Supplementary Information

Title: The rate of environmental change as an important driver across scales in ecology

Authors: Alexis D. Synodinos [1, 2, 13 *], Rajat Karnatak [3, 13], Carlos A. Aguilar-Trigueros [4, 13], Pierre Gras [5, 13], Tina Heger [3, 4, 6, 7, 13], Danny Ionescu [8, 13], Stefanie Maaß [2, 13], Camille L. Musseau [9, 10, 13], Gabriela Onandia [11, 13], Aimara Planillo [5, 13], Lina Weiss [2, 13], Sabine Wollrab [3, 13**], Masahiro Ryo [11, 12, 13**]

Affiliations:

[1] Theoretical and Experimental Ecology Station, CNRS, Moulis, 09200, France

[2] Plant Ecology and Nature Conservation, University of Potsdam, Potsdam, 14476, Germany

[3] Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany

[4] Freie Universität Berlin, Institute of Biology, 14195 Berlin, Germany.

[5] Department of Ecological Dynamics, Leibniz Institute for Zoo and Wildlife Research (IZW), Berlin, Germany

[6] Biodiversity Research/Botany, University of Potsdam, Potsdam, 14469, Germany

[7] Restoration Ecology, Technical University of Munich, Freising, 85350, Germany

[8] Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Neuglobsow, Germany

[9] Department of Biology, Chemistry, Pharmacy, Institute of Biology, Freie Universität Berlin, Berlin, Germany

[10] Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany

[11] Research Platform Data Analysis and Simulation, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Muencheberg, Germany

[12] Environment and Natural Sciences, Brandenburg University of Technology Cottbus-Senftenberg, 03046 Cottbus, Germany

[13] Berlin-Brandenburg Institute of Advanced Biodiversity Research, Berlin, 14195, Germany

*** Correspondence to**: alexios.synodinos@sete.cnrs.fr

** Joint last authors

Keywords: climate change, biodiversity, species persistence, ecological communities, ecosystem response, buffering mechanisms, r-tipping, temporal ecology, global change

Literature review description

We searched Web of Science based on the following keywords in the category ‘topic’:

climatic debt

compost-bomb instability

ecological transitions rapid change in driver

ecological transitions turnover rates

ecosystem response rate

ecosystem transition disturbance rate interactions

extinction debt

extinction debt ecosystem

extinction rate ecosystem transitions

r-tipping

r-tipping ecology

r-tipping ecosystem

r-tipping systems

rate-induced ecosystem response

rate-induced extinction

rate-induced tipping points

rate-induced tipping systems

rate-induced transition

rapid change ecosystem

rapid change ecosystem transition

rapid change rate ecosystem transition

rapid climate change

rapid ecological transitions turnover rates

rapid rate of change ecosystem

rapid rate of change ecosystem transition

rate of change

rate of climate change exceeds range shift

transitions

transitions ecosystem diversity rate of change

Only studies which explicitly investigated the impact of the rate of change on a target variable were included in the review, yielding a total of 22 studies (list provided below). The review was conducted by all co-authors with each study assigned to at least two people. Studies were classified with respect to the following categories: level of ecological organisation (organism, population, community, ecosystem/biome), kingdom (bacteria, fungi, plants, animals), ecosystem type (terrestrial, aquatic) and study type (experimental, observation, model). Studies including different species or target variables (e.g., thermal minimum and thermal maximum of an organism) were considered independently and represented different data points in our statistical analysis. Similarly, studies covering multiple classes within a category (e.g., for habitats: terrestrial and aquatic) were counted independently for each class (i.e., the same study was included for the class terrestrial once and for the class aquatic once) in order to increase the number of datapoints in our analysis. This yielded a total of 30 data points. The response variable for our statistical analysis was 'no tipping' or 'tipping'. 'No tipping' corresponds to the cases of no observable effect of the rate of change or to a linear response with respect to the rate of change. 'Tipping' occurred when the rate of change induced a qualitative or nonlinear change in the response variable. Additionally, we only defined 'tipping' as the outcome when the reported result could confidently be attributed to the rate of change; otherwise, we considered this a 'no tipping' response.

List of studies included in our statistical analysis:

Allen, J.L., Chown, S.L., Janion-Scheepers, C. & Clusella-Trullas, S. (2016). Interactions between rates of temperature change and acclimation affect latitudinal patterns of warming tolerance. *Conserv. Physiol.*, 4.

Allen, J.L., Clusella-Trullas, S. & Chown, S.L. (2012). The effects of acclimation and rates of temperature change on critical thermal limits in Tenebrio molitor (Tenebrionidae) and Cyrtobagous salviniae (Curculionidae). *J. Insect Physiol.*, 58, 669–678.

Baym, M., Lieberman, T.D., Kelsic, E.D., Chait, R., Gross, R., Yelin, I., *et al.* (2016). Spatiotemporal microbial evolution on antibiotic landscapes. *Science (80-.).*, 353, 1147–1151.

Chen, Y., Kolokolnikov, T., Tzou, J. & Gai, C. (2015). Patterned vegetation, tipping points, and the rate of climate change. *Eur. J. Appl. Math.*, 26, 945–958.

Cook, C.N., Kaspar, R.E., Flaxman, S.M. & Breed, M.D. (2016). Rapidly changing environment modulates the thermoregulatory fanning response in honeybee groups. *Anim. Behav.*, 115, 237–243.

Heijmans, M.M.P.D., van der Knaap, Y.A.M., Holmgren, M. & Limpens, J. (2013). Persistent versus transient tree encroachment of temperate peat bogs: effects of climate warming and drought events. *Glob. Chang. Biol.*, 19, 2240–2250.

Ignacio, Q., J., W.J. & Luke, H. (2013). Rates of projected climate change dramatically exceed past rates of climatic niche evolution among vertebrate species. *Ecol. Lett.*, 16, 1095–1103.

Jeroen, B., J., T.J.M., Robby, S. & Dries, B. (2013). More rapid climate change promotes evolutionary rescue through selection for increased dispersal distance. *Evol. Appl.*, 6, 353–364.

Killeen, J., Gougat-Barbera, C., Krenek, S. & Kaltz, O. (2017). Evolutionary rescue and local adaptation under different rates of temperature increase: a combined analysis of changes in phenotype expression and genotype frequency in Paramecium microcosms. *Mol. Ecol.*, 26, 1734–1746.

Klironomos, J.N., Allen, M.F., Rillig, M.C., Piotrowski, J., Makvandi-Nejad, S., Wolfe, B.E., *et al.* (2005). Abrupt rise in atmospheric CO_2 overestimates community response in a model plant–soil system. *Nature*, 433, 621–624.

Liukkonen, M., Kronholm, I. & Ketola, T. (2021). Evolutionary rescue at different rates of environmental change is affected by trade-offs between short-term performance and long-term survival. *J. Evol. Biol.*

Luke, C.M. & Cox, P.M. (2011). Soil carbon and climate change: from the Jenkinson effect to the compost-bomb instability. *Eur. J. Soil Sci.*, 62, 5–12.

Malcolm, J.R., Markham, A., Neilson, R.P. & Garaci, M. (2002). Estimated migration rates under scenarios of global climate change. *J. Biogeogr.*, 29, 835–849.

Moyano, M., Candebat, C., Ruhbaum, Y., Álvarez-Fernández, S., Claireaux, G., Zambonino-Infante, J.-L., *et al.* (2017). Effects of warming rate, acclimation temperature and ontogeny on the critical thermal maximum of temperate marine fish larvae. *PLoS One*, 12, e0179928.

Nakadai, R. (2020). Degrees of compositional shift in tree communities vary along a gradient of temperature change rates over one decade: Application of an individual-based temporal beta-diversity concept. *Ecol. Evol.*, 10, 13613–13623.

Nilsson-Örtman, V. & Johansson, F. (2017). The Rate of Seasonal Changes in Temperature Alters Acclimation of Performance under Climate Change. *Am. Nat.*, 190, 743–761.

Peck, L.S., Clark, M.S., Morley, S.A., Massey, A. & Rossetti, H. (2009). Animal temperature limits and ecological relevance: effects of size, activity and rates of change. *Funct. Ecol.*, 23, 248–256.

Perron, G.G., Gonzalez, A. & Buckling, A. (2008). The rate of environmental change drives adaptation to an antibiotic sink. *J. Evol. Biol.*, 21, 1724–1731.

Siteur, K., Eppinga, M.B., Doelman, A., Siero, E. & Rietkerk, M. (2016). Ecosystems off track: rate-induced critical transitions in ecological models. *Oikos*, 125, 1689–1699.

Stivrins, N., Soininen, J., Amon, L., Fontana, S.L., Gryguc, G., Heikkilä, M., *et al.* (2016). Biotic turnover rates during the Pleistocene-Holocene transition. *Quat. Sci. Rev.*, 151, 100–110.

Wei, W., Patrick, B. & Matthew, B. (2017). Thresholds of sea-level rise rate and sea-level rise acceleration rate in a vulnerable coastal wetland. *Ecol. Evol.*, 7, 10890–10903.

Yoshida, T., Jones, L.E., Ellner, S.P., Fussmann, G.F. & Hairston Jr, N.G. (2003). Rapid evolution drives ecological dynamics in a predator–prey system. *Nature*, 424, 303–306.