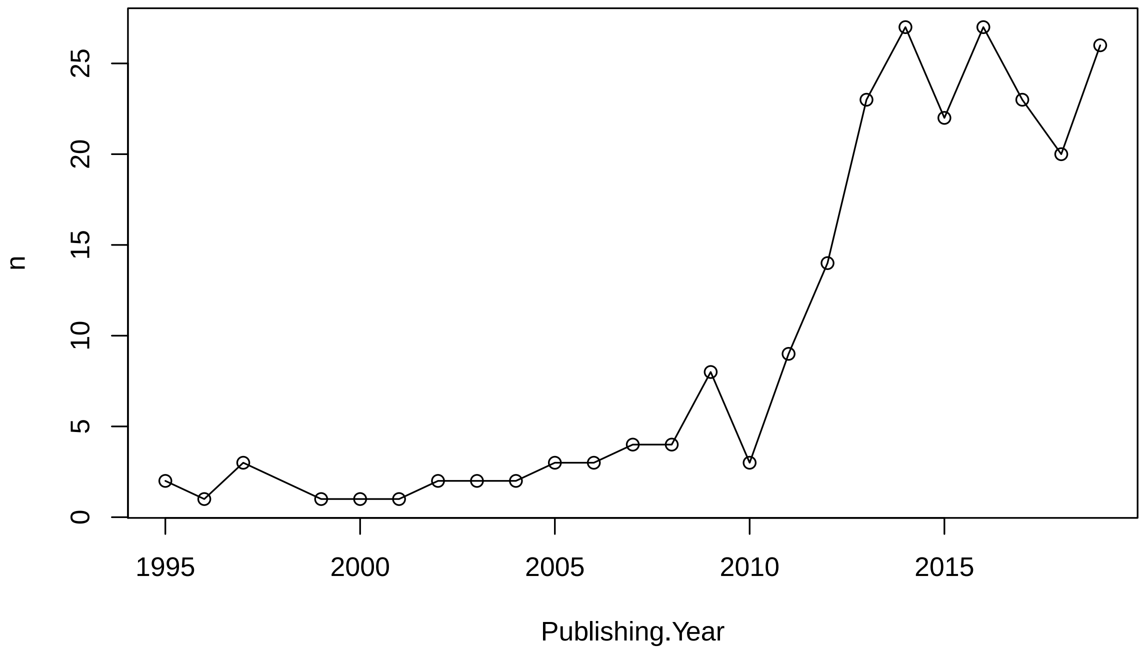

Figure S1: Trends in all papers using search terms over time. Of papers from which we could extract data all were published in 2016 or onward.

4 Tables & figures

Table S2: Summary of traits related to phenological tracking in the literature and whether papers reported statistical evidence that they were linked or not. See Table S2 for an extended version.

Trait	n linked	n not linked
diet traits	0	4
early/late phenophase	10	4
habitat traits	1	4
height	1	0
hibernation stage	0	4
leaf/shoot size	1	0
migration traits	3	3
mobility	1	3
nativeness	1	3
niche breadth	3	2
other Lepidopteran traits	3	4
other bird traits	1	1
other leaf traits	4	3
other plant traits	1	1
overwintering	2	1
range traits	1	4
root traits	3	0
seed weight/size/number	1	2
woody/herbaceous	1	0

Table S3: Summary of results from literature on phenological tracking showing which phenophases researchers found were linked to which traits, or not.

Taxa	Phenophase	Trait	n linked	n not linked
Lepidoptera	activity length	hibernation stage		1
Lepidoptera	activity length	migration traits		1
Lepidoptera	activity length	other Lepidopteran traits	1	
Lepidoptera	appearance/collection date	diet traits		1
Lepidoptera	appearance/collection date	early/late phenophase	2	
Lepidoptera	appearance/collection date	habitat traits		2
Lepidoptera	appearance/collection date	hibernation stage		1
Lepidoptera	appearance/collection date	migration traits	1	
Lepidoptera	appearance/collection date	mobility		2
Lepidoptera	appearance/collection date	niche breadth	2	1
Lepidoptera	appearance/collection date	other Lepidopteran traits	1	2
Lepidoptera	appearance/collection date	overwintering	2	
Lepidoptera	appearance/collection date	range traits	1	2
Lepidoptera	flight timing	early/late phenophase	1	1
Lepidoptera	flight timing	mobility	1	1
Lepidoptera	flight timing	niche breadth		1
Lepidoptera	flight timing	other Lepidopteran traits		1
Lepidoptera	flight timing	overwintering		1
Lepidoptera	flight timing	range traits		1
Lepidoptera	last/median emergence dates	diet traits		2
Lepidoptera	last/median emergence dates	habitat traits		2
Lepidoptera	last/median emergence dates	hibernation stage		2
Lepidoptera	last/median emergence dates	migration traits		2
Lepidoptera	last/median emergence dates	other Lepidopteran traits	1	1
passerine birds	breeding time	diet traits		1
passerine birds	breeding time	habitat traits	1	
passerine birds	breeding time	migration traits	2	
passerine birds	breeding time	niche breadth	1	
passerine birds	breeding time	other bird traits	1	1
plants	budbreak/leafing	early/late phenophase	3	1
plants	budbreak/leafing	nativeness		1
plants	budbreak/leafing	other leaf traits	2	1
plants	budbreak/leafing	range traits		1
plants	flowering/fruiting	early/late phenophase	4	2
plants	flowering/fruiting	height	1	
plants	flowering/fruiting	leaf/shoot size	1	
plants	flowering/fruiting	nativeness	1	2
plants	flowering/fruiting	other leaf traits	2	2
plants	flowering/fruiting	other plant traits	1	1
plants	flowering/fruiting	root traits	3	
plants	flowering/fruiting	seed weight/size/number	1	2
plants	flowering/fruiting	woody/herbaceous	1	

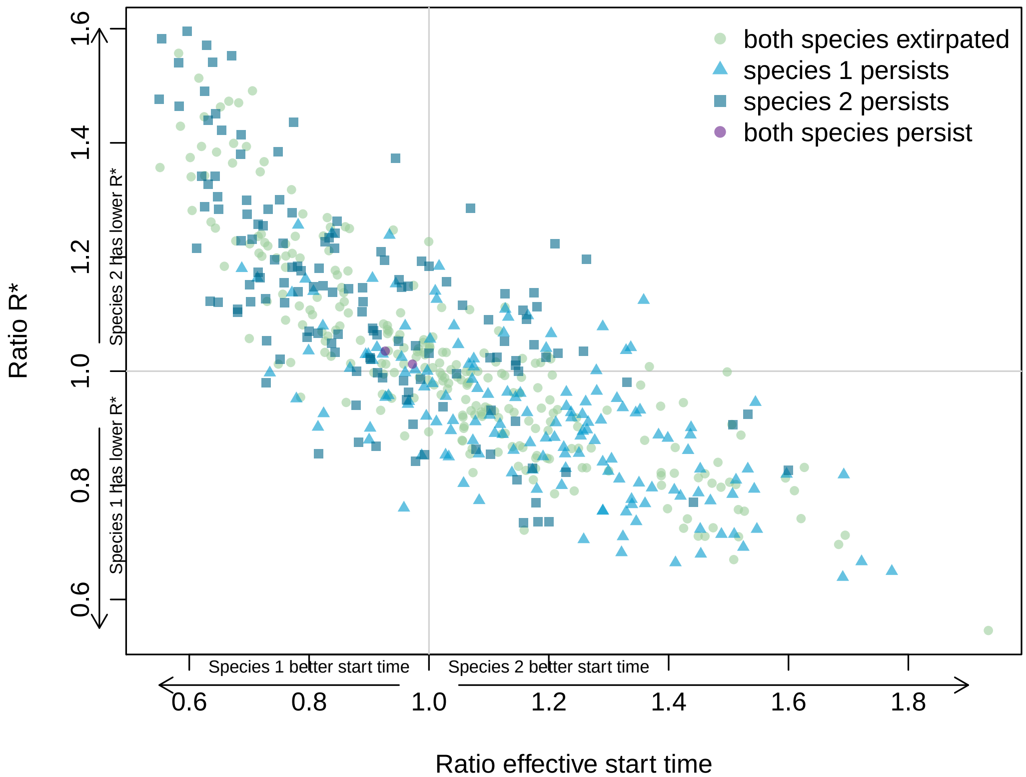

Figure S2: How non-stationarity reshapes two-species communities in a simple model where effective start time (X axis: species 1/species 2) trades off with R^* (Y axis: species 1/species 2): each point represents one two-species community that persisted through 500 years of stationary dynamics while the shape and color represent the outcome for that two-species community of 500 years of non-stationarity, where the abiotic start of the season shifts earlier.

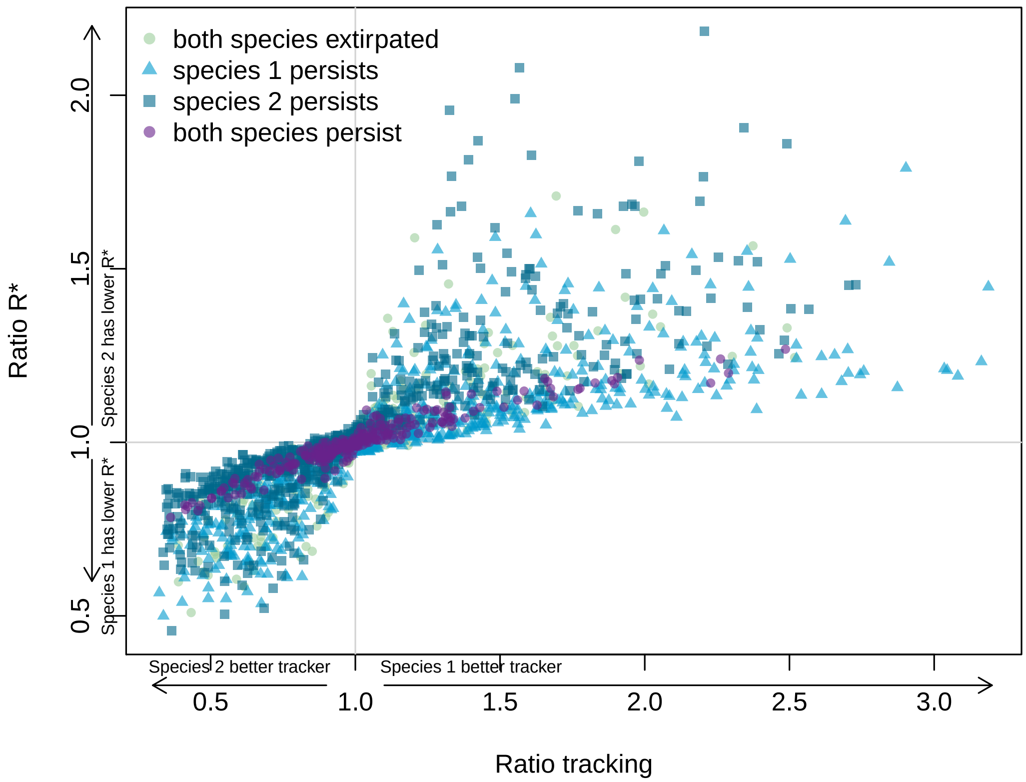

Figure S3: How non-stationarity reshapes two-species communities in a simple model where tracking (X axis: species 1/species 2) trades off with R^* (Y axis: species 1/species 2): each point represents one two-species community that persisted through 500 years of stationary dynamics while the shape and color represent the outcome for that two-species community of 500 years of non-stationarity, where the abiotic start of the season shifts earlier.