Anticipating Tipping Points: Theoretical and Practical Considerations

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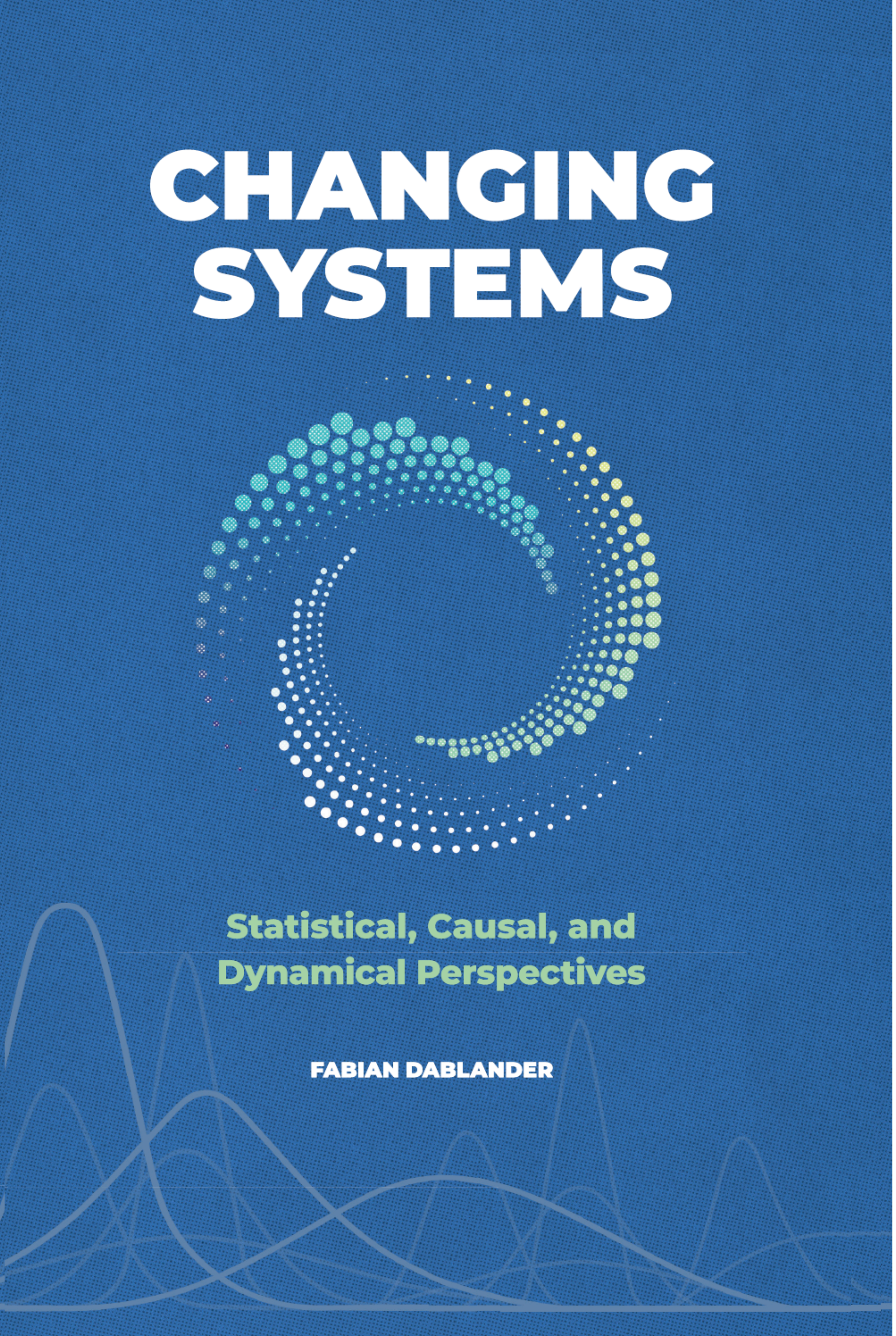
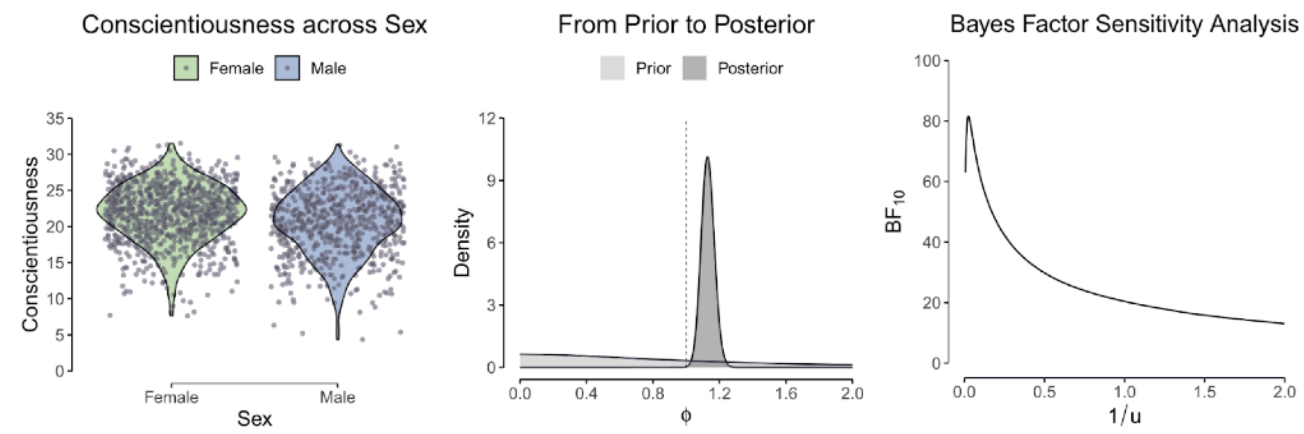
Frontiers in Early Warning Signals Research Workshop

Kaiserslautern

17th May, 2024


CHANGING SYSTEMS
Statistical, Causal, and Dynamical Perspectives
FABIAN DABLANDER


Conscientiousness across Sex
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Bayes Factor Sensitivity Analysis
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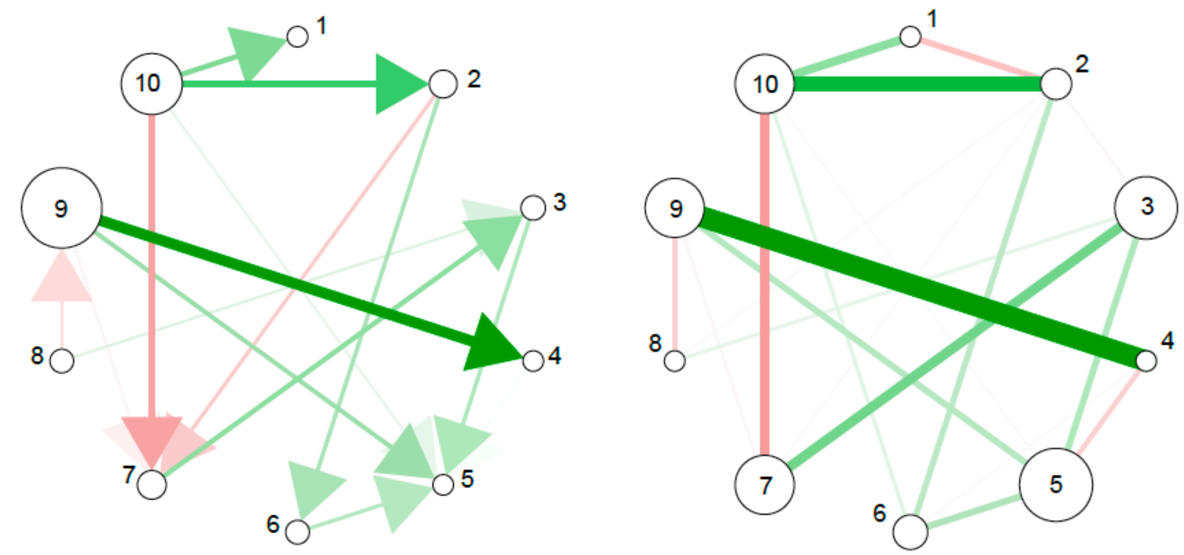
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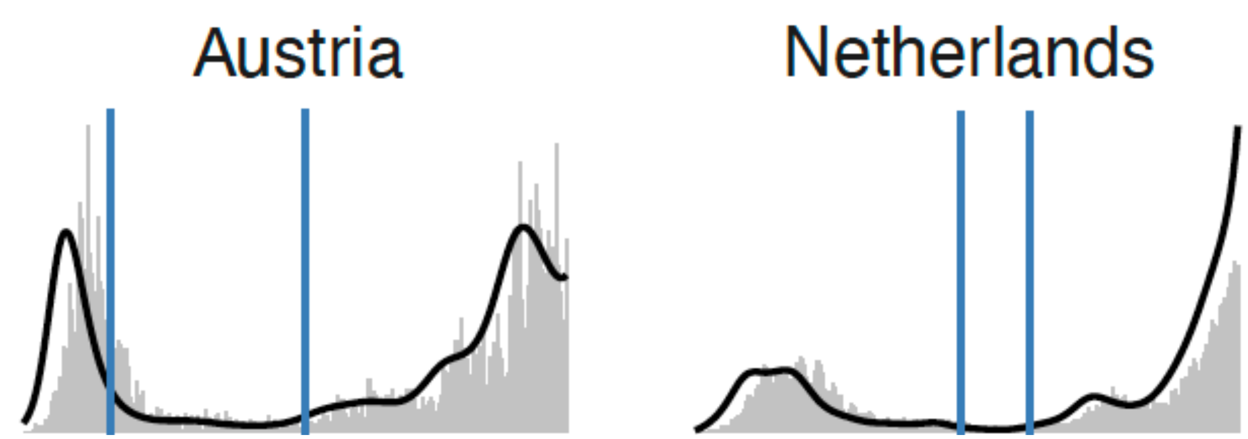

Austria
Netherlands

de Volkskrant

Opinie: Een geslaagde energietransitie begint met minder in plaats van meer

nrc

Een optimistisch klimaatverhaal kunnen we goed gebruiken, maar het moet wel kloppen

Onze leiders doen veel te weinig voor het klimaat. Daarom zijn wij nu zelf aan zet

Het Parool

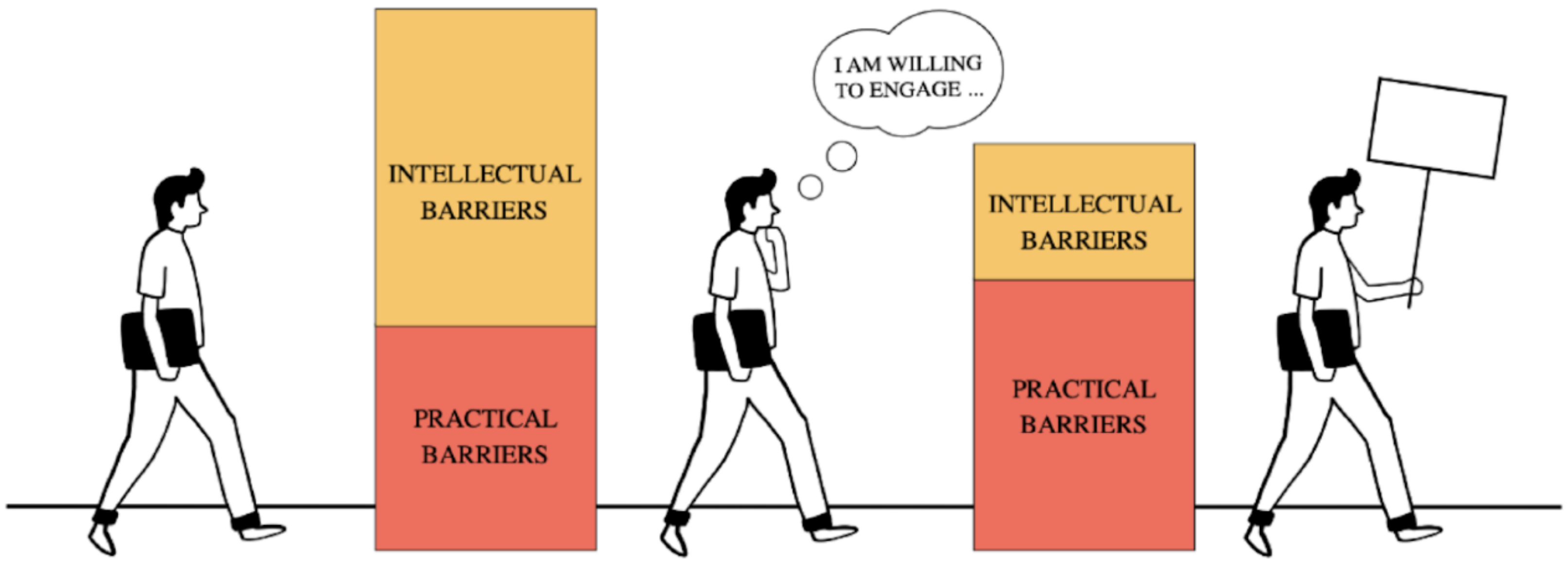
Opinie: 'Er is geen koolstofbudget meer voor rijke landen, stop met koolstofgraaien'

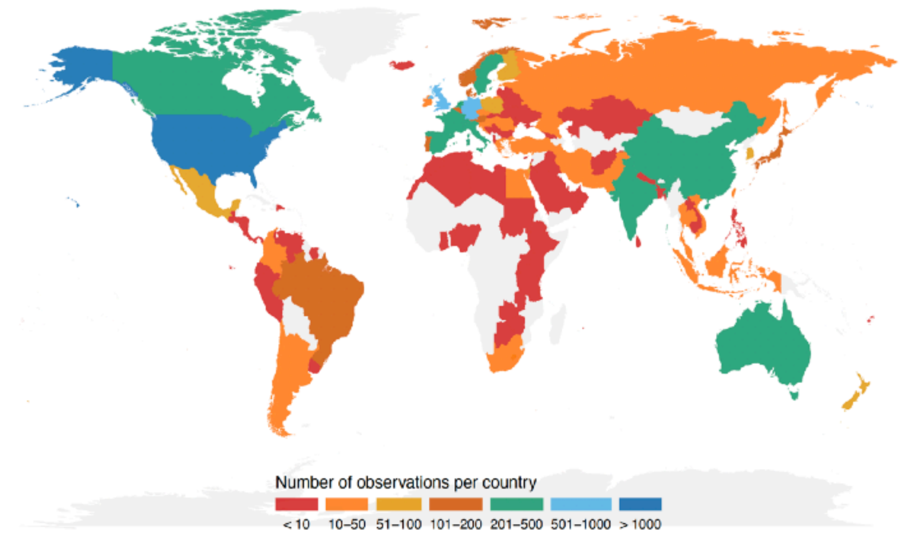
nature

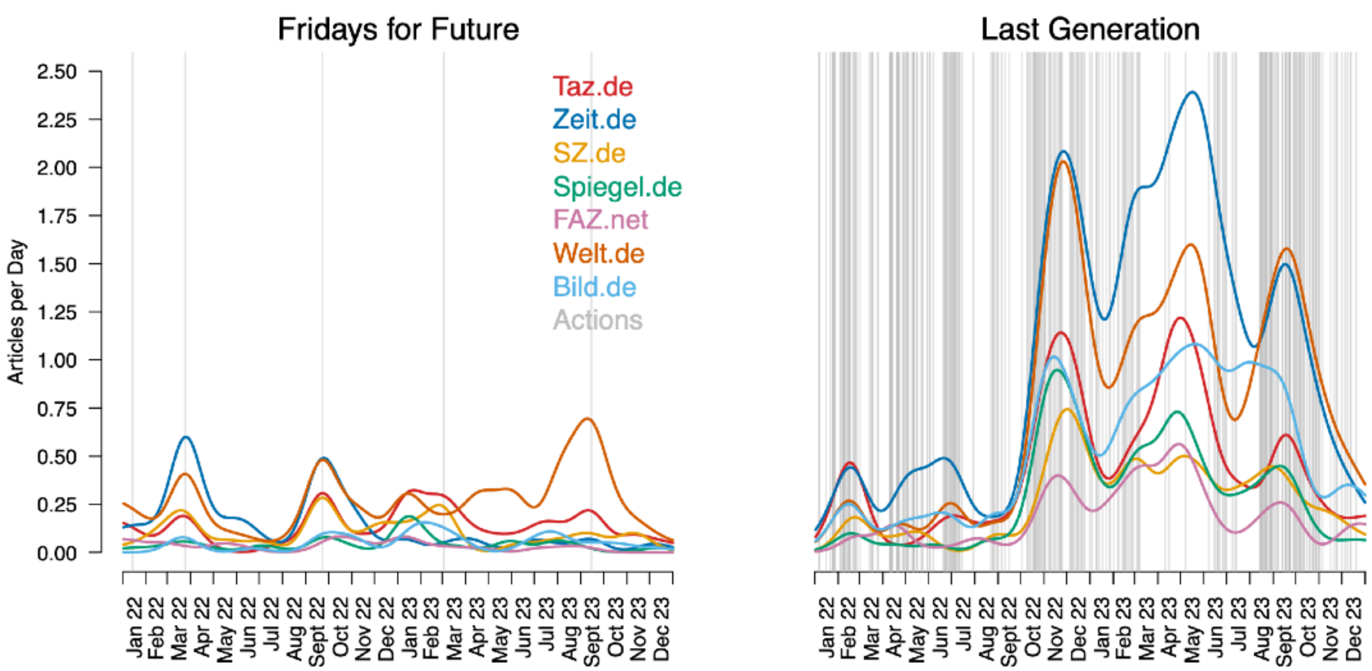
Scientists skip COP28 to demand climate action at home

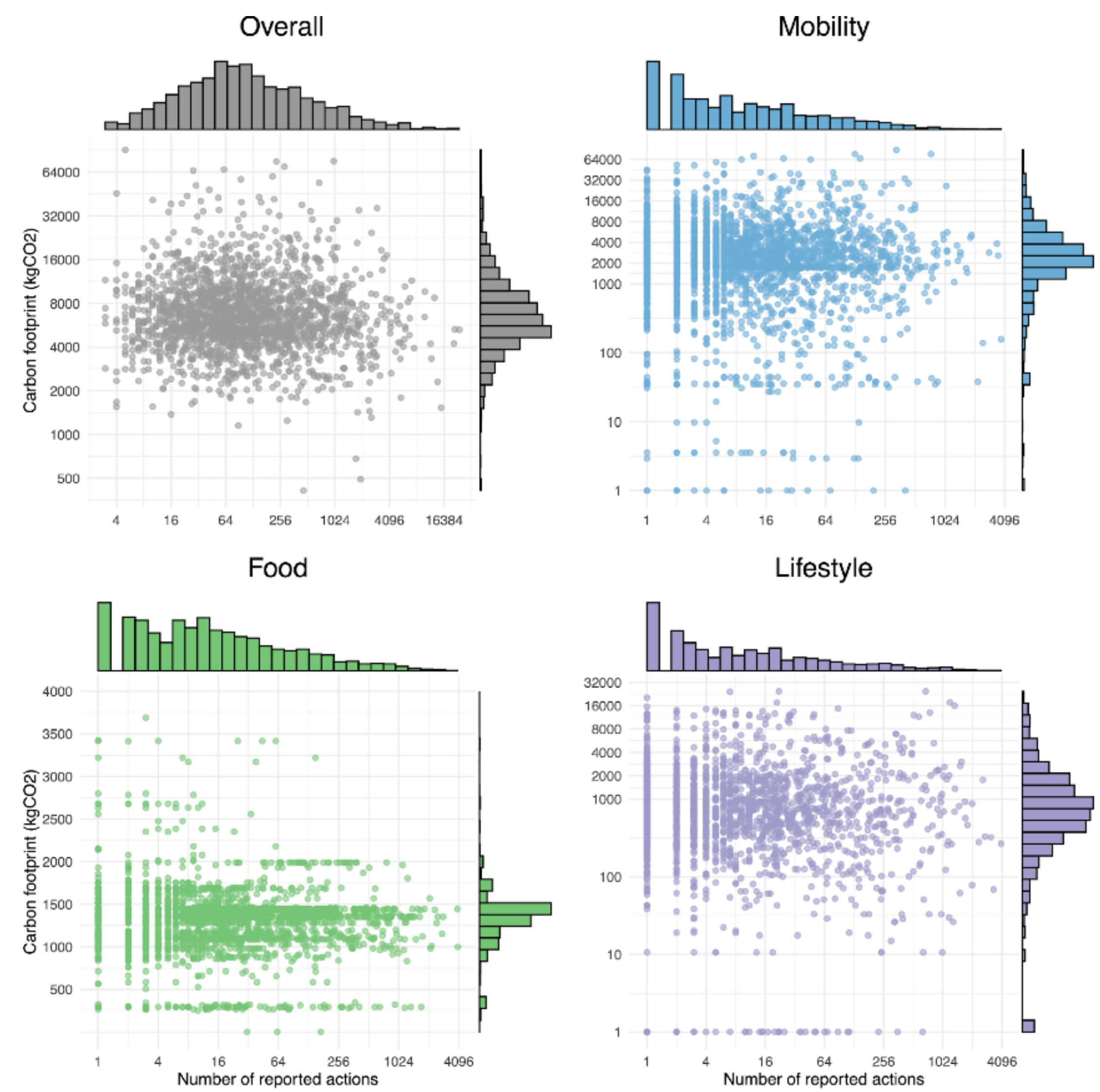
The Guardian

More than 1,000 climate scientists urge public to become activists









Barriers to climate change engagement
Effects of social movements
(Overcoming barriers) to sufficiency

Outline

A brief history

Theoretical considerations

Practical considerations

15 min

Example from Epidemiology

15 min

Conclusion & Discussion

15 min

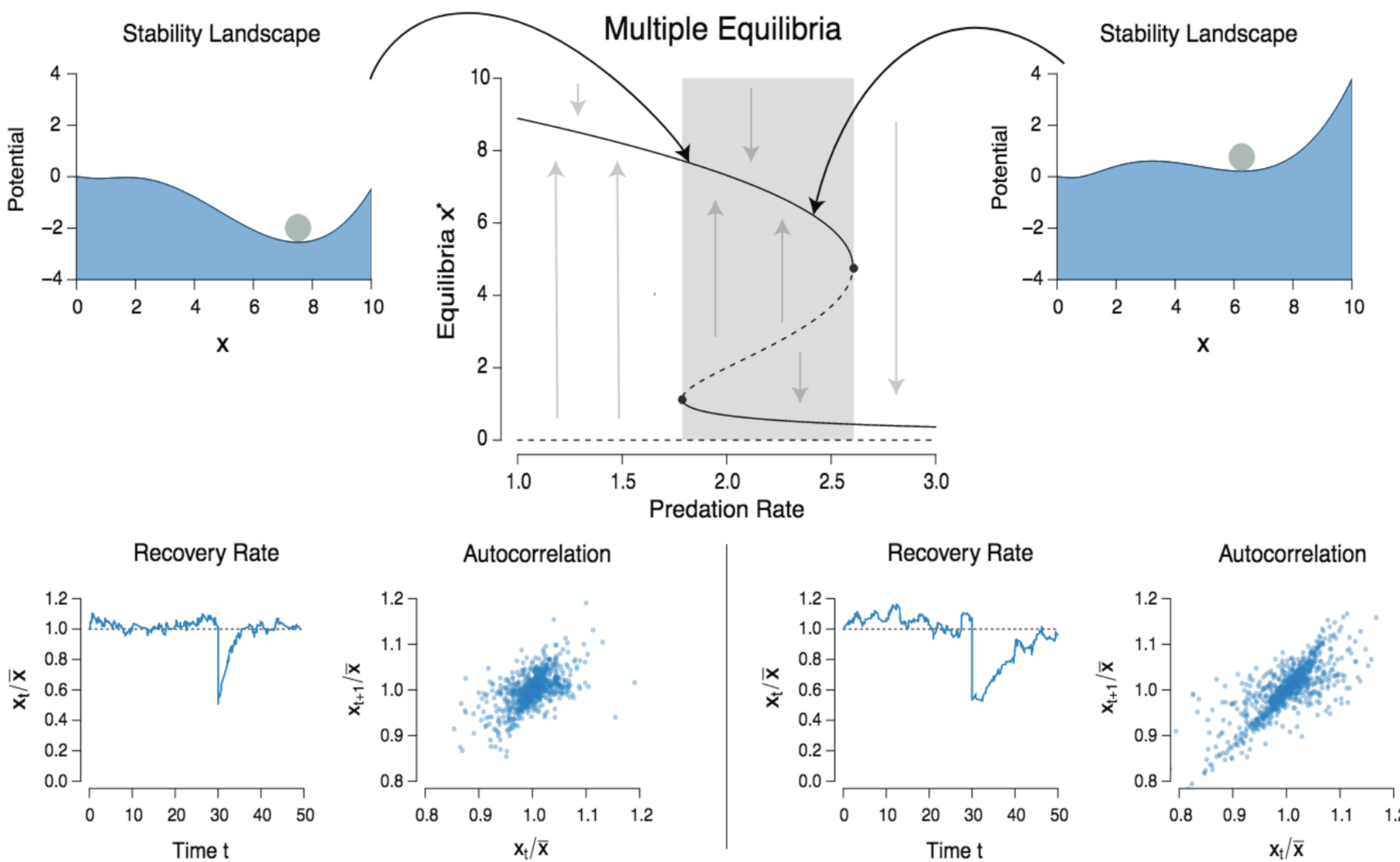
Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review

Manjana Milkoreit[1], Jennifer Hodbod[2,11], Jacopo Baggio[3], Karina Benessaiah[4], Rafael Calderón-Contreras[5], Jonathan F Donges[6,7], Jean-Denis Mathias[8], Juan Carlos Rocha[7], Michael Schoon[9] and Saskia E Werners[10]

"A tipping point is a threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible."

Higher Resilience

Lower Resilience

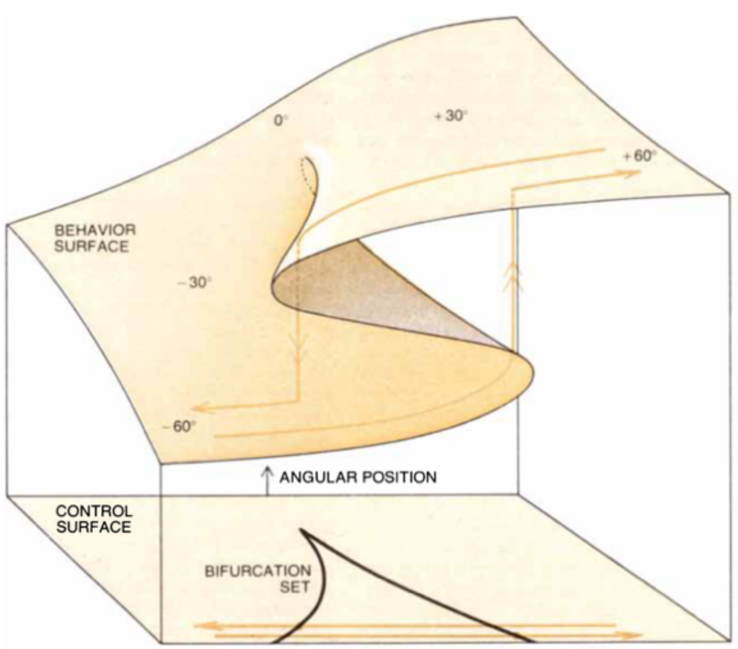


Dablander et al. (2023)

Dablander (2020)

That's not new …

- In the 1960s, René Thom developed catastrophe theory
  - Describes how (low-dimensional) systems can change suddenly
  - Popularized by Christopher Zeeman (1976), who applied it to everything
- There are a lot of key concepts in catastrophe theory:
  - Multiple stable states, critical slowing down, sudden jumps, hysteresis etc.
- However, proponents of catastrophe theory have pushed it too far
  - Catastrophe theory has been described as a great intellectual bubble
  - Zahler & Sussmann (1977) offer a prominent critique



… but it became popular again

Catastrophic shifts in ecosystems

Marten Scheffer*, Steve Carpenter†, J

* *Department of Aquatic Ecology and Water*
† *Center for Limnology, University of Wiscons*
‡ *Center for Sustainability and the Global En*
Wisconsin 53706, USA
§ *Department of Systems Ecology and Centre*
|| *CSIRO Sustainable Ecosystems, GPO Box 2*

REVIEWS

Early-warning signals for critical transitions

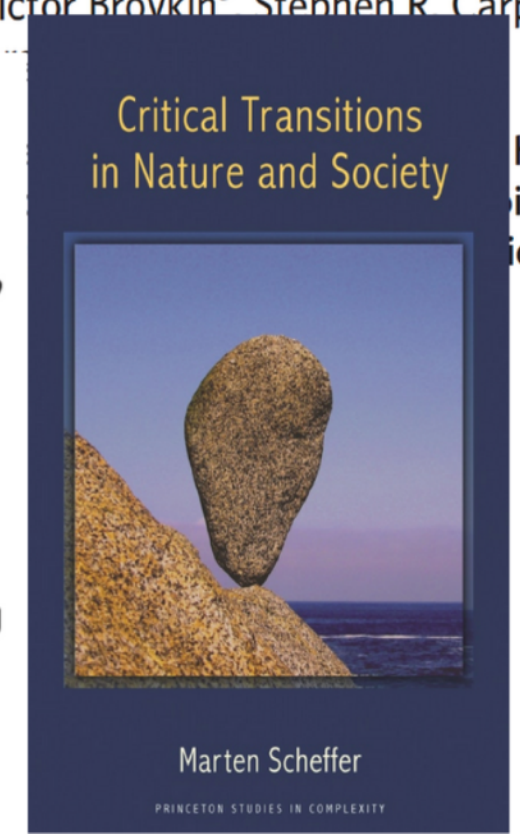
Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1],

have tipping points at which
ints before they are reached
ic early-warning signals that

Anticipating Critical Transitions

Marten Scheffer,[1,2*] Stephen R. Carpenter,[3] Timothy M. Lenton,[4] Jordi Bascompte,[5] William Brock,[6] Vasilis Dakos,[1,5] Johan van de Koppel,[7,8] Ingrid A. van de Leemput,[1] Simon A. Levin,[9] Egbert H. van Nes,[1] Mercedes Pascual,[10,11] John Vandermeer[10]

Tipping points in complex systems may imply risks of unwanted collapse, but also opportunities for positive change. Our capacity to navigate such risks and opportunities can be boosted by combining emerging insights from two unconnected fields of research. One line of work is revealing fundamental architectural features that may cause ecological networks, financial markets, and other complex systems to have tipping points. Another field of research is uncovering generic empirical indicators of the proximity to such critical thresholds. Although sudden shifts in complex systems will inevitably continue to surprise us, work at the crossroads of these emerging fields offers new approaches for anticipating critical transitions.



Published: 11 October 2001

Catastrophic shifts in ecosystems

Marten Scheffer, Steve Carpenter, Jonathan A. Foley, Carl Folke & Brian Walker

Nature **413**, 591–596 (2001) | Cite this article

REPORT

Generic Indicators for Loss of Resilience Before a Tipping Point Leading to Population Collapse

Lei Dai[1,*], Daan Vorselen[2,*], Kirill S. Korolev[1], Jeff Gore[1,†]

LETTER | Full Access

Rising variance: a leading indicator of ecological transition

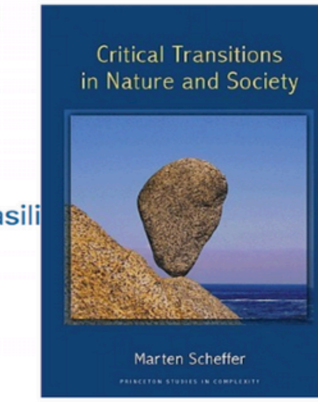
S. R. Carpenter, W. A. Brock

Published: 03 September 2009

Early-warning signals for critical transitions

Marten Scheffer, Jordi Bascompte, William A. Brock, Victor Brovkin, Stephen R. Carpenter, Vasili Dakos, Hermann Held, Egbert H. van Nes, Max Rietkerk & George Sugihara

Nature **461**, 53–59 (2009) | Cite this article



REVIEW

Anticipating Critical Transitions

Marten Scheffer[1,2,*], Stephen R. Carpenter[3], Timothy M. Lenton[4], Jordi Bascompte[5], William Brock[6], Vasilis Dakos[1,5], van de K… Vanderm…

Published: 10 April 2013

Slower recovery in space before collapse of connected populations

Lei Dai, Kirill S. Korolev & Jeff Gore

Nature **496**, 355–358 (2013) | Cite this article

REPORT

Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment

S. R. Carpenter[1,*], J. J. Cole[2], M. L. Pace[3], R. Batt[1], W. A. Brock[4], T. Cline[1], J. Coloso[3], J. R. Hodgson[5], J. F. Kitchell[1], D. A. Seekell[3], L. Smith[1], B. Weidel[1]

Evaluating early-warning indicators of critical transitions in natural aquatic ecosystems

Alena Sonia Gsell[a,b,1], Ulrike Scharfenberger[a,c], Deniz Özkundakci[d], Annika Walters[e], Lars-Anders Hansson[f], Annette B. G. Janssen[b,g], Peeter Nõges[h], Philip C. Reid[i,j,k], Daniel E. Schindler[l], Ellen Van Donk[b], Vasilis Dakos[m], and Rita Adrian[a,c]

Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data

Vasilis Dakos[1,2*], Stephen R. Carpenter[3], William A. Brock[4], Aaron M. Ellison[5], Vishwesha Guttal[6], Antho…

Turning back from the brink: Detecting an impending regime shift in time to avert it

Reinette Biggs[a,1], Stephen R. Carpenter[a,2], and William A. Brock[b]

Early Warning Signals of Ecological Transitions: Methods for Spatial Patterns

Sonia Kéfi[1*9], Vishwesha Guttal[2,9], William A. Brock[3,4], Stephen R. Carpenter…, Valerie N. Livina[7], David A. Seekell[8], Marten Scheffer[9], Egbert H. van Nes[9], …

Quantifying resilience of humans and other animals

Marten Scheffer[a,1], J. Elizabeth Bolhuis[b], Denny Borsboom[c], Timothy G. Buchman[d], Sanne M. W. Gijzel[a,e], Dave Goulson[f], Jan E. Kammenga[g], Bas Kemp[b], Ingrid A. van de Leemput[a], Simon Levin[h], Carmel Mary Martin[i], René J. F. Melis[e], Egbert H. van Nes[a], L. Michael Romero[j], and Marcel G. M. Olde Rikkert[e]

Published: 08 September 2010

Early warning signals of extinction in deteriorating environments

John M. Drake & Blaine D. Griffen

Nature 467, 456–459 (2010) | Cite thi

Waiting time to infectious disease emergence

Christopher J. Dibble[1], Eamon B. O'Dea[1,2], Andrew W. Park[1,2] and John M. Drake[1,2]

Transient indicators of tipping points in infectious diseases

Suzanne M. O'Regan[1,†], Eamon B. O'Dea[2,3,†], Pejman Rohani[2,3,4] and John M. Drake[2,3]

Estimating the distance to an epidemic threshold

Eamon B. O'Dea[1,2], Andrew W. Park[3,4] and John M. Drake[2,3]

Theory of early warning signals of disease emergence and leading indicators of elimination

Suzanne M. O'Regan · John M. Drake

Anticipating the emergence of infectious diseases

Tobias S. Brett[1,2], John M. Drake[1,2] and Pejman Rohani[1,2,3]

PERSPECTIVE

The statistics of epidemic transitions

John M. Drake[1,2*], Tobias S. Brett[1,2], Shiyang Chen[3], Bogdan I. Epureanu[3,4], Matthew J. Ferrari[5], Éric Marty[1,2], Paige B. Miller[1,2], Eamon B. O'Dea[1,2], Suzanne M. O'Regan[6], Andrew W. Park[1,2], Pejman Rohani[1,2]

Early warning signals of malaria resurgence in Kericho, Kenya

Mallory J. Harris[1,3], Simon I. Hay[4,5] and John M. Drake[1,2]

RESEARCH ARTICLE

Detecting critical slowing down in high-dimensional epidemiological systems

Tobias Brett[1,2*], Marco Ajelli[3,4], Quan-Hui Liu[3,5], Mary G. Krauland[6], John J. Grefenstette[6], Willem G. van Panhuis[7,8], Alessandro Vespignani[3,9], John M. Drake[1,2], Pejman Rohani[1,2,10]

RESEARCH ARTICLE

Anticipating epidemic transitions with imperfect data

Tobias S. Brett[1,2*], Eamon B. O'Dea[1,2], Éric Marty[1], Paige B. Miller[1,2], Andrew W. Park[1,2,3], John M. Drake[1,2], Pejman Rohani[1,2,3]

RESEARCH ARTICLE

Dynamical footprints enable detection of disease emergence

Tobias S. Brett[1,2*], Pejman Rohani[1,2,3]

Slowing Down of Recovery as Generic Risk Ma for Acute Severity Transitions in Chronic Disea

Marcel G. M. Olde Rikkert, MD, PhD[1]; Vasilis Dakos, PhD[2]; Timothy G. Buchman, PhD, MD
Rob de Boer, PhD[4]; Leon Glass, PhD[5]; Angélique O. J. Cramer, PhD[6]; Simon Levin, PhD[7];
Egbert van Nes, PhD[8]; George Sugihara, PhD[9]; Michel D. Ferrari, MD, PhD[10]; Else A. Tolner,
Ingrid van de Leemput, MSc[8]; Joep Lagro, MD, PhD[11]; René Melis, MD, PhD[1]; Marten Scheff

Critical slowing down as early warning for the onset and termination of depression

Ingrid A. van de Leemput[a,1,2], Marieke Wichers[b,1], Angélique O. J. Cramer[c], Denny Borsboom[c], Francis Tuerlinckx[d], Peter Kuppens[d,e], Egbert H. van Nes[a], Wolfgang Viechtbauer[b], Erik J. Giltay[f], Steven H. Aggen[g], Catherine Derom[h,i], neth S. Kendler[g,k], Han L. J. van der Maas[c], Michael C. Neale[g], Frenk Peeters[b], Evert Thiery[l], l Marten Scheffer[a]

Critical Fluctuations as an Early-Warning Signal for Sudden Gains and Losses in Patients Receiving Psychotherapy for Mood Disorders

Merlijn Olthof[1], Fred Hasselman[1,2], Guido Strunk[3,4,5],

Clinical Psychological Science
1–11

DOI: 10.1177/216770261986596
www.psychologicalscience.org/
SAGE

Measurement of Dynamical Resilience Indicators Improves the Prediction of Recovery Following Hospitalization in Older Adults

Sanne M.W. Gijzel MD[a,b], Jerrald Rector PhD[a], Fokke B. van Meulen PhD[a], Rolinka Schim van der Loeff MSc[a], Ingrid A. van de Leemput PhD[b], Marten Scheffer PhD[b], Marcel G.M. Olde Rikkert MD, PhD[a], René J.F. Melis MD, PhD[a,*]

[a] Department of Geriatrics, Radboud Institute for Health Sciences, Radboud University Medical Center, Nijmegen, the Netherlands
[b] Department of Environmental Sciences, Wageningen University, Wageningen, the Netherlands

RESEARCH ARTICLE Open Access

Early warning signals in psychopathology: what do they tell?

Marieke J. Schreuder[1*], Catharina A. Hartman[1], Sandip V. George[1], Claudia Menne-Lothmann[2],
Jeroen D
Bart P. F

Psychother Psychosom 2016;85:114–116
DOI: 10.1159/000441458

Critical Slowing Down as a Personalized Early Warning Signal for Depression

Psychological Medicine

cambridge.org/psm

Invited Review

Can we predict the direction of sudden shifts in symptoms? Transdiagnostic implications from a complex systems perspective on psychopathology

Cite this article: Wichers M, Schreuder MJ, Goekoop R, Groen RN (2018). Can we predict the direction of sudden shifts in symptoms? Transdiagnostic implications from a complex systems perspective on psychopathology. *Psychological Medicine* **49**, 380–387. https://

Marieke Wichers[1], Marieke J. Schreuder[1], Rutger Goekoop[2] and Robin N. Groen[1]

[1]University of Groningen, University Medical Center Groningen, Department of Psychiatrie, Interdisciplinary Center Psychopathology and Emotion Regulation (ICPE), Groningen, The Netherlands and [2]Department of Mood Disorders, Parnassia Group, PsyQ, The Hague, The Netherlands

Early Warning Signals Based on Momentary Affect Dynamics can Expose Nearby Transitions in Depression: A Confirmatory Single-Subject Time-Series Study

Marieke Wichers, Arnout C. Smit, and Evelien Snippe

University of Groningen, University Medical Center Groningen (UMCG), Dept. of Psychiatry, Interdisciplinary Center Psychopathology and Emotion regulation (ICPE), Groningen, The Netherlands

Tipping elements in the Earth's climate system

Timothy M. Lenton[*,†], Hermann Held[‡], Elmar Kriegler[‡,§], Jim W. Hall[¶], Wolfgang Lucht[‡], Stefan Rahmstorf[‡], and Hans Joachim Schellnhuber[†,‡,‖,**]

Slowing down as an early warning signal for abrupt climate change

Vasilis Dakos[*], Marten Scheffer[*,†], Egbert H. van Nes[*], Victor Brovkin[‡,§], Vladimir Petoukhov[‡], and Hermann Held[‡]

ORIGINAL PAPER | Open Access | Published: 29 May 2013

Early warning signals of simulated Amazon rainforest dieback

Chris A. Boulton, Peter Good & Timothy M. Lenton

Theoretical Ecology **6**, 373–384 (2013) | Cite this article

The tipping points and early warning indicators for Pine Island Glacier, West Antarctica

Sebastian H. R. Rosier[1], Ronja Reese[2], Jonathan F. Donges[2,3], Jan De Rydt[1], G. Hilmar Gudmundsson[1], and Ricarda Winkelmann[2,4]

Review Article | Published: 29 July 2021

Past abrupt changes, tipping points and cascading impacts in the Earth system

Victor Brovkin, Edward Brook, John W. Williams, Sebastian Bathiany, Timothy M. Lenton, Michael Barton, Robert M. DeConto, Jonathan F. Donges, Andrey Ganopolski, Jerry McManus, Summer Praetorius, Anne de Vernal, Ayako Abe-Ouchi, Hai Cheng, Martin Claussen, Michel Crucifix, Gilberto Gallopín, Virginia Iglesias, Darrell S. Kaufman, Thomas Kleinen, Fabrice Lambert, Sander van der Leeuw, Hannah Liddy, Marie-France Loutre, David McGee, Kira Rehfeld, Rachael Rhodes, Alistair W. R. Seddon, Martin H. Trauth, Lilian Vanderveken & Zicheng Yu -Show fewer authors

Published: 19 June 2011

Early warning of climate tipping points

Timothy M. Lenton

Nature Climate Change **1**, 201–209 (2011) | Cite this article

Open Access | Published: 08 December 2014

Early warning signals of Atlantic Meridional Overturning Circulation collapse in a fully coupled climate model

Chris A. Boulton, Lesley C. Allison & Timothy M. Lenton

Nature Communications **5**, Article number: 5752 (2014) | Cite this article

Article | Published: 05 August 2021

Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation

Niklas Boers

Nature Climate Change **11**, 680–688 (2021) | Cite this article

RESEARCH ARTICLE

Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point

Niklas Boers and Martin Rypdal

AMERICAN PSYCHOLOGICAL ASSOCIATION

Psychological Methods

ISSN: 1082-989X

2023, Vol. 28, No. 4, 765–790
https://doi.org/10.1037/met0000450

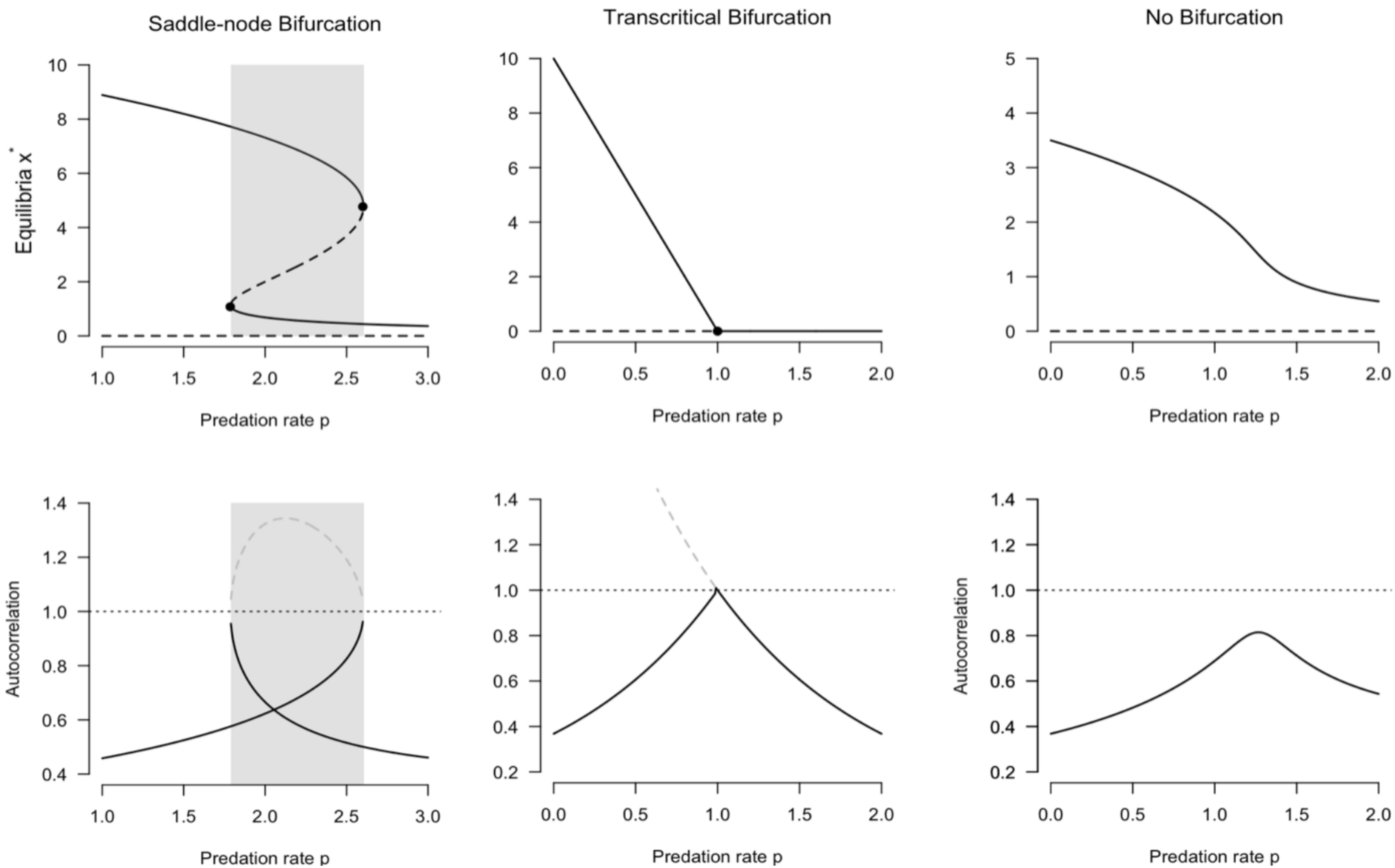
Anticipating Critical Transitions in Psychological Systems Using Early Warning Signals: Theoretical and Practical Considerations

Fabian Dablander[1], Anton Pichler[2, 3], Arta Cika[4], and Andrea Bacilieri[2, 5]
[1] Department of Psychological Methods, University of Amsterdam
[2] Institute for New Economic Thinking at the Oxford Martin School, University of Oxford
[3] Complexity Science Hub Vienna, Vienna, Austria
[4] Department of Engineering Science, University of Oxford
[5] Smith School of Enterprise and Environment, University of Oxford

Theoretical considerations

EWS without critical transitions	Critical transitions without EWS
EWS can occur prior to smooth transitions between stable states (Drake & Griffen, 2010; Kéfi et al., 2013).	Strong external perturbations can lead to transitions without EWS (Ditlevsen & Johnsen, 2010; van Nes et al., 2016).
EWS can occur when there is no transition (e.g., Wagner & Eisenman, 2015).	EWS may not occur prior to critical transitions in systems with nonsmooth potentials (Hastings & Wysham, 2010).
	Not all variables in a system generally express EWS equally strongly or at all (Boerlijst et al., 2013; Patterson et al., 2021).
	EWS may not occur under correlated or extrinsic noise (Dakos, van Nes, et al., 2012; O'Regan & Burton, 2018; Qin & Tang, 2018).

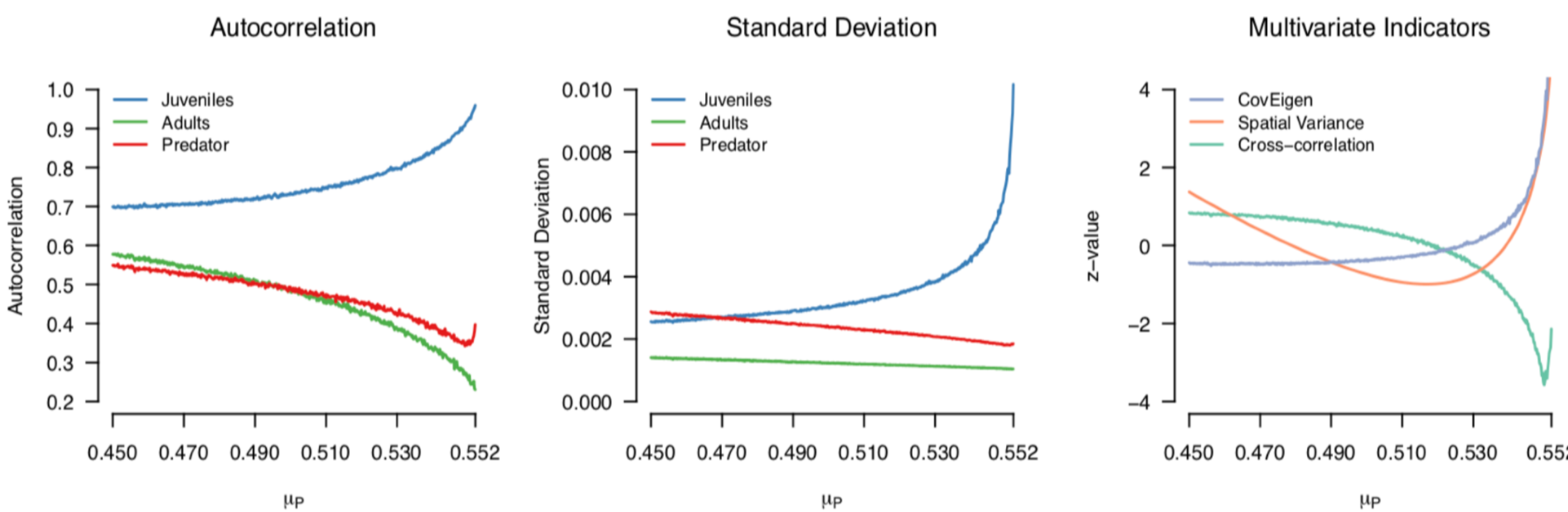
EWS prior to non-catastrophic transitions



Kefi et al. (2013)

EWS not in all variables

- Not all variables express critical slowing down equally strongly or at all
- Boerlijst et al. ([2013]) study a staged predator-prey system
  - Predator preys on adult prey but not on juvenile prey
  - $\mu \sim 0.553$ is the bifurcation point for which the predators collapse

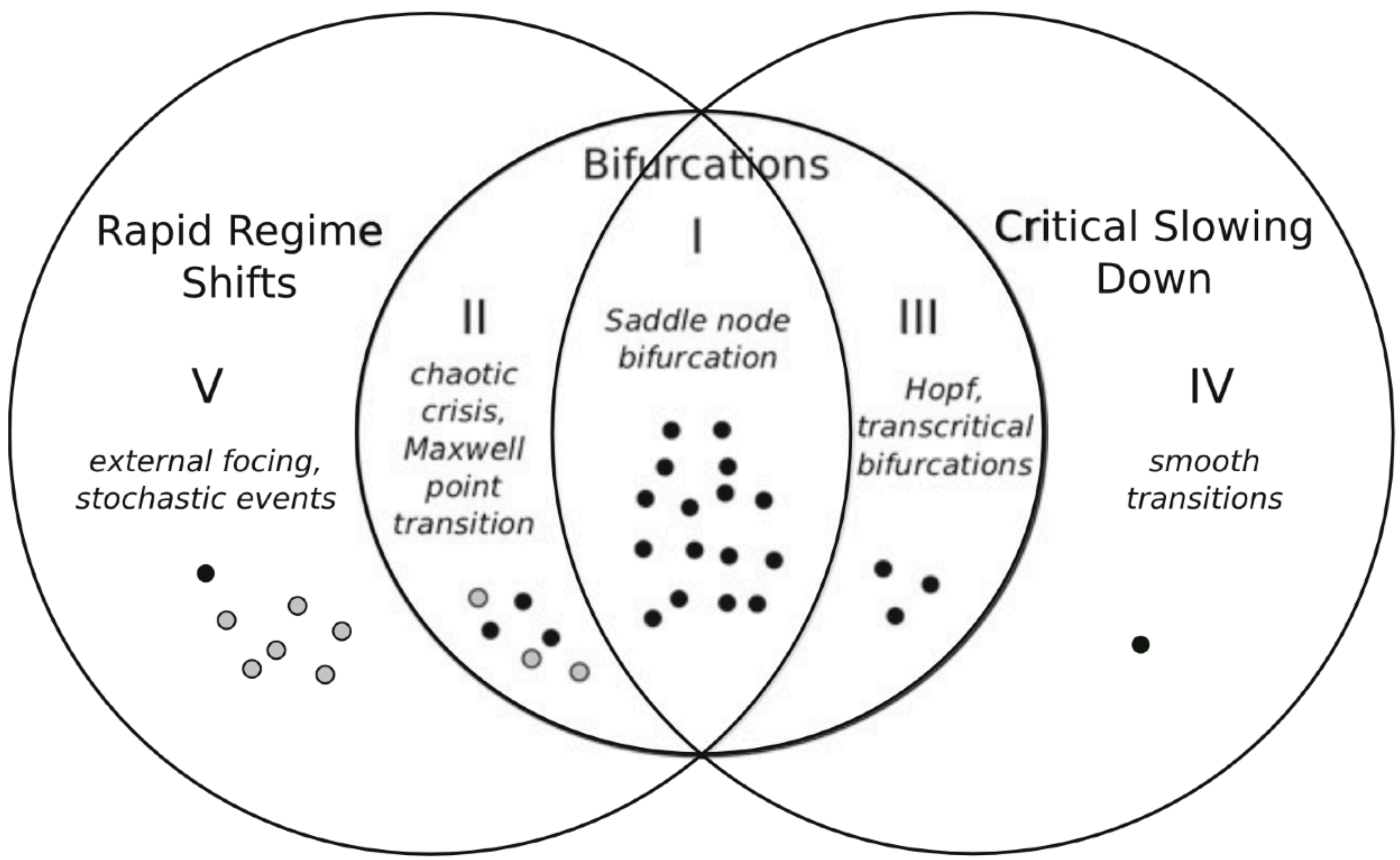


Patterson et al. (2021)

Interim conclusion II

- To use EWS sensibly, we need to have a good understanding of the system
  - Some vague references to “complex systems” will not do

- Finding that EWS rise **does not** mean that a tipping point is near
  - Need independent evidence of a tipping point, then EWS potentially useful



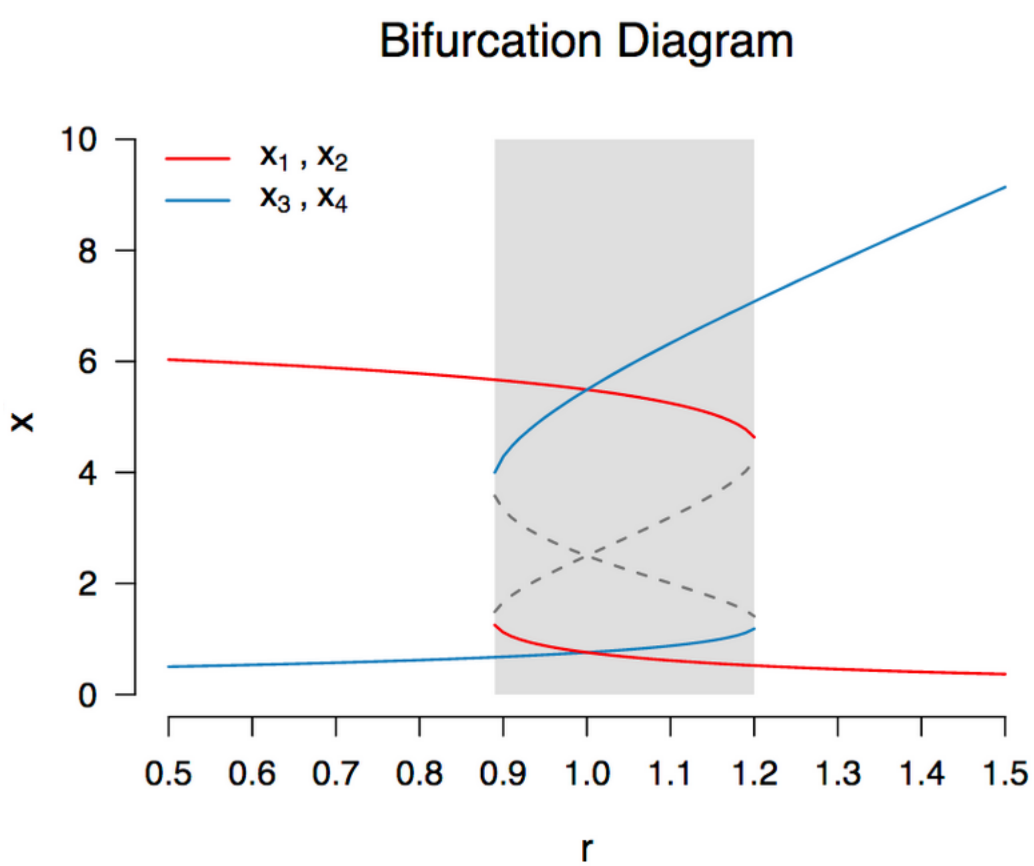
Boettiger, Ross, & Hastings (2013)

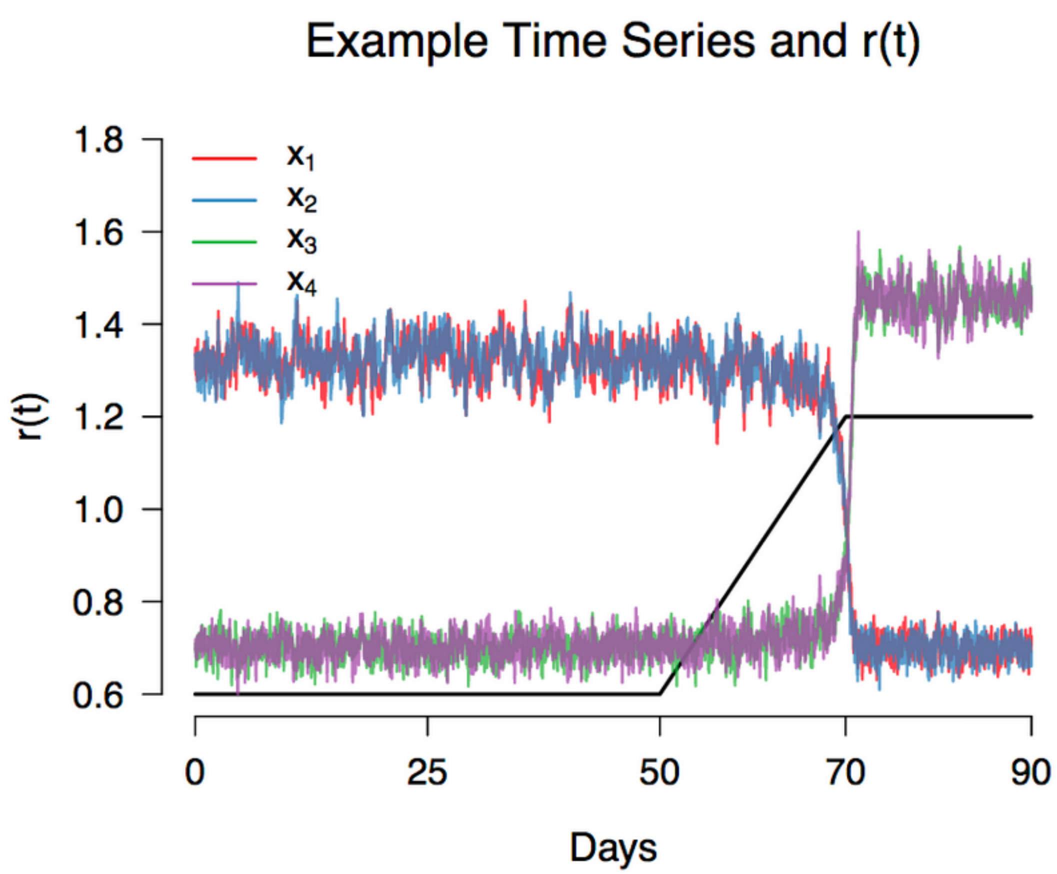
Practical considerations

EWS performance in simulation

- EWS as online-monitoring tool for systems
  - Signal potential bad transition → intervene to prevent transition
  - Signal potential good transition → intervene to bring about transition

- Difficult statistical challenge!
  - Need to correctly estimate increasing EWS (stationarity violation)
  - Need to adequately test increase against baseline (not all EWS)

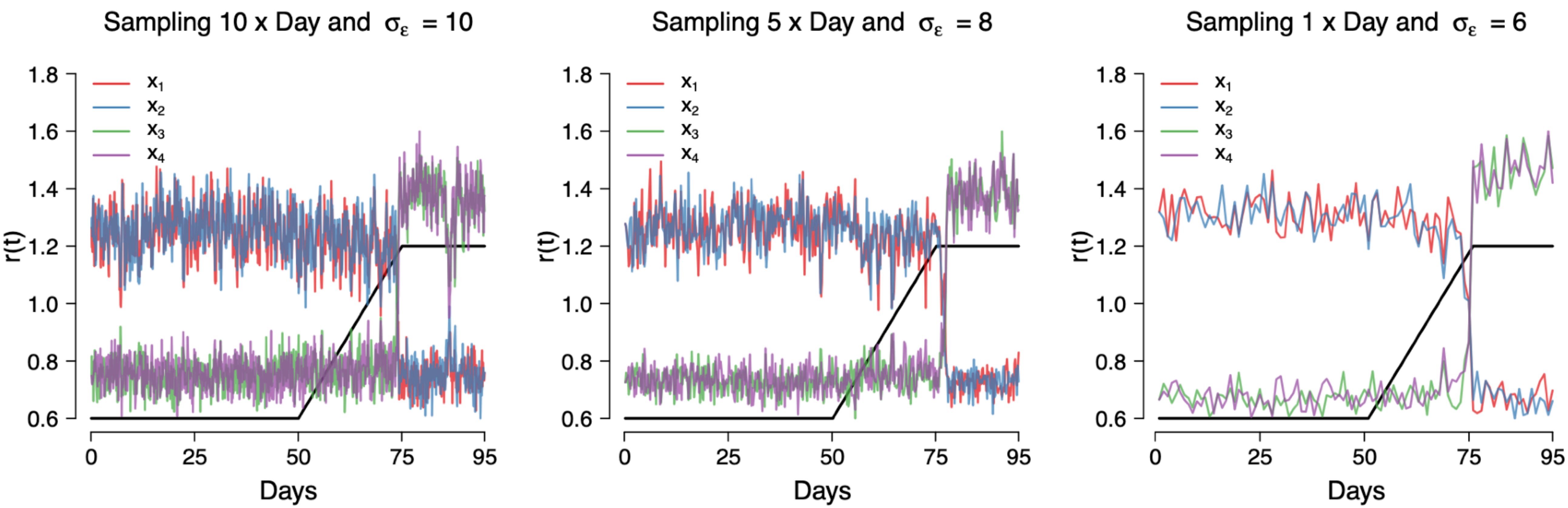


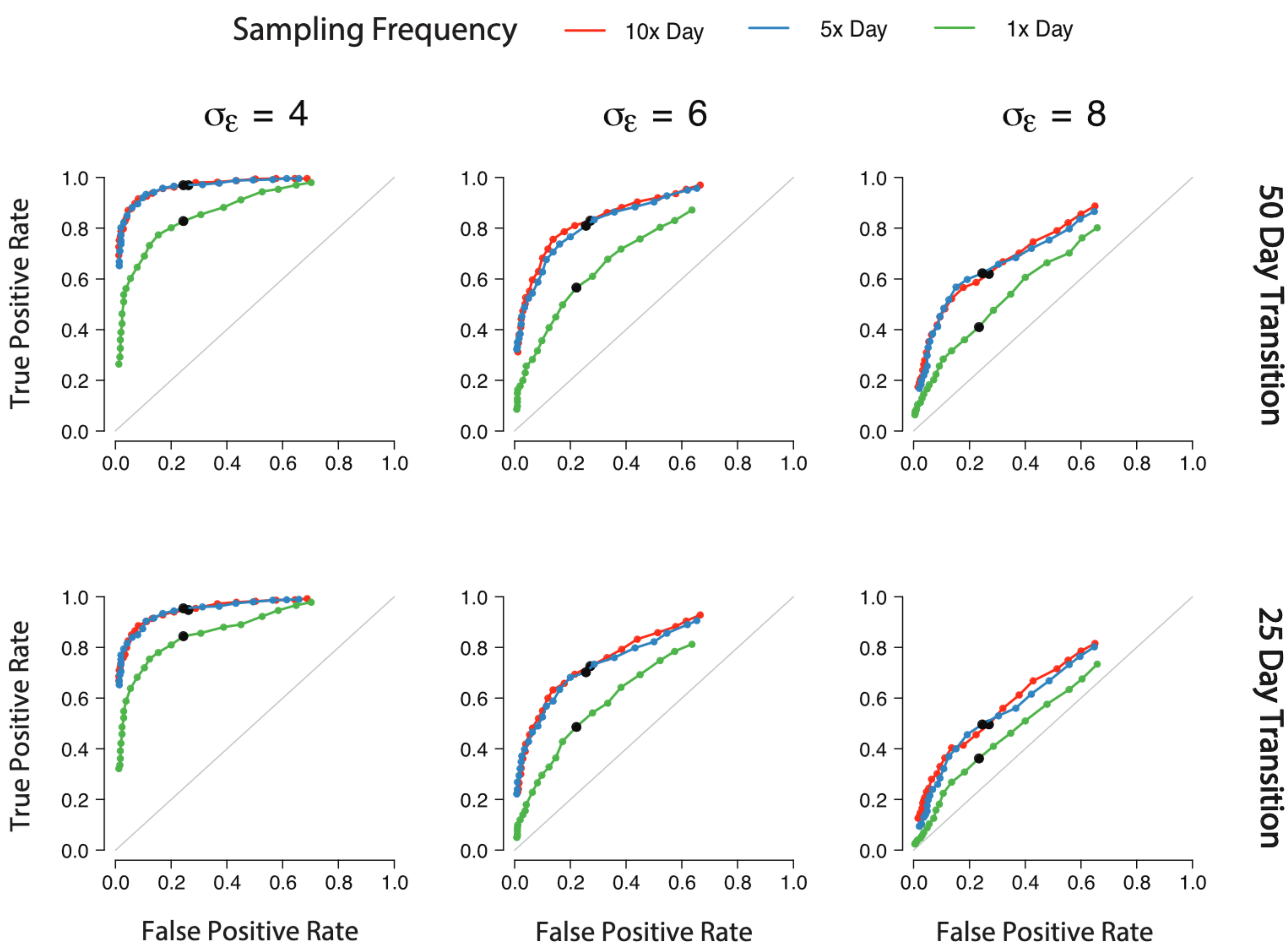


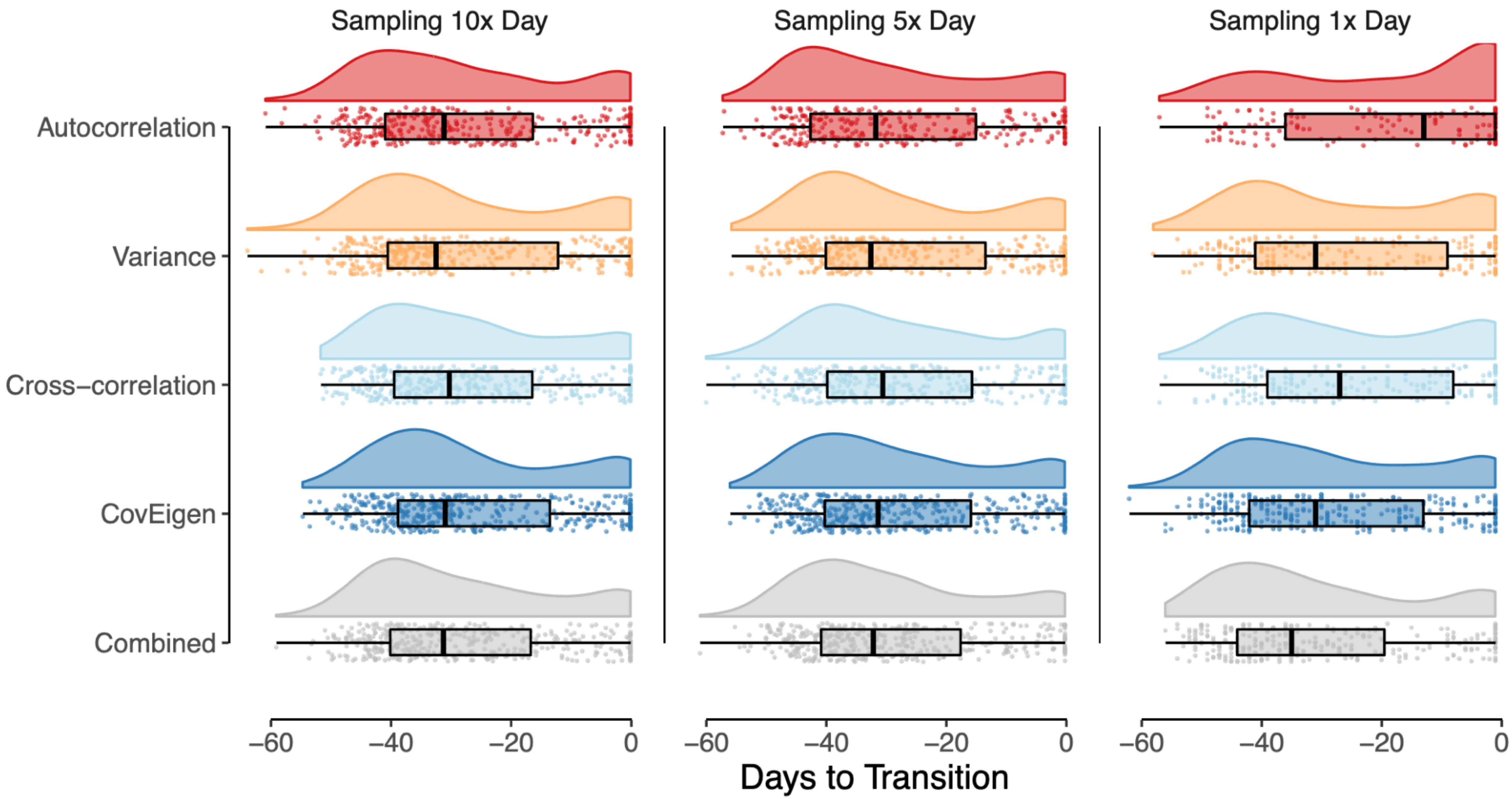
EWS performance in simulation

Early Warning Indicator	Source
Autocorrelation and Variance	Scheffer et al. (2009)
Skewness and Kurtosis	Guttal and Jayaprakash (2008)
Cross-correlation	Dakos et al. (2010)
Dominant eigenvalue of covariance matrix	Chen et al. (2019)
Spatial-Variance, Spatial-Kurtosis, and Spatial-Skewness	Kéfi et al. (2014)
Parameter	Values
Uncontrollable	
Noise intensity σ_ε	4, 6, 8, 10
Transition Period	10, 25, 50 days
Controllable	
Sampling Frequency	1x, 5x, 10x per day
Baseline	25, 50, 100 days
Rolling Window Size	10, 25, 50 days

EWS performance in simulation




Sampling Frequency
10x Day
5x Day
1x Day
σ_ε = 4
σ_ε = 6
σ_ε = 8
50 Day Transition
25 Day Transition
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0



Sampling 10x Day
Sampling 5x Day
Sampling 1x Day
Autocorrelation
Variance
Cross−correlation
CovEigen
Combined
−60
−40
−20
0
Days to Transition

Interim conclusion II

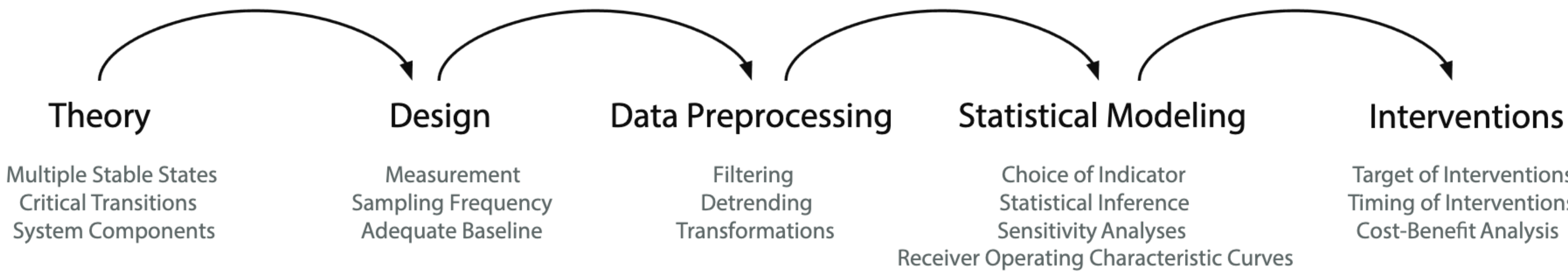
Article | Open access | Published: 01 December 2023

Early warning signals have limited applicability to empirical lake data

Duncan A. O'Brien, Smita Deb, Gideon Gal, Stephen J. Thackeray, Partha S. Dutta, Shin-ichiro S. Matsuzaki, Linda May & Christopher F. Clements

Nature Communications **14**, Article number: 7942 (2023) | Cite this article

- **Even if tipping points exist**, using EWS successfully is very difficult
  - Extent of noise and sampling frequency huge impact on performance
  - Time to transition, extent of baseline, decision threshold, …
  - Caveat: type of system



Overlapping timescales obscure early warning signals of the second COVID-19 wave

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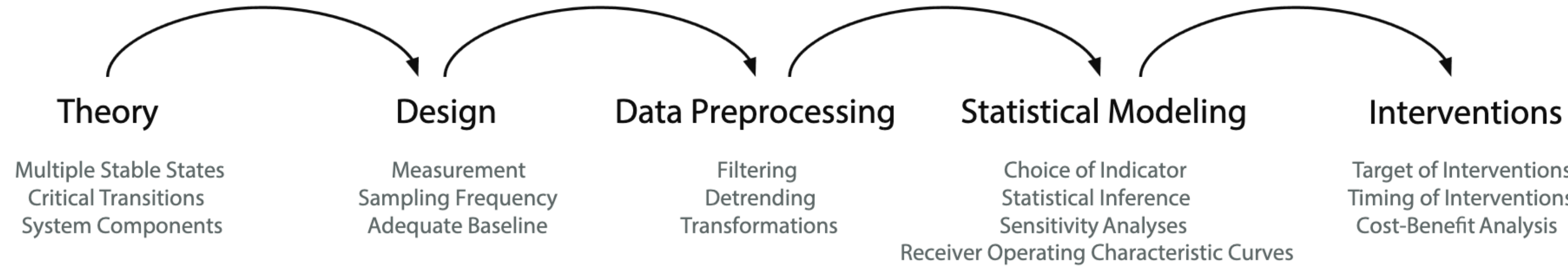
Ahead of the curve

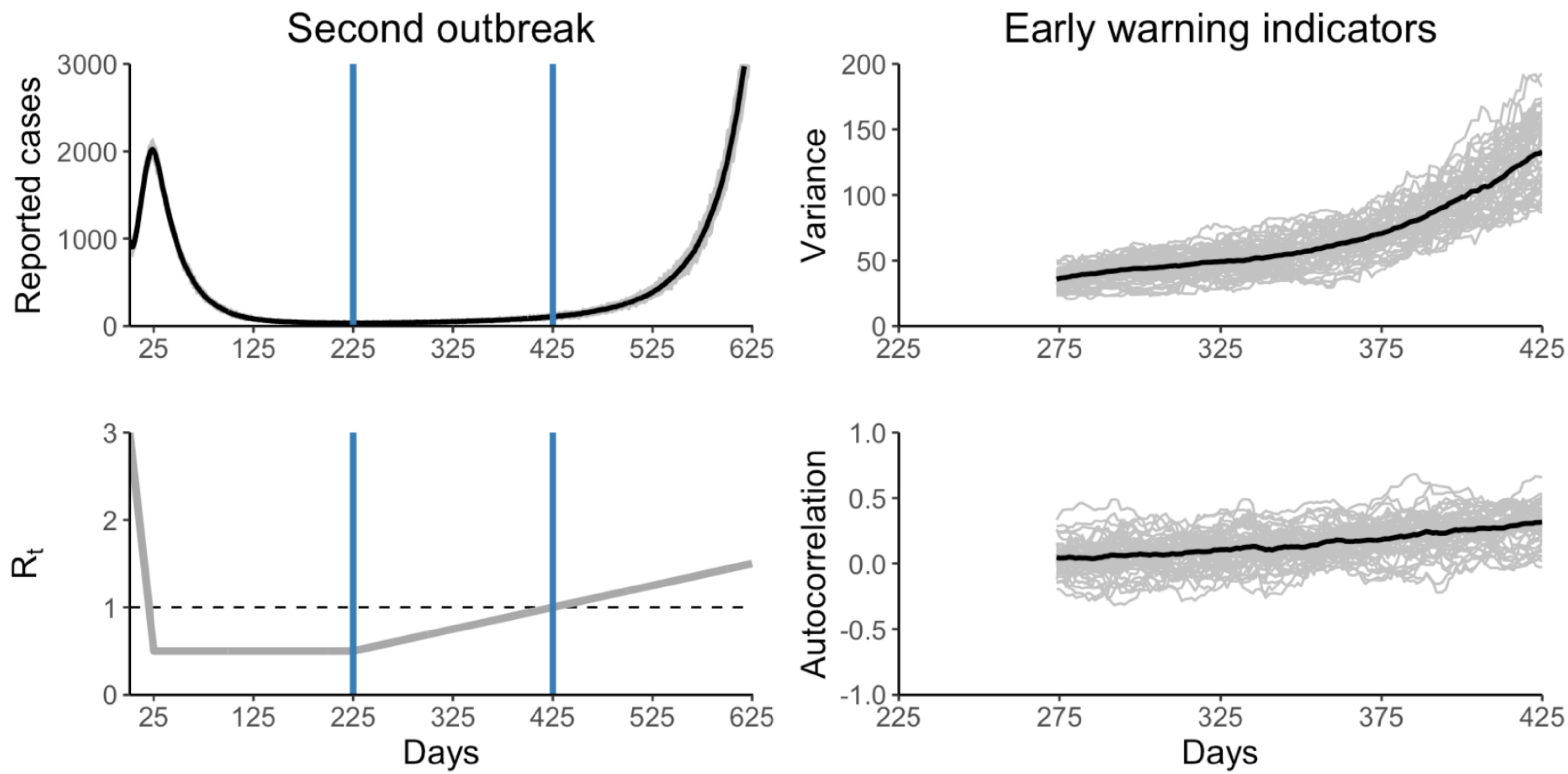
- O'Regan & Drake ([2013]())
  - Critical slowing down occurs in the basic SIS and SIR compartmental models

- O'Dea et al. ([2018]())
  - In a SIR model, the autocorrelation of the number of infected provides a better estimate of the distance to the epidemic threshold than the autocorrelation of the number of susceptibles

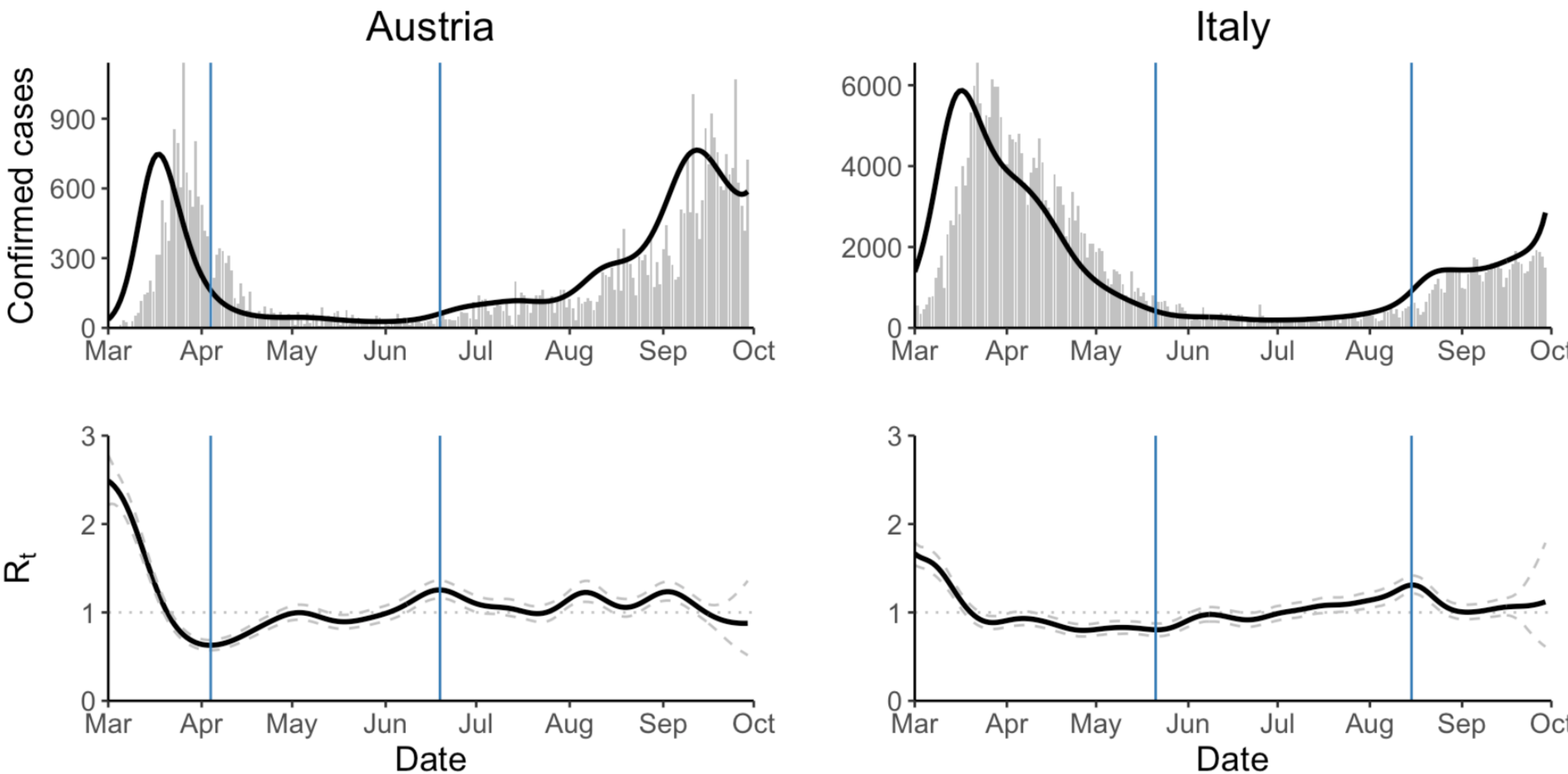
- Brett et al. ([2018]())
  - Case reports are lagging behind; deaths lag behind substantially
  - Estimating *Rt* is extremely difficult
  - Several early warning indicators robust to reporting errors and aggregation in anticipating epidemic transitions

- Brett et al. ([2020]())
  - Critical slowing down occurs in high-dimensional models

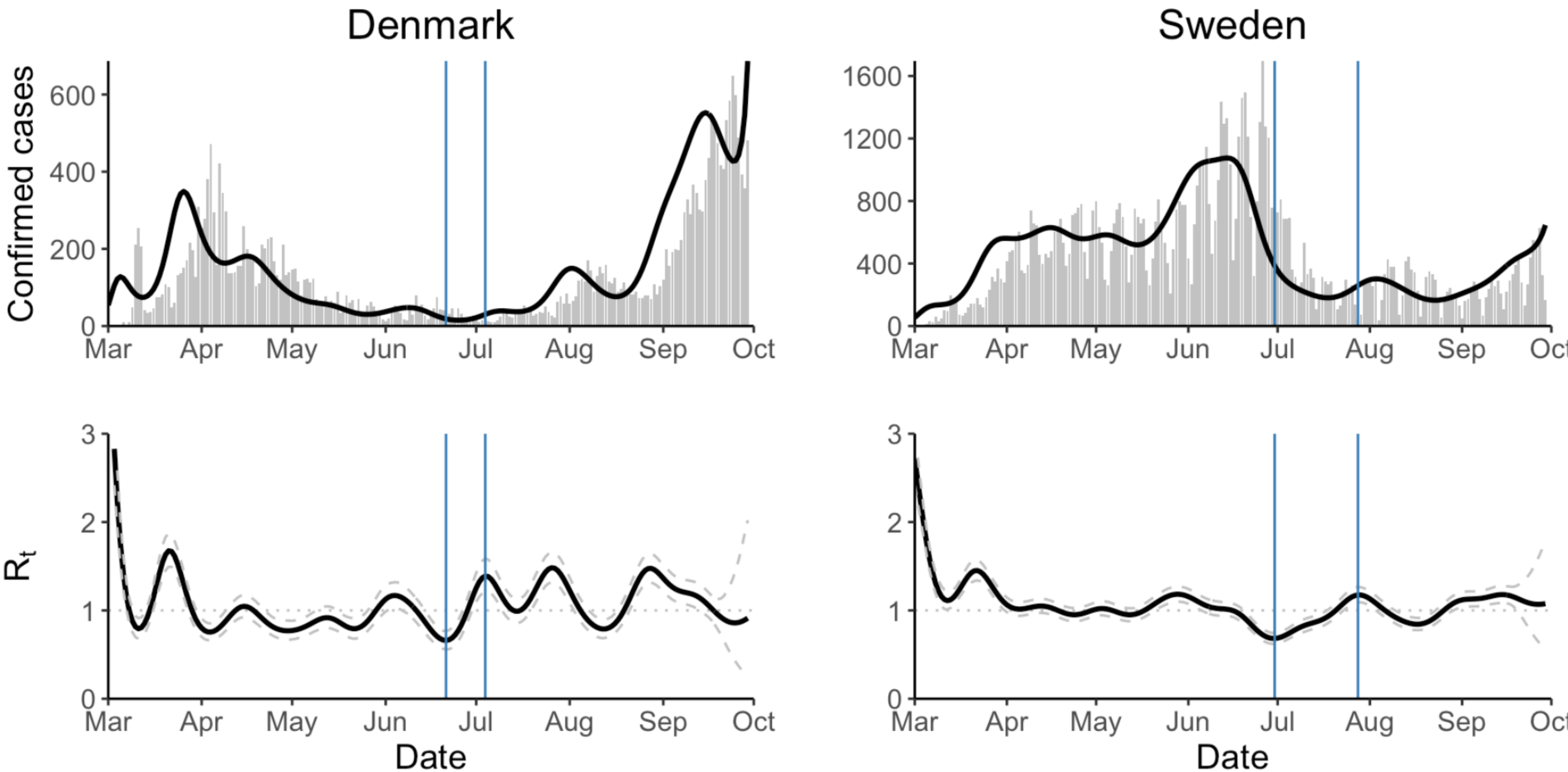




Dablander et al. (2022)



Abbott et al. (2020); Gostic et al. (2020)



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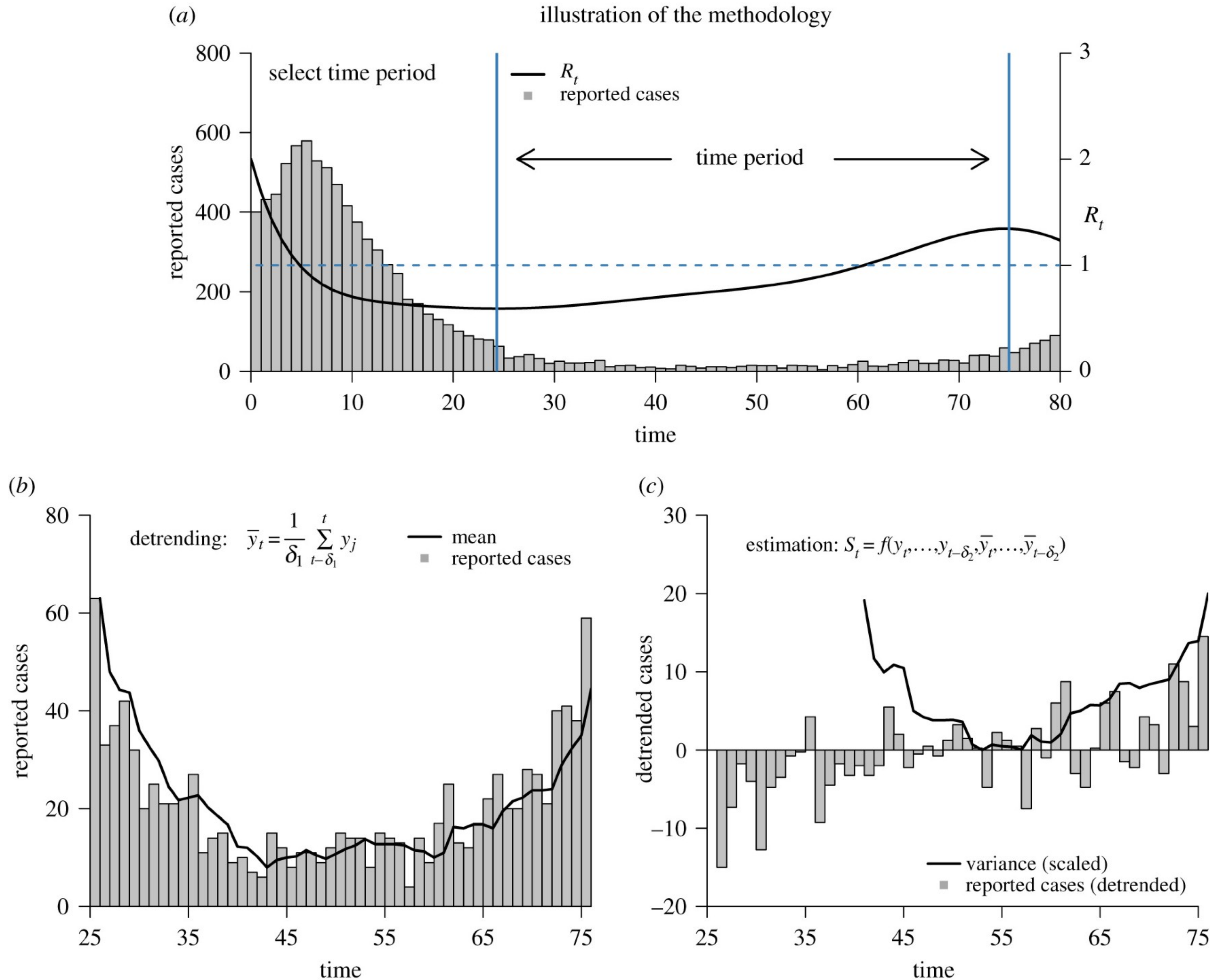

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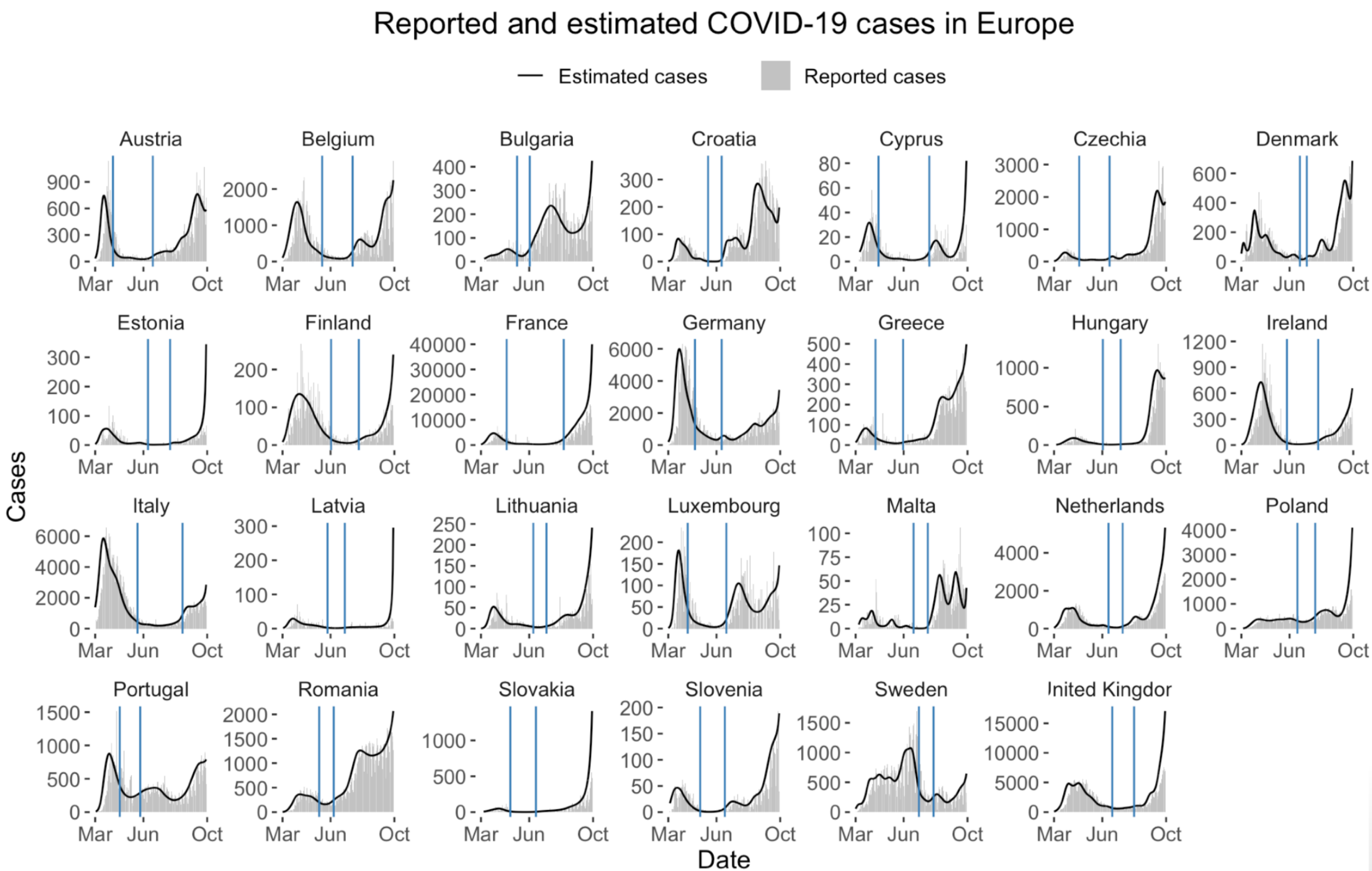

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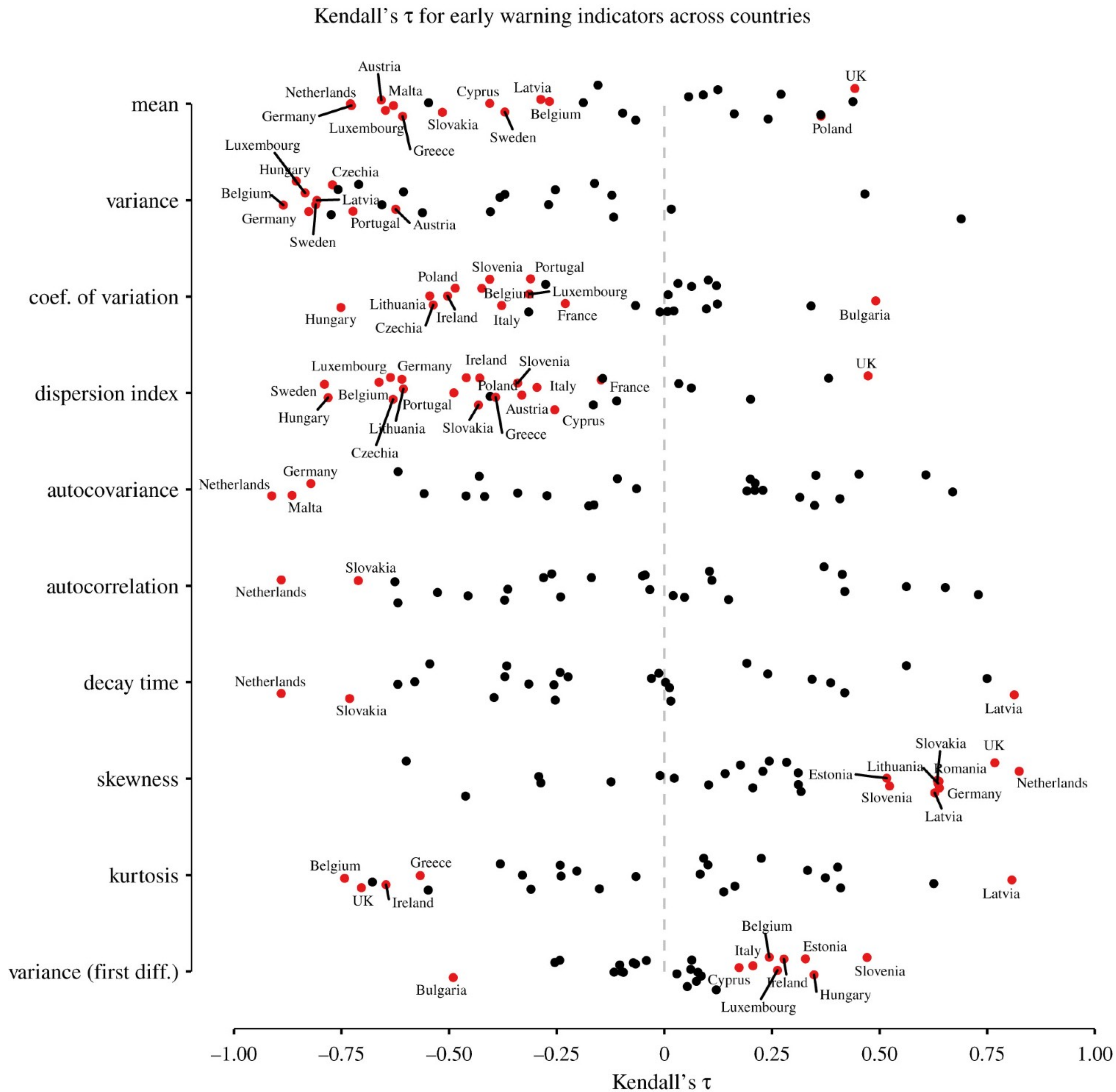

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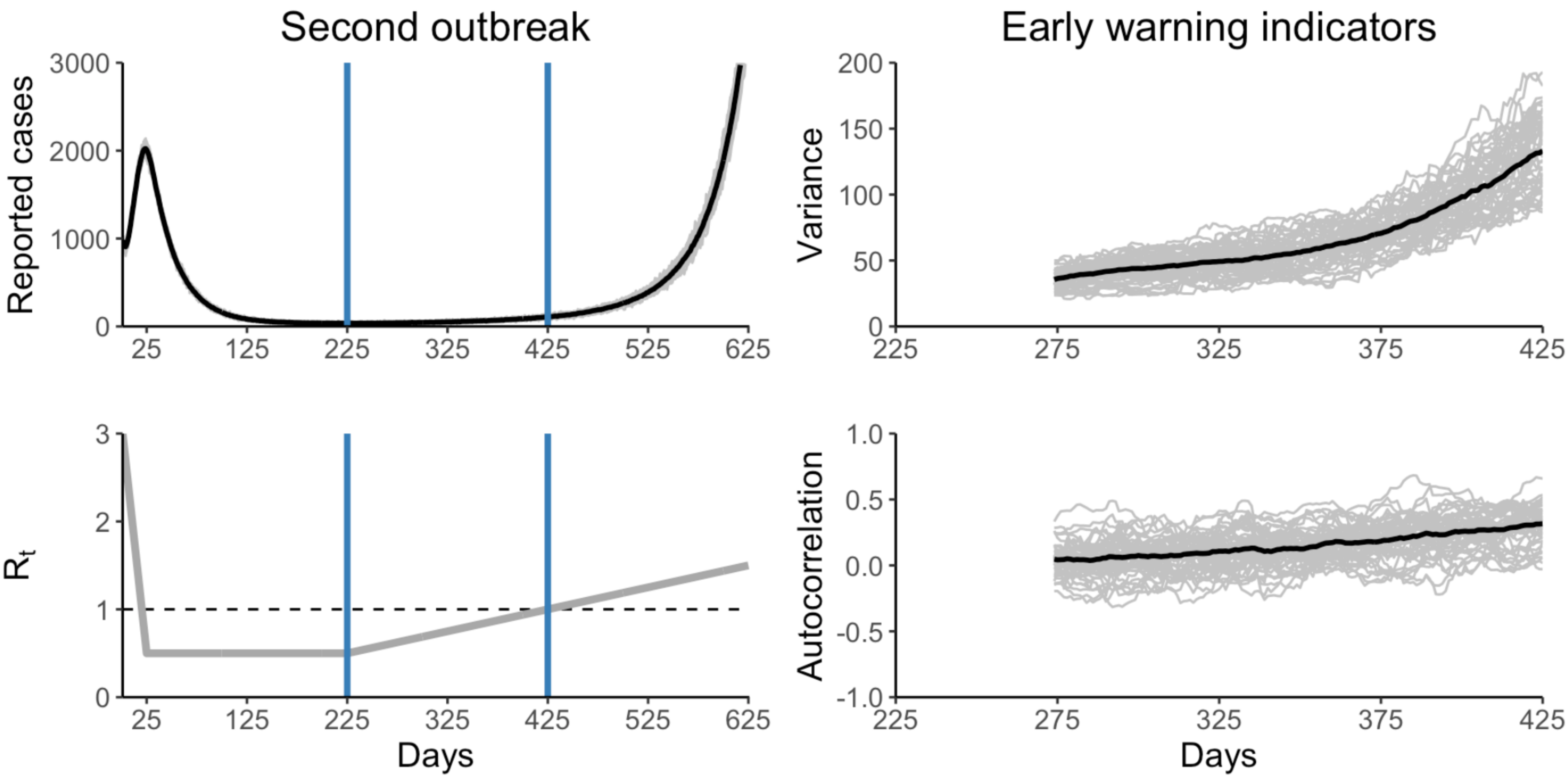

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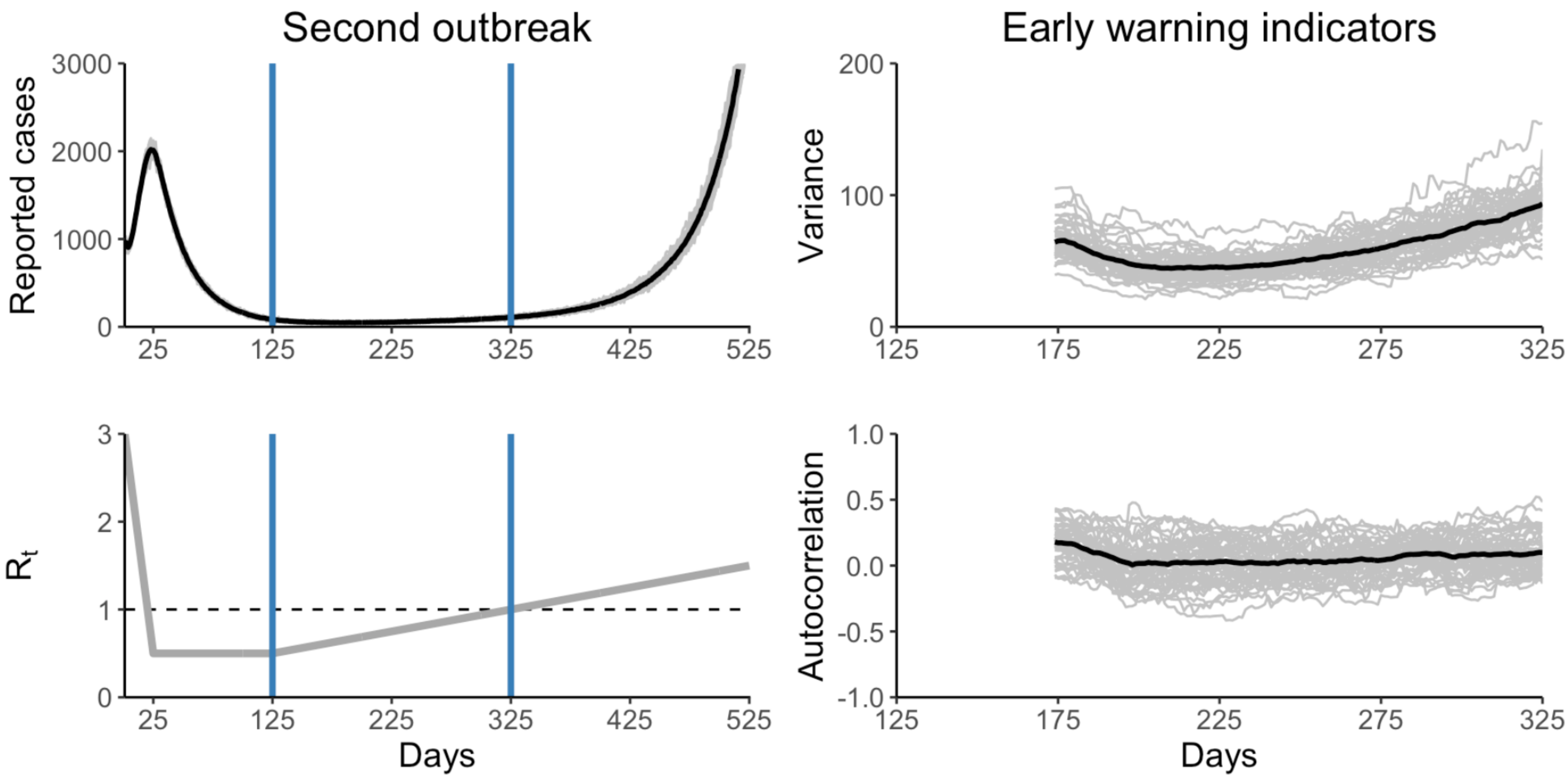

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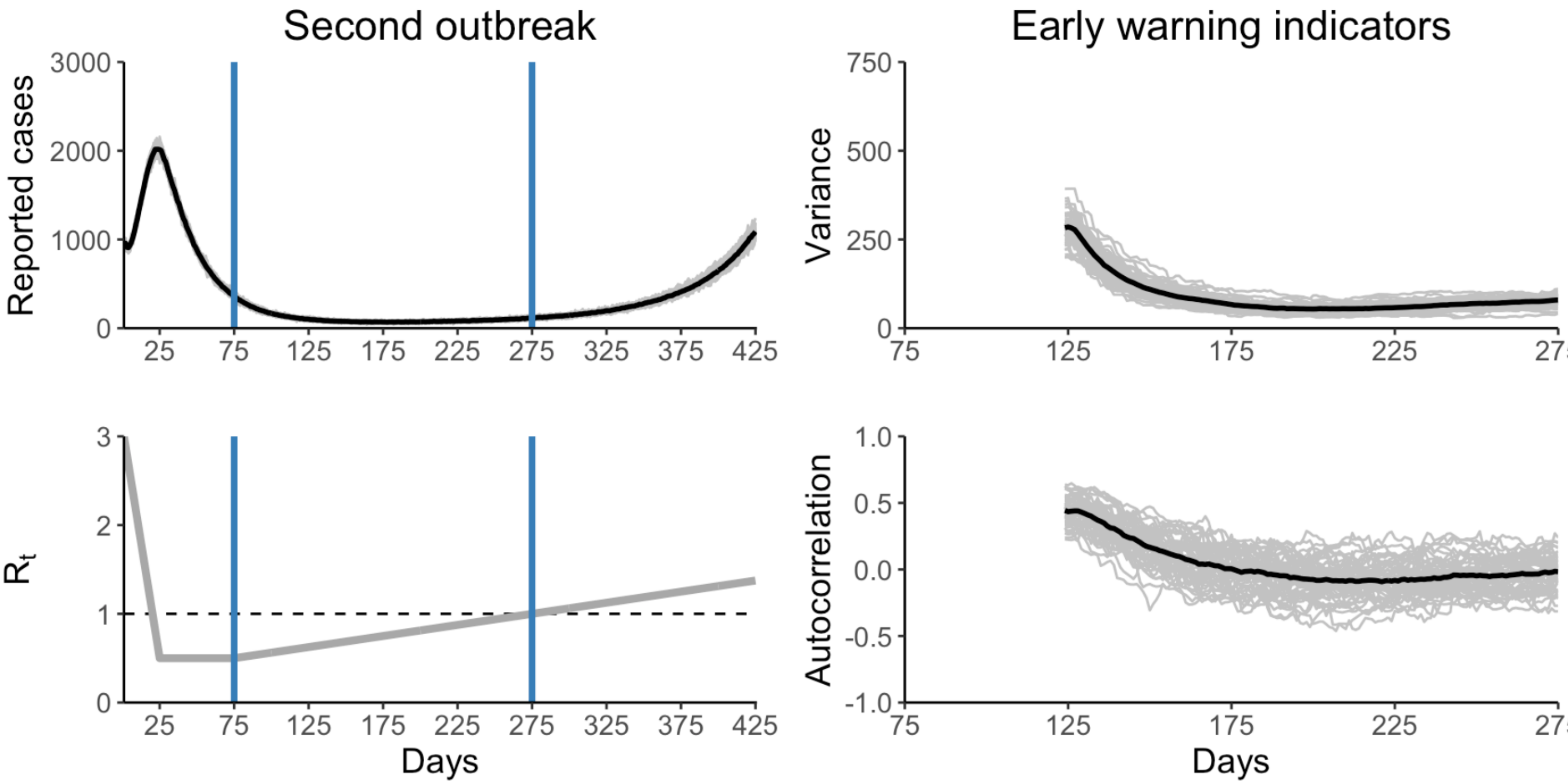

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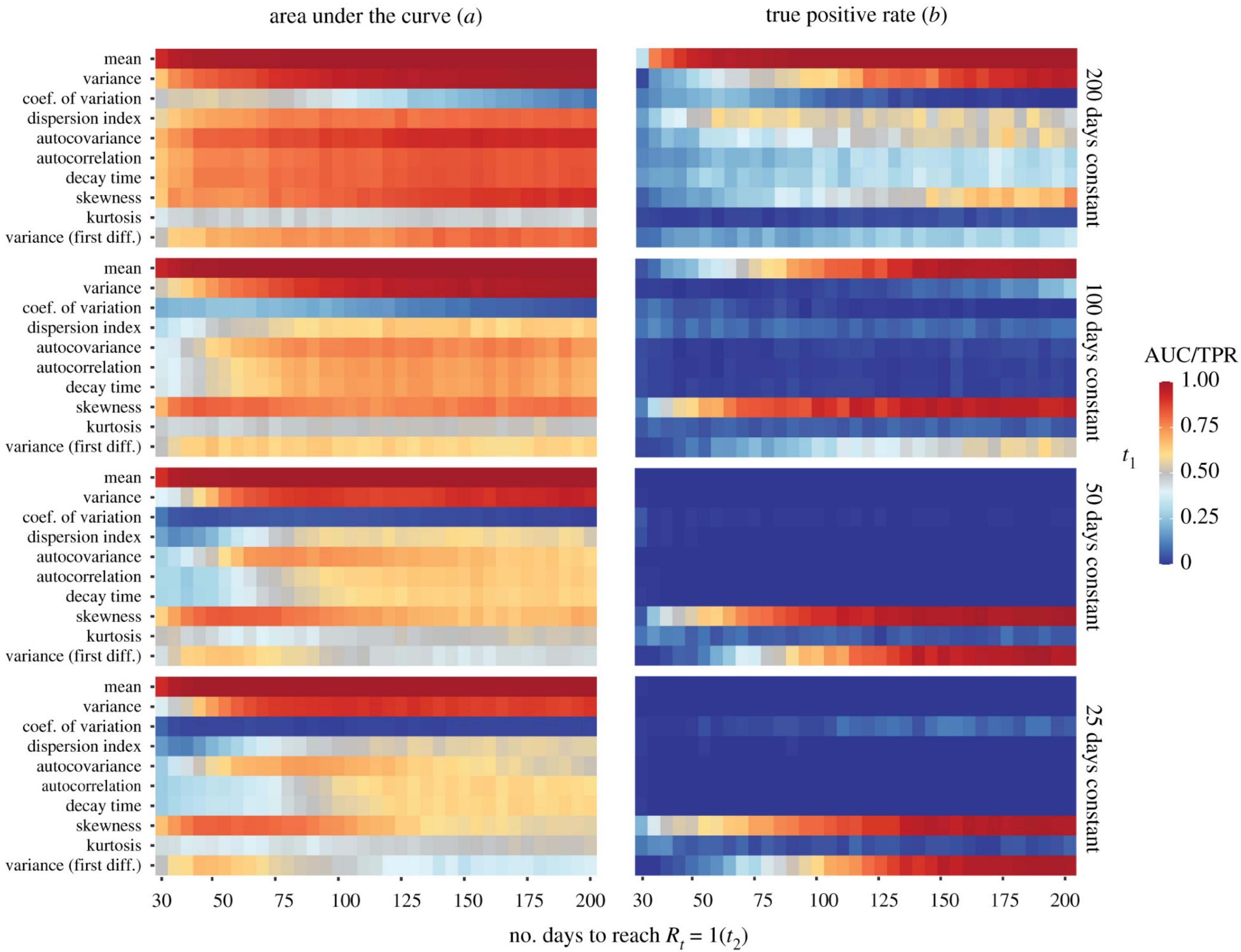


Dablander et al. (2022)

Interim conclusion III

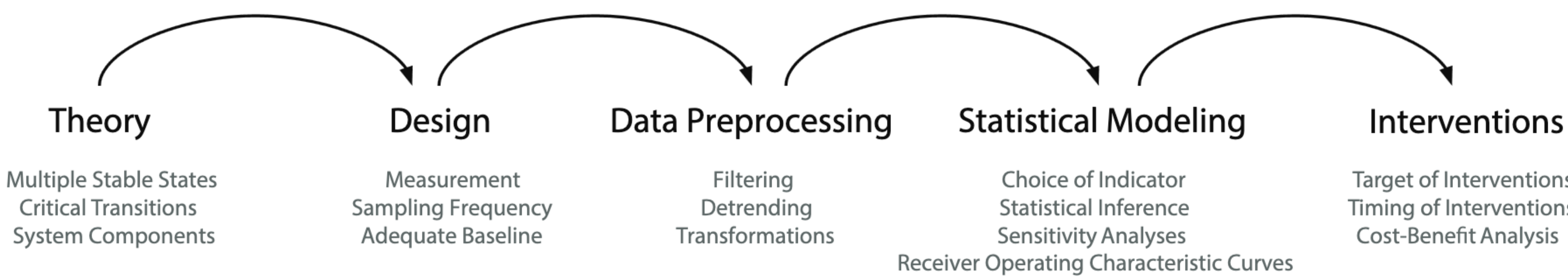
- Indicators did not reliably rise prior to the 2nd COVID-19 wave
  - In fact, they tended to *decrease* rather than *increase*
  - This is due to the persistent transient of the first wave
  - Assumption of slow forcing critical

- Theoretical understanding helped to make sense of “peculiar” patterns

- Even if indicators would reliably rise, many practical challenges remain
- For details, see Dablander, Heesterbeek, Borsboom, & Drake (2022)

Conclusion I

- **Allure of generic early warning signals may have led some fields astray (again)**
- **Successfully applying EWS in practice requires a good understanding of the system**
  - Type of bifurcation, linear / nonlinear driver, timescales, measurement, system components, type of noise, …
  - Dampen enthusiasm for “softer” sciences and social tipping points



Conclusion II

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Early warning signals have limited applicability to empirical lake data

Duncan A. O'Brien, Smita Deb, Gideon Gal, Stephen J. Thackeray, Partha S. Dutta, Shin-ichiro S. Matsuzaki, Linda May & Christopher F. Clements

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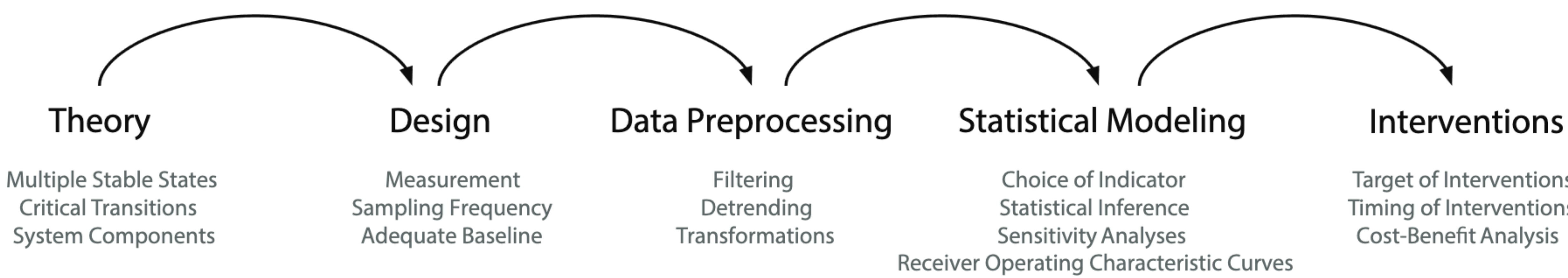
- **Even with a good understanding, statistical challenges remain tough**
  - Distinguish the bifurcation type promising (Bury et al, Grziwotz et al)
  - Move towards more general prediction tools? (Boettiger & Hastings, 2013)

- **Lots of EWS research — but remains mostly an "intellectual" exercise?**



Thank you!