

Relation between stability and resilience determines the performance of early warning signals under different environmental drivers

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Edited by Stephen R. Carpenter, University of Wisconsin, Madison, WI, and approved June 19, 2015 (received for review September 23, 2014)

Shifting patterns of temporal fluctuations have been found to signal critical transitions in a variety of systems, from ecological communities to human physiology. However, failure of these early warning signals in some systems calls for a better understanding of their limitations. In particular, little is known about the generality of early warning signals in different deteriorating environments. In this study, we characterized how multiple environmental drivers influence the dynamics of laboratory yeast populations, which was previously shown to display alternative stable states [Dai et al., *Science*, 2012]. We observed that both the coefficient of variation and autocorrelation increased before population collapse in two slowly deteriorating environments, one with a rising death rate and the other one with decreasing nutrient availability. We compared the performance of early warning signals across multiple environments as “indicators for loss of resilience.” We find that the varying performance is determined by how a system responds to changes in a specific driver, which can be captured by a relation between stability (recovery rate) and resilience (size of the basin of attraction). Furthermore, we demonstrate that the positive correlation between stability and resilience, as the essential assumption of indicators based on critical slowing down, can break down in this system when multiple environmental drivers are changed simultaneously. Our results suggest that the stability–resilience relation needs to be better understood for the application of early warning signals in different scenarios.

early warning signals | population collapse | environmental drivers | stability–resilience relation

Complex systems are often subject to multiple environmental drivers. Microenvironmental cues such as growth factors and drug concentrations control the progression of cancer cells (1). Parasites, insecticides, and habitat destruction have all been blamed for the rapid decline of honey bee colonies in the North America (2). The global biodiversity is influenced by factors including habitat fragmentation, climate change, etc. For a system with alternative stable states (3, 4), pressure on an environmental driver pushes the system closer to a tipping point (5, 6). Once the driver crosses a certain threshold, the system goes through a critical transition and shifts to a different state [e.g., the malignant behavior of cancer (1), the collapse of pollinator populations (7), or a large-scale mass extinction (8, 9)].

There has been a growing interest in developing a toolbox of early warning signals to avoid such undesirable transitions (10–17). Theoretical and empirical studies have found that signatures of “critical slowing down” in the spatiotemporal dynamics may be used to indicate impending tipping points (18–29). These indicators are based on the fact that the dynamics around the equilibrium of a system slows down near a tipping point (19, 30, 31). This would lead to an increase in recovery time from perturbations or changes in the pattern of fluctuations (e.g., increases in variation and autocorrelation) (20, 32). The appeal of these generic indicators is that they do not rely on detailed knowledge of a complex system, thus complementing the use of system-specific modeling to determine when critical transitions may occur. However, the failure of early warning

signals before certain transitions has raised concerns on their generality (33, 34). In some cases, the failure of detection is merely a statistical problem, e.g., insufficient quality or quantity of data. The real concern, however, is that critical slowing down does not precede all types of transitions. In two recent reviews (35, 36), the authors summarize the potential of observing critical slowing down before regime shifts caused by different mechanisms. They also highlighted the need for a better understanding of the limitation of our current toolbox, which would aid the application to real-world scenarios.

One gap in our understanding is the generality of early warning signals in a system subject to multiple environmental drivers. Previous experimental studies have focused solely on transitions induced by a single, specific driver. In this study, we tune multiple environmental drivers in laboratory yeast populations, which have been shown to display cooperative growth and alternative stable states under daily dilution (22, 37). To overcome the difficulty in comparing early warning signals between different deteriorating environments, we propose to evaluate them as “indicators for loss of resilience.” Finally, we find that the relation between stability and resilience determines the performance of statistical indicators and provides further insight to their limitation.

Results

We pushed yeast populations to collapse by slowly tuning two different environmental drivers (Fig. 1). We grew yeast cells in

Significance

Alternative stable states and critical transitions are widespread in nature and can have profound consequences for conservation, climate changes, and human health. Our current toolbox of early warning signals before critical transitions has seen both successes and failures. Understanding the limitations of these indicators is crucial for application in real-world scenarios. In this study, we explored the population dynamics of laboratory yeast under different forms of environmental deterioration. We found that the performance of early warning signals under different environmental drivers is determined by the underlying relation between stability and resilience. This work presents a framework to evaluate the utility of early warning signals, and it sets a foundation for further studies on how dynamical systems respond to environmental changes.

Author contributions: L.D., K.S.K., and J.G. designed research; L.D. performed research; L.D. analyzed data; and L.D., K.S.K., and J.G. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The data reported in this paper have been deposited in the Dryad database, [datadryad.org \(10.5061/dryad.k30v3\)](https://doi.org/10.5061/dryad.k30v3).

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1418415112/-DCSupplemental.

batch culture using synthetic media supplemented with sugar sucrose; on each day the cells were diluted and transferred into fresh media. As demonstrated previously (22, 23), yeast populations experience a tipping point (fold bifurcation) leading to sudden collapse as a result of the cooperative breakdown of sucrose outside of the cell. The first driver is the dilution factor used for daily transfer into fresh media (Fig. 1A). After an initial period of 4 days to stabilize the yeast populations at a dilution factor of 500, we increased the dilution factor by 10% per day and pushed populations to collapse in a few weeks (Fig. 1B). The steady increase in dilution factor mimics a rising death rate. Consistent with previous experimental measurements probing this environmental driver (22), we found that both the coefficient of variation (CV) and autocorrelation time of the deteriorating-environment group increased substantially before the estimated

tipping point (SI Appendix, Fig. S1), whereas no increase in these indicators was observed in the constant-environment group with a fixed dilution factor of 500 (Fig. 1C and D). In the second deteriorating environment, we imposed increasingly severe nutrient limitation by reducing the sucrose concentration by 20% per day (Fig. 1E). The yeast populations collapsed in a similar fashion over the course of 3 wk (Fig. 1F). In this case, we also observed increases in CV and autocorrelation time before population collapse (Fig. 1G and H), although the warning signals were not as pronounced as those seen with an increasing dilution factor. Consistent with visual inspection (Fig. 1C, D, G, and H), for both statistical indicators the Kendall's τ coefficient under increasing dilution factor (CV: $\tau = 0.71, P = 6.7 \times 10^{-5}$; autocorrelation time: $\tau = 0.27$, nonsignificant) is larger than those under decreasing sucrose availability (CV: $\tau = 0.59, P = 2.2 \times 10^{-4}$; autocorrelation time: $\tau = 0.09$, nonsignificant).

Our empirical observation of early warning signals before population collapse under two drivers is encouraging for the use of these indicators in a system subject to different forms of stress. Nevertheless, the clear difference in the performance of the indicators across the two deteriorating environments is not well understood. In real-time deteriorating environments, the performance of early warning signals can be complicated by the rate of environmental changes. For example, an abruptly large shift in the environment can clearly push the system to an alternative state before it is possible to observe any warning signal. To exclude any effect caused by the rate of environmental changes, we characterized the dynamics of yeast populations over a range of fixed environmental conditions. Such an experiment can be considered as an infinitely slowly deteriorating environment, thus allowing us to compare the strength of the early warning indicators without the complexity introduced by potentially different rates of environmental deterioration. We experimentally mapped out the bifurcation diagram for sucrose availability and observed a fold bifurcation at low concentration of sucrose (Fig. 2B). A similar bifurcation diagram for dilution factor was mapped in our previous study (Fig. 2A) (22). We then tracked the fluctuations around the equilibrium and measured statistical indicators over an ensemble of replicate populations. Under both environmental drivers, CV (Fig. 2C and D) and autocorrelation time (SI Appendix, Fig. S2A and B) of yeast population increased before the fold bifurcation.

Because the proximity to a fold bifurcation is measured by the unit of a specific driver (dilution factor or sucrose concentration), we cannot directly compare the performance of statistical indicators across multiple environments as a function of the underlying driver. In fact, we cannot necessarily say that the early warning indicators perform better under increasing dilution than under decreasing sucrose concentrations, because the indicators would presumably get stronger if the sucrose concentration was closer to the threshold at the critical transition.

Here we propose to evaluate the early warning signals before a fold bifurcation with respect to the underlying loss of resilience. For the yeast populations, we define resilience as the distance between the stable and unstable fixed points (Fig. 2A and B), which measures the maximal pulse perturbation (i.e., the number of individuals lost) a population can tolerate without going extinct. This definition of resilience therefore has a natural interpretation relative to environmental perturbations and also corresponds to the (one-sided) size of the basin of attraction of the stable state. In our system, we have experimentally mapped out the bifurcation diagrams with two different environmental drivers, thus allowing for a direct measure of resilience. As the pressure on a driver increases, a population loses resilience approaching the fold bifurcation. Right at the fold bifurcation, resilience is reduced to zero as the stable and unstable fixed points meet and “collide.”

With the experimental bifurcation diagrams mapped out, we can quantify the performance of early warning signals as a function

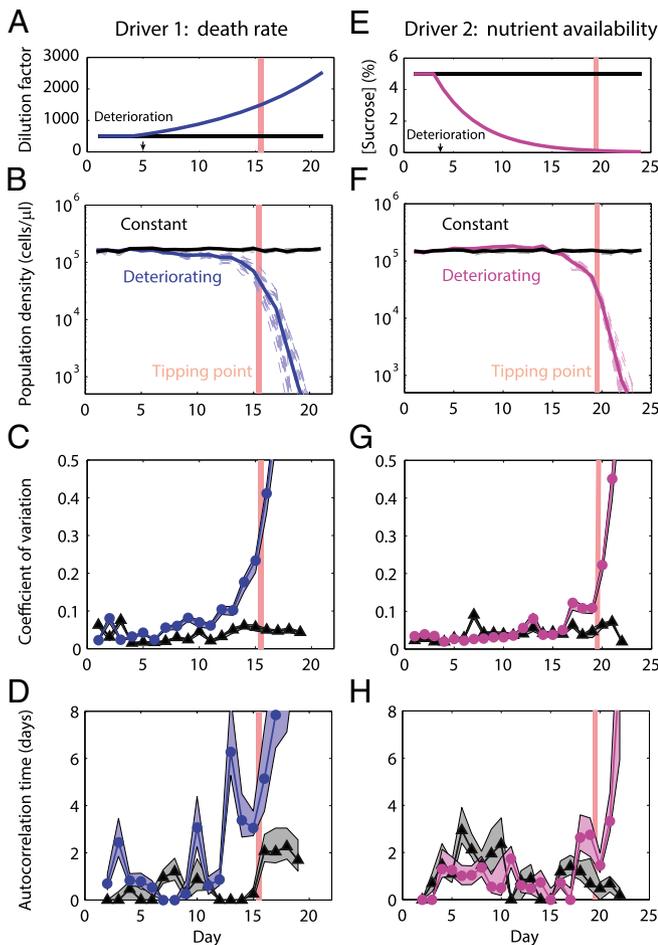


Fig. 1. Increased variation and autocorrelation time in population density were observed before population collapse in two different deteriorating environments. (A) A slowly deteriorating environment with a rising death rate. Dilution factor of the constant-environment group (black) was fixed at 500. After an initial phase of 4 d to stabilize the populations, the dilution factor of the deteriorating-environment group (blue) was increased from 500 to over 2,500 (SI Appendix, Table S1). The red line marks the estimated day when the populations crossed a tipping point (SI Appendix, Fig. S1). (B) Population density of individual replicates (dashed lines) and the mean population density among replicates (solid line) over time. Coefficient of variation (C) and autocorrelation time (D) of the deteriorating-environment group (circle) increased substantially at least 3 d in advance. The indicators for the constant-environment group (triangle) did not show any trend. The shaded regions for the indicators correspond to the 25–75% confidence interval given by bootstrap. (E–H) A slowly deteriorating environment with decreasing nutrient availability. Conventions for symbols are the same as in A–D.

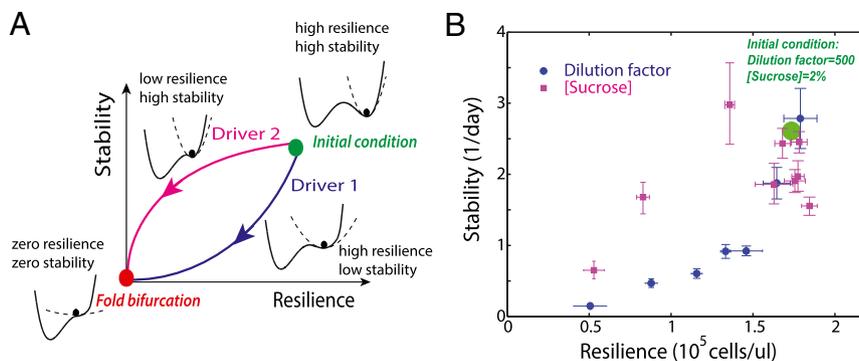


Fig. 4. Stability–resilience relation under different environmental drivers. (A) Starting from an initial condition with high resilience and high stability (green dot), pressure on an environmental driver pushes the system toward a fold bifurcation (red dot) where both resilience and stability are reduced to zero. Along such a path, changes in the dynamics can be visualized by a changing potential landscape. Loss of resilience corresponds to shrinkage in the basin of attraction, whereas loss of stability leads to a flattened curvature around the bottom of the potential. The exact path taken can vary between drivers. (B) Stability–resilience relation under the two experimental drivers in yeast populations. Starting from the same initial condition (green dot), the loss of stability under increasing dilution factor is greater than that under decreasing sucrose, given the same loss of resilience. This explains the observed difference in the performance of CV and autocorrelation time under the two drivers. Error bars are SEs given by bootstrap.

(resilience = 0, stability = 0). For different drivers leading to a fold bifurcation, the system will always end at the origin with zero resilience and zero stability. Nevertheless, it is plausible that the precise path taken (i.e., the exact relation between stability and resilience) can vary between drivers. For example, under one environmental deterioration (“driver 1”), the system may lose much stability while maintaining a high resilience (a wide but flattened potential well). On the other hand, a different form of environmental deterioration (“driver 2”) may result in a significant loss of resilience with little reduction in stability (a narrow but steep potential well). Therefore, given the same loss of resilience, the loss of stability under driver 1 is always greater than that under driver 2 (Fig. 4A). Environmental perturbations such as severe weather will often cause a complex system to transition before the deterministic bifurcation point (10, 17, 44), meaning that it is important for early warning signals to precede a severe loss of resilience. As resilience is reduced, a large external perturbation is more likely to push a population below its extinction threshold (i.e., the unstable fixed point). Given this need to maintain a minimal resilience, the early warning indicators based on loss of stability will be more effective for driver 1 compared with driver 2 as a result of their different paths on the stability–resilience diagram.

To confirm our hypothesis, we measured the relation between stability and resilience for yeast populations under two drivers: dilution factor and sucrose concentration. For a given environmental condition, we determined resilience and stability from the deterministic growth profile (Fig. 3C). Indeed, we found that the stability–resilience relation was dependent on the driver (Fig. 4B). Yeast populations lost resilience and approached a fold bifurcation with either an increase in dilution factor or a decrease in sucrose concentration. However, with an increasing dilution factor, populations lost stability more rapidly, which explained why the early warning signals based on loss of stability had a better performance under environmental deterioration induced by this driver.

In addition, we measured the dynamics of yeast populations under a third environmental driver, osmotic stress caused by salt (NaCl). Our yeast populations again lost both stability and resilience at higher concentration of salt, before eventually reaching a fold bifurcation (SI Appendix, Fig. S3). The exact path of this driver on the stability–resilience diagram was observed to be between the paths of dilution factor and sucrose. As the environment deteriorates with an increasing concentration of salt, we found that changes in statistical indicators as a function of resilience were also intermediate among the three drivers. Thus, our data supported the hypothesis that the performance of early warning signals under

different environmental drivers was governed by the relation between stability and resilience.

The stability–resilience relation also informs us of possible scenarios under which early warning signals will fail (Fig. 5). On a stability–resilience diagram, we can find environmental conditions that display a tradeoff between resilience and stability (Fig. 4B and SI Appendix, Fig. S4A). This tradeoff demonstrates that the positive correlation between stability and resilience breaks down in this system when multiple drivers are changed simultaneously. We simulated a simple phenomenological model of yeast populations, which had been shown to capture the cooperative growth dynamics and bistability in our system (SI Appendix, Supplementary Methods) (22). We tuned two parameters as environmental drivers, dilution factor and the carrying capacity. As expected, changing an individual parameter of the model corresponds to a path on the stability–resilience diagram (Fig. 5A). We also simulated another scenario in which the growth rate during slow growth phase was decreased (SI Appendix, Fig. S5). In our experiment, lowering the sucrose concentration would limit the carrying capacity as well as how fast yeast cells grow at low cell densities. So the outputs of our model were consistent with the experimental observation that tuning sucrose concentration led to a less convex path than tuning dilution factor. Surprisingly, when we tuned two parameters simultaneously in opposite directions (i.e., the pressure on one driver increased while it decreased on the other), we found that under certain conditions, a population can lose resilience while gaining stability (Fig. 5A). In this case, as the population becomes less resilient (i.e., approaching a fold bifurcation), the warning signals would actually fade away because of the increase in stability. To illustrate how anticorrelation between stability and resilience may occur, we used our model to plot contours of stability and resilience in the parameter space of the two drivers (Fig. 5B and SI Appendix, Fig. S4B). If the two contours intersect, it is possible to alter the environmental drivers together along certain directions such that changes in stability and resilience are inversely correlated (SI Appendix, Fig. S4C and Text S3). Thus, this phenomenon is not specific to our system; rather it is likely a general scenario for systems under the influence of multiple environmental drivers.

Discussion

We have proposed to evaluate critical slowing down indicators before a fold bifurcation with respect to the underlying loss of resilience, and we have shown that the stability–resilience relation can vary between different environmental drivers. Resilience, which is defined on state space instead of parameter space, provides a metric

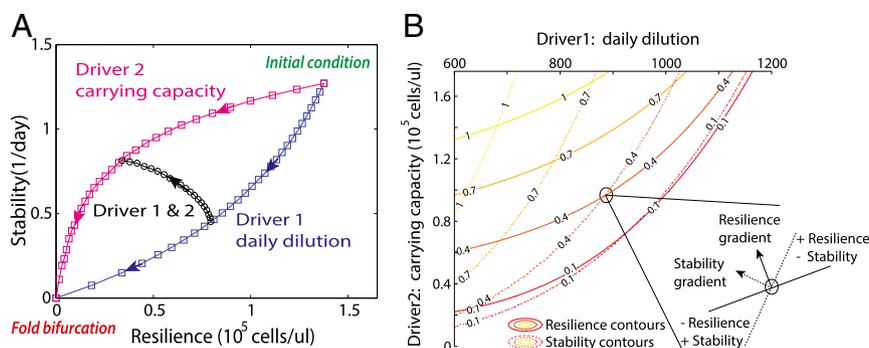


Fig. 5. Anticorrelation between stability and resilience is possible when multiple drivers are changed simultaneously in a phenomenological model of yeast populations. (A) Three scenarios were simulated: (i) a gradual increase in dilution factor (blue squares), (ii) a gradual decrease in carrying capacity (magenta squares), and (iii) a decrease in carrying capacity together with a decrease in dilution factor (black circles). With simultaneous changes of two drivers in opposite directions (*SI Appendix, Table S3*), we observed that stability and resilience can be anticorrelated. (B) Simulated resilience contours (solid lines) and stability contours (dashed lines) in the parameter space of two drivers. If the two contours intersect (black circle), the system can lose resilience while gaining stability (or vice versa) with simultaneous changes of two drivers (*Inset*). The units of stability and resilience are the same as labeled in A.

for the distance to a fold bifurcation when multiple drivers are involved. More than being a convenient metric, resilience is an important property of the population, which together with stability determines the likelihood of extinction due to demographic or environmental noise. The utility of early warning indicators is therefore at least partially related to their ability to predict both changes in stability and resilience, assuming a positive correlation between these two metrics (19, 36).

In practice, we need to observe changes in indicators before resilience and stability become so small that stochastic transitions occur (44, 45). Moreover, to take actions to reverse the environmental deterioration requires a sufficiently early detection of warning signals. The successful detection of warning signals is determined by many factors, such as the magnitude of external perturbations, the sampling frequency, etc. In our study, we find that the utility of warning signals also depends on a system's response to specific environmental drivers. Although different drivers are known to differ in their threat to populations or ecological systems, previous work has attributed that largely to the distance to bifurcation or the degree of deterioration, whereas we show that the intrinsic difference between environmental drivers is at least equally important. We expect more loss of stability and a larger increase in statistical indicators along a more convex path on the stability–resilience diagram (driver 1, Fig. 4A) than a concave path (drive 2). This observation does not depend on the location of the starting condition, i.e., distance from the bifurcation (*SI Appendix, Fig. S9A*). In addition, the shape of the stability–resilience relation determines how rapidly the critical slowing down indicators would increase as a function of loss of resilience under a specific driver. Along a concave curve, the slope becomes steeper near the bifurcation, so one might be tempted to think that the increase in indicators would become more visible immediately before the transition. However, we should be aware that warning indicators need to be observed before the deterministic bifurcation (*SI Appendix, Fig. S9B*), i.e., before a complete loss of resilience. Indeed, large environmental perturbations (e.g., external forcing events) can push populations below the critical level if the resilience is too small. Alternatively, extinctions can be triggered by repeated small perturbations due to environmental or demographic noise, and in this case, both stability and resilience need to be large to avoid stochastic extinction (*SI Appendix, Fig. S9C*). In both scenarios, however, changes in driver 1 lead to the greater loss of stability (i.e., stronger warning signals), given the same increase in the risk of extinction.

In addition to the difficulty of detecting warning signs in time, we should be aware of possible scenarios of false negatives. Failures of

indicators based on critical slowing down have been discussed in a few contexts (33–35, 46). To use changes in the pattern of fluctuations (or a decrease in recovery rate) to indicate loss of resilience is based on the assumption that there is a positive correlation between changes in stability and resilience. Our finding of anticorrelation under multiple drivers may seem nonintuitive, as we are accustomed to extrapolate the positive correlation near a bifurcation (as a result of critical slowing down) to conditions further away from the bifurcation. Such extrapolations have been supported by theoretical (19) and empirical (22, 24) work in various systems; however, previous studies largely ignored the possibility that more than one driver can be involved in environmental changes. Our analysis suggests that early warning signals may fail more frequently when two drivers are changed in opposite directions (for example, a wildlife population subject to continued habitat fragmentation but less killing by humans). In principle, even a single driver may cause loss of resilience with no decrease in stability (*SI Appendix, Text S3*), although we did not observe this in our system. We believe that understanding the limitation of our current toolbox of warning indicators will help us make better decisions on when and how to apply them.

One interesting question that begs future studies is how to use the stability–resilience analysis to inform the performance of indicators in other systems, where we usually cannot measure the stability–resilience relation directly or no parameterized model is available. It is worth noting that to map and compare stability–resilience curves does not require perfect knowledge of the system. For example, we simulated the stability–resilience relation under sucrose reduction by decreasing carrying capacity or decreasing the growth rate at low cell density, which is a crude approximation of how sucrose reduction affects growth of yeast cells. Nevertheless the model outputs were able to reproduce the qualitative pattern in experimental data. This suggests that perhaps one way to apply our analysis to other systems is through a model-based approach. Even for systems with relatively little information, models that only capture the structure of a system (47) may be sufficient to infer the stability–resilience relation. Moreover, studying a range of ecological models may inform us whether there is any general pattern between the type of environmental driver and the shape of stability–resilience relation, such as which drivers tend to allow strong warning signals.

To use the stability–resilience framework to study the dynamical behavior of complex systems, one important consideration is how to choose appropriate metrics. Defining resilience for systems with higher dimensions is not always straightforward, especially when the basin of attraction has a complex geometry (34). In our one-dimensional system (single species), we quantified resilience as the

distance between stable and unstable fixed points, which is the number of individuals a population with a strong Allee effect (48) can lose without going extinct deterministically. However, if perturbations are proportional to the total abundance, then the ratio between stable and unstable fixed points may be a more appropriate metric, which is essentially the distance between stable and unstable fixed points for log transformed abundance. The proper metric for resilience therefore depends on both the intrinsic properties of a system and also the nature of the environmental perturbations.

In our study, we find that the exact relation between recovery rate and the size of the basin of attraction is dependent on the environmental driver. This improves our understanding of when we may rely on knowledge about the local properties around equilibrium to infer changes in the global properties of a dynamical system. If we have some prior knowledge about a specific system, one strategy to look for warning indicators is to identify properties that change monotonically under environmental deterioration. For example, equilibrium population size will decline before a trans-critical bifurcation, so a small population can be considered as a warning signal. The motivation for ongoing studies on critical slowing down indicators, among many other warning signals, is to identify their potential as well as their limitations (26) and develop a toolbox of indicators. Investigations into other properties [e.g.,

resistance (49), reactivity (50, 51), invasiveness, etc.] and their relations will help us address a fundamental question: how to measure the “stability” of a system (52, 53). A better assessment of complex ecosystems may guide our efforts to avoid systemic risks of financial networks (54), engineer a healthy gut microbiota (55), and cope with regime shifts in the environment (9).

Materials and Methods

We grew the budding yeast *Saccharomyces cerevisiae* in 200 μ L batch culture at 30 °C using synthetic media supplemented with variable concentrations of sucrose (22). Serial dilutions were performed daily with variable dilution factors. Population densities were recorded each day by measuring optical density.

Statistical indicators were calculated at each observation time over an ensemble of replicate populations. We extracted stability and resilience from the daily growth profile of yeast populations. Simulations were based on a phenomenological model of yeast populations with two phases of daily growth: a slow exponential growth phase at low cell densities, followed by a logistic growth phase with a higher per capita growth rate at intermediate cell densities. Full details are available in *SI Appendix, Supplementary Methods*.

ACKNOWLEDGMENTS. The authors thank D. Vorselen, M. Villarreal, and J. Friedman for insightful discussions and help collecting preliminary data. E. Yurtsev, A. Conwill, and members of the Gore laboratory provided helpful comments on the manuscript. This work was supported by an NIH New Innovator Award (NIH DP2).

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