

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed
☐	☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒ The statistical test(s) used AND whether they are one- or two-sided <i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>
☒	☐ A description of all covariates tested
☒	☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted <i>Give P values as exact values whenever suitable.</i>
☐	☒ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	N/A
Data analysis	All analysis are performed in R 4.4.1. Foundational data import, cleaning, and manipulation are performed using the "tidyverse" suite (v2.0.0), with specific capabilities for reading Excel files provided by "readxl" (v1.4.3). To ensure project portability, file paths are managed with the "here" package (v1.0.1), and all date-time data is systematically handled by "lubridate" (v1.9.4). The graphical visualization process, centered on ggplot2, is significantly enhanced by a collection of specialized packages: "patchwork" (v1.3.0) is used to combine multiple plots into cohesive arrangements, "ggtext" (v0.1.2) enables rich text formatting within graphics, and advanced visual modifications are achieved through "ggh4x" (v0.2.8) for facet and scale customization and "ggblend" (v0.1.0) for sophisticated layer blending. The analytical core of the project relies on the "tidymodels" framework (v1.2.0) for statistical modeling and the "ecoModelOracle" package (v0.1.0; available on https://github.com/clsong/ecoModelOracle) for covariance criteria analyses. Finally, computational performance is optimized by implementing parallel processing with "furrr" (v0.3.1) to accelerate demanding calculations.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

Empirical data of aquatic invertebrate and the green algae is available from <https://www.nature.com/articles/s41586-019-1857-0>. Empirical dataset of consumer-resource dynamics is available from <https://onlinelibrary.wiley.com/doi/full/10.1111/ele.12291>.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender [Human participants, their data, or biological material are not involved in our research.](#)

Reporting on race, ethnicity, or other socially relevant groupings [Human participants, their data, or biological material are not involved in our research.](#)

Population characteristics [Human participants, their data, or biological material are not involved in our research.](#)

Recruitment [Human participants, their data, or biological material are not involved in our research.](#)

Ethics oversight [Human participants, their data, or biological material are not involved in our research.](#)

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Our study introduces and applies a novel method, termed the covariance criteria, for the rigorous validation of ecological models against time series data. This approach, rooted in queueing theory, establishes a test based on the covariance relationships between a species' abundance and its model-defined gain and loss rates. We demonstrate the method's utility by applying it to test competing models across three long-standing ecological challenges: the functional form of predator-prey interactions, the role of rapid evolution in population dynamics, and the detection of higher-order interactions.
Research sample	To test our theoretical approach, we use published time series data on species abundances from various ecological systems. The datasets are drawn from several key sources cited in the literature, including a long-term, replicated dataset of an aquatic predator-prey system, a compilation of consumer-resource time series from diverse ecosystems, a long-term dataset of a rocky intertidal community in New Zealand, and a curated subset of single-species time series from the Global Population Dynamics Database.
Sampling strategy	The core of our analysis is the application of the covariance criteria. For a given ecological model and a species' time series, we partition the model's dynamics into terms representing the total gain rate and loss rate. We then calculate the normalized covariances of these inferred rates with the observed species abundance over the time series. The model is considered valid if the normalized covariance of the gain rate with abundance is equal to the normalized covariance of the loss rate with abundance. To assess statistical uncertainty and test this equality, we employ a bootstrapping approach, where we repeatedly resample the time series data with replacement to generate distributions for the two normalized covariance terms.
Data collection	This study involves the analysis of pre-existing, published data. We did not perform new experiments or field observations. The specific data collection protocols for each dataset are detailed in the original publications from which the data were obtained.
Timing and spatial scale	The timing and spatial scale of the data vary across the different studies we analyzed. For example, the rocky intertidal community data were collected monthly over a period of more than 20 years at a single location. The consumer-resource datasets are typically from laboratory microcosm experiments with frequent sampling over many generations. The Global Population Dynamics Database datasets represent a wide variety of sampling frequencies and durations from many distinct locations.

Data exclusions	Our analysis requires time series of sufficient length and quality to reliably estimate covariance. For the meta-analysis of single-species dynamics, we explicitly used a curated subset of the Global Population Dynamics Database, which excludes time series that are too short or noisy for robust analysis. For other analyses, we relied on datasets previously established in the literature as being of high quality for studying population dynamics.
Reproducibility	The analyses presented are reproducible. The primary data sources are publicly available and are referenced with citations and, where possible, URLs in the manuscript. All computational methods and statistical analyses were performed using our custom R package, ecoModelOracle, which is publicly available on GitHub.
Randomization	This is a computational study based on observational and experimental data, so there was no randomization of subjects to experimental treatments. However, randomization is a key component of our statistical procedure. We use bootstrapping, which involves repeatedly drawing random samples (with replacement) from the original time series, to generate distributions of our test statistic and quantify uncertainty.
Blinding	Not applicable because published data were used and we did not perform experiments or observations.
Did the study involve field work?	☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	Not applicable because published data were used and we did not perform experiments or observations.
Novel plant genotypes	Not applicable because published data were used and we did not perform experiments or observations.
Authentication	Not applicable because published data were used and we did not perform experiments or observations.