

Opinion

Ecosystem synchrony: an emerging property to elucidate ecosystem responses to global change

Chloé Vagnon ^{1,*}, Julian D. Olden ², Stéphanie Boulêtreau ¹, Rosalie Bruel ^{3,4},
Mathieu Chevalier ⁵, Flavien Garcia ¹, Gordon Holtgrieve ², Michelle Jackson ⁶, Elisa Thebault ⁷,
Pablo A. Tedesco ¹, and Julien Cucherousset ¹

Understanding ecosystem responses to global change have long challenged scientists due to notoriously complex properties arising from the interplay between biological and environmental factors. We propose the concept of ecosystem synchrony – that is, similarity in the temporal fluctuations of an ecosystem function between multiple ecosystems – to overcome this challenge. Ecosystem synchrony can manifest due to spatially correlated environmental fluctuations (Moran effect), exchange of energy, nutrients, and organic matter and similarity in biotic characteristics across ecosystems. By taking advantage of long-term surveys, remote sensing and the increased use of high-frequency sensors to assess ecosystem functions, ecosystem synchrony can foster our understanding of the coordinated ecosystem responses at unexplored spatiotemporal scales, identify emerging portfolio effects among ecosystems, and deliver signals of ecosystem perturbations.

Ecosystem dynamics under global change

The Anthropocene is an era of unprecedented planetary upheaval, associated with rapid biodiversity loss [1] and dramatic changes in **ecosystem functioning** (see [Glossary](#)) [2]. Understanding and anticipating ecosystem responses in the future, however, remains hampered by the fact that environmental perturbations are acting across different levels of biological organization, at multiple spatial extents (e.g., local, regional, or global), and with varying magnitudes, durations, and frequencies. Meeting this challenge requires studying ecological dynamics through a prism that illuminates the processes driving the conversion and translocation of energy and materials in ecosystems over time [3].

Ecosystem processes are the complex physical, chemical, and biological interactions that link organisms to their environment, culminating in what are known as emergent properties [4]. Despite considerable research, our mechanistic understanding of these entangled interactions is still often limited. This has led to calls for more dedicated investigations of ecosystem function dynamics, referring to the performance of an ecosystem resulting from one or multiple ecosystem processes operating over time [5]. Although quantifying the impacts of global change on ecosystem functioning across space and time is associated with well-recognized challenges, scientists answering this call will be better poised to predict the future state of ecosystems.

Spatial synchrony has been the focus of increasing attention when studying the long-term persistence of populations and community stability in response to global change [6–8]. During the past

Highlights

Global change induces multiple perturbations that can directly and indirectly affect the dynamic of ecosystems. To date, studies have primarily focused on ecological responses at lower levels of biological organization using population and community synchrony.

Ecosystem synchrony, that is, the similarity in the temporal fluctuations of an ecosystem function between multiple ecosystems, is an emergent property of ecosystems that is affected by the interplay between biotic and abiotic dynamics.

Ecosystem synchrony represents an integrative approach to quantify the spatial and temporal extents of the coordinated ecosystem responses to natural and human-induced perturbations. It opens avenues for advances in studies on ecological dynamics which could ultimately deliver future advanced warning methods and actionable management.

¹Centre de Recherche sur la Biodiversité et l'Environnement (CRBE), Université de Toulouse, CNRS, IRD, Toulouse INP, Université Toulouse 3 – Paul Sabatier (UT3), Toulouse, France

²School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98105, USA

³OFB, DRAS, Service EcoAqua, Aix-en-Provence, France

⁴Pôle R&D ECLA, Aix-en-Provence, France

⁵IFREMER-DYNECO-LEBCO, Centre de Bretagne, CS 10070, 29280 Plouzané, France

⁶Department of Biology, University of Oxford, Oxford, OX1 3SZ, UK



50 years, scientific investigations of population synchrony have helped to better understand the effects of environmental perturbations on population dynamics and related risks to species extinction [9–11]. Changes to population synchrony have also been shown to scale up to higher organizational levels, for instance by impacting community structure and persistence, ultimately affecting meta-population and meta-community stability [6,8,12–14]. Despite providing substantial insights into the ecology of species, much less attention has focused on the critical emergent properties of ecosystems, including dynamic responses expressed over multiple spatial and temporal scales. To address this need, the present study seeks to advance the concept of **ecosystem synchrony**. Specifically, we demonstrate how ecosystem synchrony may represent a powerful and integrative property to understand the spatiotemporal extents of coordinated ecosystem dynamics that emerge from the complex interplay between biotic and abiotic factors.

Ecosystem synchrony to understand ecological dynamics

We define ecosystem synchrony as the similarity in the temporal fluctuations of a given ecosystem function among multiple ecosystems. Ecosystem synchrony is characterized by the direction and the magnitude of the variations in this ecosystem function (Box 1) [11]. Two ecosystems can display positive synchrony (i.e., ecosystem function dynamics are in-phase), negative synchrony (i.e., ecosystem function dynamics are out-of-phase), or asynchrony (i.e., nonsimilarity in the fluctuations) (Box 2). Following ecological theory and previous investigations on population and community synchrony [14–16], we hypothesize that positive ecosystem synchrony will be more likely with increasing biotic and abiotic similarity among ecosystems.

Ecosystem synchrony is expected to emerge from three primary mechanisms: (i) the **Moran effect** [10] which is caused by spatially autocorrelated fluctuations in environmental conditions (e.g., climatic conditions); (ii) the fluxes of energy, nutrients, and organic matter between ecosystems, including the dispersal of organisms that, through their response traits, drive critical functions in ecosystems [17]; and (iii) similarities in biotic characteristics that describe the number, the nature (e.g., predatory and mutualistic), and the strength of interactions between organisms which are known to influence the above-mentioned fluxes [18]. Consequently, ecosystem synchrony ultimately emerges from the synchrony found in hydrological, geomorphological, and biogeochemistry processes [11,19] and in biological dynamics at lower levels of biological organization (e.g., populations and communities [8,13,14]). Ecosystem synchrony is thus embedded within the **meta-ecosystem** framework because it integrates the ideas of shared environmental conditions and fluxes between ecosystems [20–22].

Investigating ecosystem synchrony can help enhance our knowledge of the underlying mechanisms driving ecological dynamics [23]. From a conceptual perspective, ecosystem synchrony represents a level of aggregation that allows addressing changes in both additive (e.g., sum of all species biomass in an ecosystem) and nonadditive (e.g., water use efficiency) ecosystem properties. Previous studies on metacommunity stability have already discussed the concept of spatial synchrony regarding additive properties [6,8], suggesting that similar results could be obtained regardless of the level of aggregation (i.e., at community or ecosystem level). The concept of ecosystem synchrony should apply more broadly (and depart more strongly from the concept of community synchrony) to nonadditive ecosystem properties owing to the complex interplay between biotic and abiotic factors and the fluxes of energy, nutrients, and organic matter that are difficult to represent solely using lower levels of biological organization. These properties cover primary productivity, nutrient cycling, recycling, and stocking of organic and mineral matters processed in soil, sediment, water, and at their interface [24]. From a more practical perspective, it can be challenging to account for all the organisms involved in a particular ecosystem process, such as the entirety of food web to assess energy fluxes or the complete microbial

⁷Sorbonne Université, CNRS, IRD, INRAE, Université Paris Est Créteil, Université Paris Cité, Institute of Ecology and Environmental Science (IEES), Paris, France

*Correspondence: chloe.vagnon@gmail.com (C. Vagnon).

community involved in matter recycling, whereas ecosystem synchrony can be derived from integrative monitoring and quantification of ecosystem functions. For example, the recycling of organic matter can be investigated using measurements of decomposition rates, variations in nitrogen or phosphorus concentrations, and gas exchange (e.g., methane and CO₂) at the interface between sediments and the water column or in soils [25,26]. Alternatively, ecosystem functions can be inferred indirectly. For instance, measurements of the diel cycle of dissolved oxygen (O₂) concentration in aquatic ecosystems reflects the overall contribution of heterotrophic and autotrophic organisms to ecosystem metabolism [27].

Ecosystem synchrony represents a novel opportunity to investigate the spatial extent of coordinated ecosystem dynamics which was originally addressed through approaches such as distance-decay of synchrony among populations [9,15]. While comparing ecological synchrony between populations and communities from different types of ecosystems and from different realms can be challenging due to taxonomic and functional traits differences, ecosystem synchrony provides a new way for comparing ecosystems across space. For instance, ecosystem metabolism can be calculated based on changes in O₂ and CO₂ concentrations to reflect the relative balance between primary production and heterotrophic respiration in all ecosystem types [4,28]. While ecological synchrony measured at lower levels of biological organization is a long-standing history thanks to long-term monitoring programs (e.g., BioTIME database; [29]), the quantification of ecosystem synchrony is now possible thanks to the development of spatially extensive programs that monitor ecosystem functions. This includes broad sensor arrays and large-scale deployment of remote sensing approaches (e.g., satellite images) (Figure 1) [30] allowing the measurement of ecological parameters relevant to ecosystem functions at large scale.

Ecosystem synchrony also provides a unique opportunity to assess the temporal extent of coordinated ecosystem dynamics by studying changes in ecosystem functioning at variable time scales (e.g., hours, days, months, seasons, and years) which are paramount to address new questions related to the stability, resilience, and resistance of ecosystems [31]. The methodology and sensors used to collect time series of ecosystem functions and investigate levels of synchrony can be adjusted regarding their duration and frequency to follow the characteristics of the studied function and the time scale of interest (Box 2). For instance, data collected from remote sensing or monitoring programs that span several decades can be used to explore long-term changes (e.g., under press perturbations) on ecosystem synchrony. The use of sensor arrays that collect high frequency data (Figure 1C) usually over shorter time periods, can shed light on near-term changes on synchrony patterns (e.g., under pulse perturbations). Overall, the frequency, duration and spatial scale at which data can be made available through emerging technologies [32,33] must warrant revisiting existing notions but also open avenues to investigate emerging questions in ecology. These advances can provide new insights regarding the time scale at which some ecological processes (e.g., hourly or diurnal variations in O₂ concentrations) change relative to what is known from low-frequency historical data that are classically used in population and community synchrony analyses [9,14].

Alteration of ecosystem synchrony by perturbations

Heightened focus on the coupled spatiotemporal dimensions of ecosystem functioning provided by ecosystem synchrony is a marked departure from long-standing investigations of single ecosystem responses to a given perturbation [31]. Explicit consideration of multiple ecosystems provides opportunities to identify the spatial extent of perturbations affecting ecosystem dynamics, and can help highlight temporal divergences in the natural cycles of ecosystem functioning (i.e., temporal extent) that are challenging to address when studying ecosystems in isolation [16,20,21]. In addition, ecosystem synchrony may help pinpoint **portfolio effects** [34] offered

Glossary

Desynchronization: decreasing of the initial degree of ecosystem synchrony between two ecosystems.

Ecosystem functioning: physical, chemical and biological processes in an ecosystem resulting from the total activity of biodiversity therein (e.g., decomposition, metabolism, and energy flows).

Ecosystem synchrony: similarity in the temporal fluctuations of an ecosystem function between multiple ecosystems.

Frequency (in signal analyses): number of events of a reiterating pattern per unit of time.

Meta-ecosystem: group of ecosystems related by flows of energy, materials and organisms across ecosystems (i.e., includes all kinds of spatial flows among systems) and/or submitted to the same environmental conditions.

Moran effect: synchrony in biological dynamics across several sites due to positive covariations in temporal fluctuations in the environment.

Period (in signal analyses): the shortest duration after which the elementary pattern reproduces itself identically.

Portfolio effect: ecosystem fluctuations are compensated by heterogeneous responses at the meta-ecosystem level, allowing for overall stability in the face of perturbation.

Synchronization: increasing of the initial degree of synchrony between two ecosystems.

Box 1. A vocabulary for ecosystem synchrony

Ecosystem synchrony can be characterized by considering the direction and the amplitude of variations when comparing a time series from two ecosystems. Positive ecosystem synchrony corresponds to the synchrony of an ecosystem function between two ecosystems exhibiting in-phase dynamics (Figure 1A,B). By contrast, negative ecosystem synchrony corresponds to the synchrony of an ecosystem function between two ecosystems exhibiting out-of-phase dynamics (i.e., inverse trends in the function of interest) (Figure 1C,D). In both cases, the magnitude of the dynamic of a given ecosystem function can either be similar (Figure 1A,C) or different (Figure 1B,D), ultimately contributing to the degree of ecosystem synchrony.

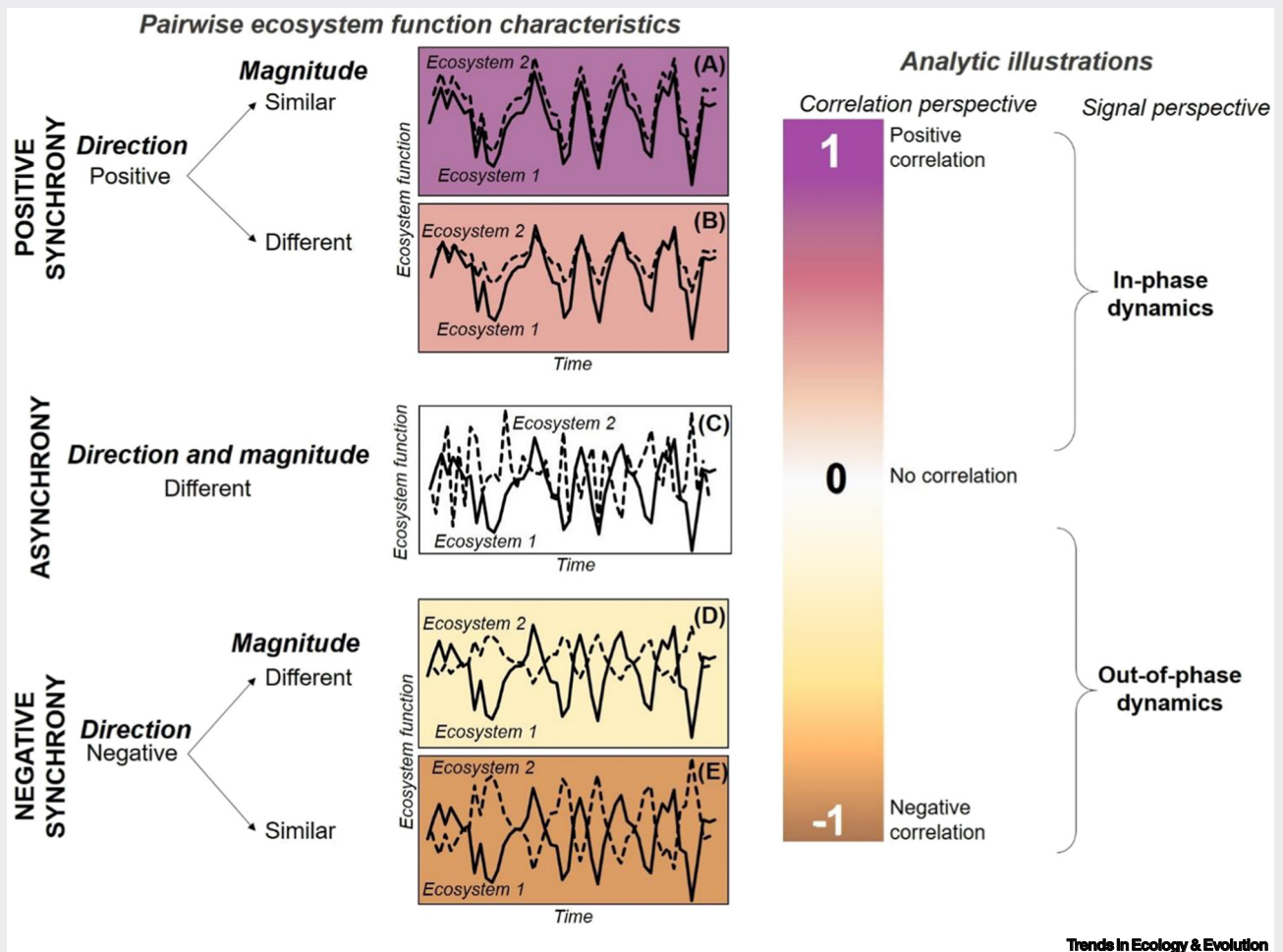


Figure 1. Vocabulary of ecosystem synchrony (A, B, D, E) and asynchrony (C) based on the direction and magnitude of the dynamic fluctuations of the same ecosystem function measured in two ecosystems (broken and unbroken lines). Synchrony/asynchrony are illustrated using a correlation with: 1 = highest positive synchrony with highly similar amplitude, -1 = highest negative synchrony with highly similar amplitude and 0 = asynchrony. In signal analyses, positive correlations represent in-phase dynamics, while negative correlations represent out-of-phase dynamics.

by multiple ecosystems facing perturbations. In fact, the averaging of ecosystem functions across meta-ecosystems might promote variance dampening in ecosystem functioning across large time scales, thus enhancing stability at the meta-ecosystem scale. Overall, the use of ecosystem synchrony represents a promising approach to unravel coordinated ecosystem responses to global change, to identify the alteration drivers and paths by which local ecosystem functioning influences ecosystem stability at larger scales [14,16] and to provide warning signals allowing to anticipate profound ecosystem changes [35,36].

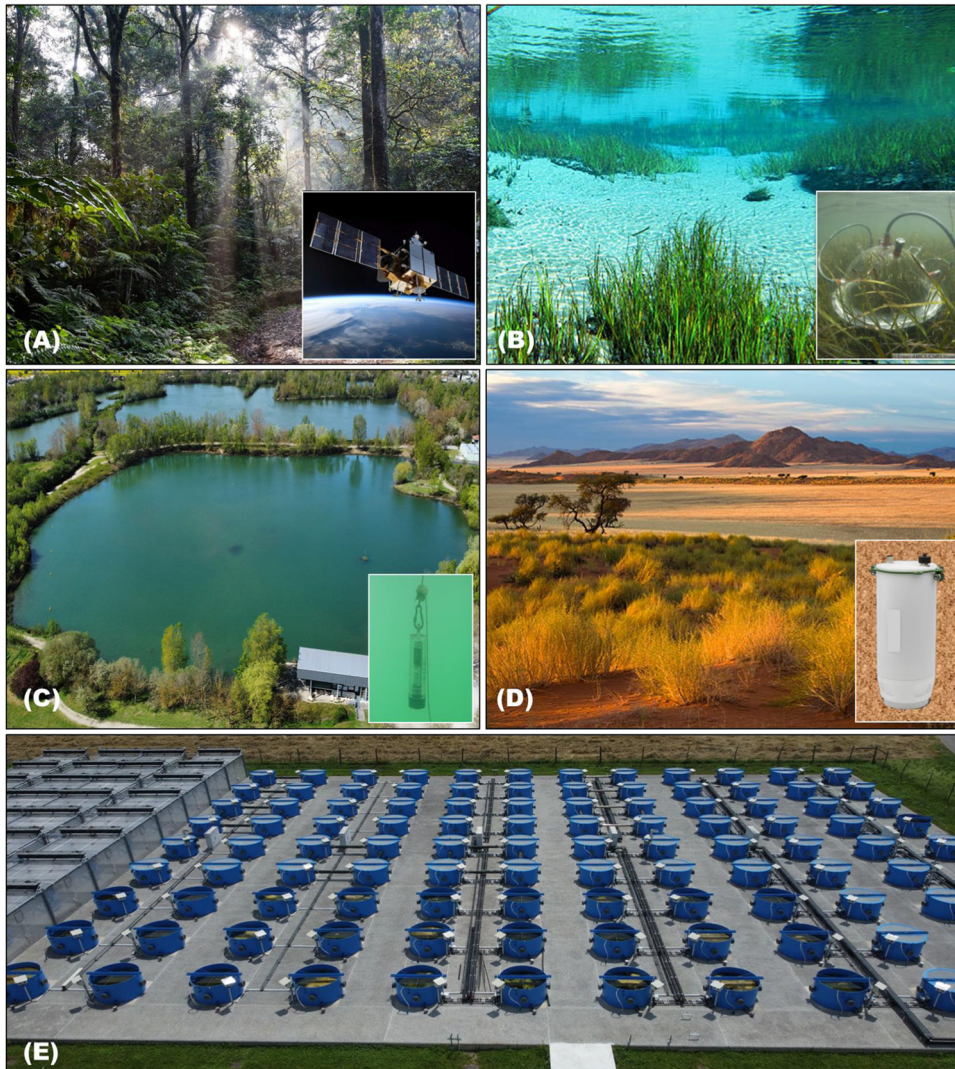
Box 2. Quantifying ecosystem synchrony

Aligned with previous investigations of population and community synchrony, a standardized estimate of ecosystem synchrony can be quantified using correlative methods (e.g., Spearman’s correlation) to indicate out-of-phase dynamics (i.e., negative correlation coefficient) versus in-phase dynamics (i.e., positive correlation coefficient) (Table I). This approach is sensitive to the nonlinearity and/or the nonmonotony of the relationship and should preferentially be used in preliminary investigations with time series of similar lengths. These limitations can be overcome using other approaches such as dynamic time warping that aims at aligning time series across all feasible temporal alignments. Dynamic time warping can manage time distortions and varying velocity in dynamic changes found in time-dependent data [45]. In addition, time series of ecosystem functions represent temporal signals characterized by their **period** and their **frequency**. Time series can be transformed in the frequency domain to identify temporal patterns in signals detectable at different temporal scales using methods such as wavelet analyses. Wavelet analyses help to highlight different levels of synchrony depending on the frequency of variation considered (e.g., hourly or seasonal variations). Finally, autoregressive models such as multivariate autoregressive state–space models (MARSS) [46] that consider the temporal autocorrelation in the processes hidden in observed time series can also be used to estimate the magnitude and drivers of synchrony (Table I). These two last methods are well adapted to long-term time series (i.e., monitoring programs) and/or time series with a high frequency of measurement (i.e., sensor arrays), ultimately paving the way toward a finer scale of analysis of ecosystem dynamics.

Table I. Methodological approaches to quantify ecosystem synchrony

Type of analysis	Description and application for ecosystem synchrony
Correlation and crosscorrelation [37,47–50]	Measures monotonous linear (Pearson) or nonlinear (Spearman) similarity between two time series Facilitates comparison among different studies Accounts for the entire time series or across a sliding time window Reveals time-lags relationships using cross-correlation statistics Example: identify the strength and direction of changes in the covariation of an ecosystem function between ecosystems
Dynamic time warping [51,52]	Computes the minimum path (distance) between two time series based on the temporal matching of similar elements Provides reliable estimates of the association between time series, especially when they differ in shape and phase Suit for analyzing time series with different lengths Example: identify the ecosystem synchrony from time series with different frequency of sampling
Wavelet analyses [53–55]	Converts time series from a time-value system to a timescale (frequency) system, thus computing an analysis of frequency change in the time domain Allows to quantify the period of the synchrony and handle multiple periods (e.g., both short-term and long-term synchrony in a signal) Simultaneously extracts local spectral and temporal information from the time series Example: identify the different temporal extent at which ecosystem synchrony is impacted
Auto-regressive models (e.g., MARSS) [56–58]	Class of dynamic linear model and vector autoregressive model that directly models temporal autocorrelation Tests the effect of various factors on synchrony to identify process and mechanisms Detects time lags in synchrony Example: discriminate anthropogenic mechanisms from natural mechanisms modifying ecosystem functioning after identifying synchrony in the hidden processes of their dynamics

Global change can affect ecosystem synchrony through modifications of physical (e.g., temperature) and chemical (e.g., pollution) environmental conditions, together with changes in biotic components. The biotic characteristics of ecosystems can be altered through mechanisms such as community reassembly (e.g., native species replacement by non-native species), dispersal limitation caused by habitat fragmentation, changes in species interactions, or biomass redistribution across trophic levels (e.g., overexploitation of top predators) [15,37–39]. These changes may directly and indirectly modify biochemical cycles, energy conversion and energy fluxes within and among ecosystems, influencing the initial level of synchrony between



Trends in Ecology & Evolution

Figure 1. High-frequency monitoring to assess ecosystem functions. (A) Satellite remote sensing to measure primary production in forests. (B) Benthic incubation cloche to quantify gas exchanges between the sediment and the water column. (C) Autonomous dissolved oxygen sensor to measure lake metabolism. (D) CO₂ flux sensor to measure soil respiration in savannah. (E) Dissolved oxygen sensor to assess ecosystem metabolism in experimental mesocosms (Aquatic Metatron, Moulis, France). (B, C, and E) Image source: CNRS. (D) Sensor image source: <https://www.campbellsci.ca/eosfd>.

ecosystems. In some cases, perturbations can induce **desynchronization** of ecosystems (i.e., decreasing in the initial level of synchrony) that can ultimately lead to their asynchrony. In other cases, these perturbations can lead to the **synchronization** (i.e., increasing in the initial level of synchrony) of ecosystems that originally displayed limited level of synchrony.

The alteration of ecosystem synchrony can be detected via changes in the amplitude of the dynamics of an ecosystem function (Figure 2A) [37]. For example, heat waves can cause abrupt increases in O₂ consumption [40], ultimately modifying the hourly amplitude of the balance between CO₂ and O₂ without altering the diurnal frequency of the lake metabolism cycle. Synchrony

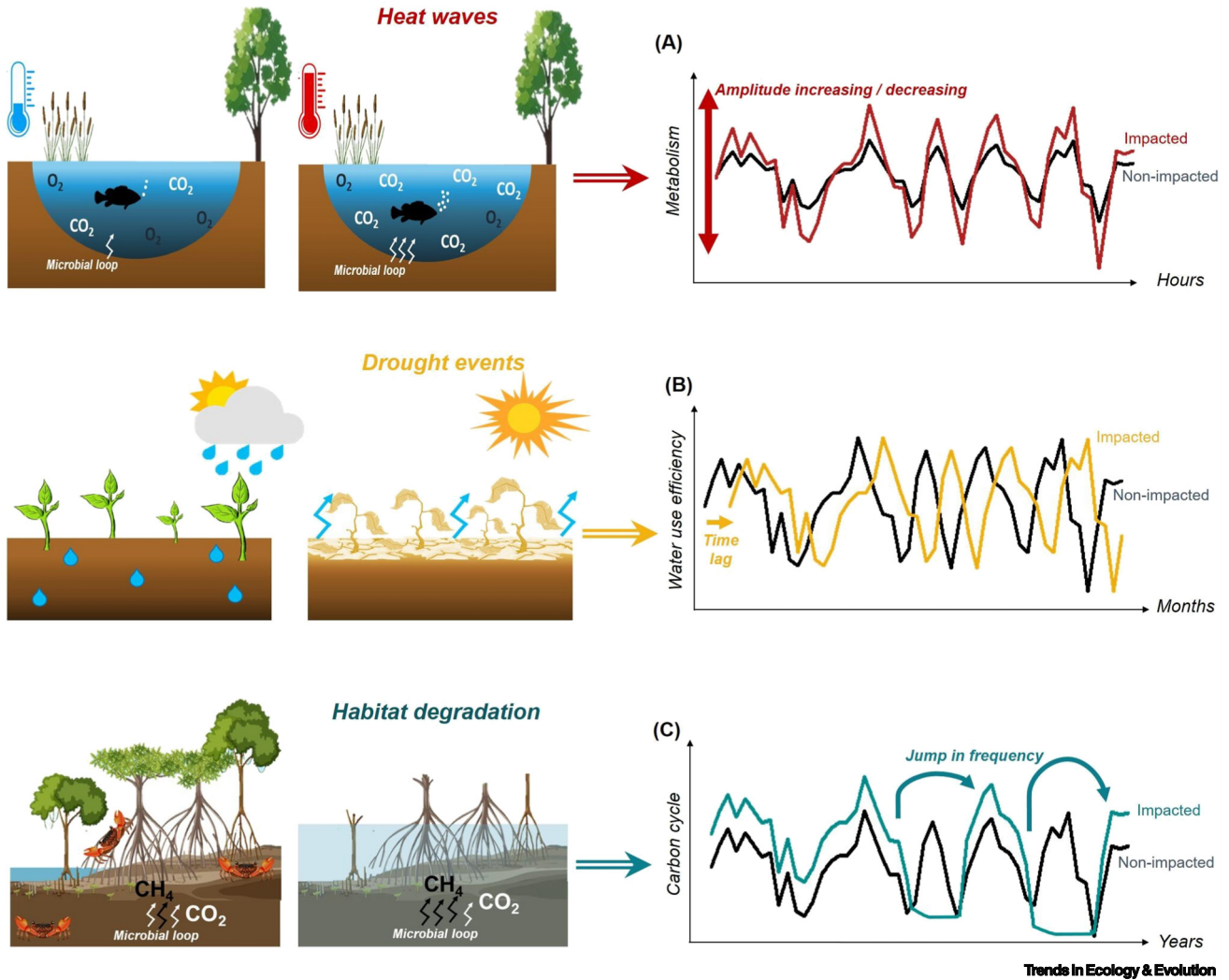


Figure 2. Using ecosystem synchrony to assess the spatial and temporal extents of the impacts of global change on ecosystems. Different examples of desynchronization induced by global change factors such as (A) heat waves [40], (B) drought events [41], and (C) habitat degradation [43]. In these illustrations, metabolism is a proxy of the balance between respiration and oxygen production, water use efficiency is the balance between gross primary productivity and evapotranspiration, and carbon cycle is a simplification of the balance between fixed and released carbon and methane. These examples are defined in the case of a positive initial synchrony (with similar amplitude and mean of the time series) of a given ecosystem function between two ecosystems: a reference ecosystem (in black) and an impacted ecosystem (colored).

alteration can also emerge from a time lag in the dynamics of an ecosystem function (Figure 2B). For instance, Ji *et al.* [41] demonstrated that drought events can induce a time lag of several months in the water use efficiency of terrestrial ecosystems at the global scale. Lastly, synchrony alteration can be detected from changes in the frequency of variations in a given ecosystem function (Figure 2C) [42]. For example, seasonal carbon flows in mangroves during the wet, dry and windy seasons are altered by human-induced flooding of mangroves, triggering decreases in CO₂ emissions and increases in methane emissions through amplified methanogenesis [43]. These examples highlight that ecosystem synchrony can provide significant advances to understand the mechanisms (e.g., biotic changes at lower levels of biological organization) and the time scale associated to the alteration of ecosystem functioning.

Finally, the alteration of ecosystem synchrony by a perturbation can exhibit different temporal persistence and thus have varying consequences for ecosystem dynamics. Ecosystems hypothesized to exhibit high levels of synchrony (e.g., spatially close with same environmental constraints) can already be desynchronized by ongoing perturbations when analyzing the time series (Box 3). In this case, it is not possible to assess the dynamic of desynchronization. Differently, when the alteration of ecosystem synchrony occurs during ecosystem monitoring, its duration can vary, reflecting different consequences of perturbations on ecosystem dynamics. In some cases, the phase of alteration of ecosystem synchrony can be transitory and ecosystems return to their original level of synchrony, demonstrating their resilience [31]. In other cases, the alteration of ecosystem synchrony can last despite removing the perturbation which can reflect a change in ecosystem state (i.e., regime shift) [44].

Box 3. Ecosystem synchrony in a lake meta-socio-ecosystem

In south-western France, a network of gravel pit lakes located within 250 km² (Figure 1A) faces variable levels of anthropic perturbations such as biological invasions [59], recreational fisheries [60,61] and production of renewable energies [62]. This lake network represents a meta-socio-ecosystem [63] that provides an opportunity to determine whether the level of ecosystem synchrony differs between geographically close ecosystems. Lakes are equipped with high-frequency sensors quantifying the concentration of dissolved oxygen (see illustration in Figure 1C in main text). These data were used to calculate the synchrony (correlation) in dissolved O₂ concentration in three lakes located 50 km apart and facing similar climatic conditions. Interestingly, these lakes can exhibit strong positive synchrony (Lakes 1 and 2; $\rho = 0.68$, $P < 0.001$), negative synchrony (Lakes 1 and 3; $\rho = -0.11$, $P < 0.05$), or asynchrony (Lakes 2 and 3; $\rho = 0.04$, $P = 0.45$) (Figure 1B). This preliminary observation supports the idea that ecosystem synchrony is not driven only by the spatial distance or the environmental similarity between lakes and could be influenced by local perturbations or local differences in biotic settings (e.g., difference in community composition). Investigating ecosystem synchrony could allow understanding the mechanisms driving shifts in ecosystem functioning and provide robust basis to improve freshwater ecosystem management at the meta-socio-ecosystem level by identifying lakes, or group of lakes, displaying similar synchrony levels. It could also provide new perspectives to understand the additivity, synergy, or antagonism of the impacts caused by local (e.g., fish stocking, floating photovoltaic, pollution), regional (e.g., heat waves, biological invasion), and global (e.g., climate imbalance) environmental changes on ecosystem properties.

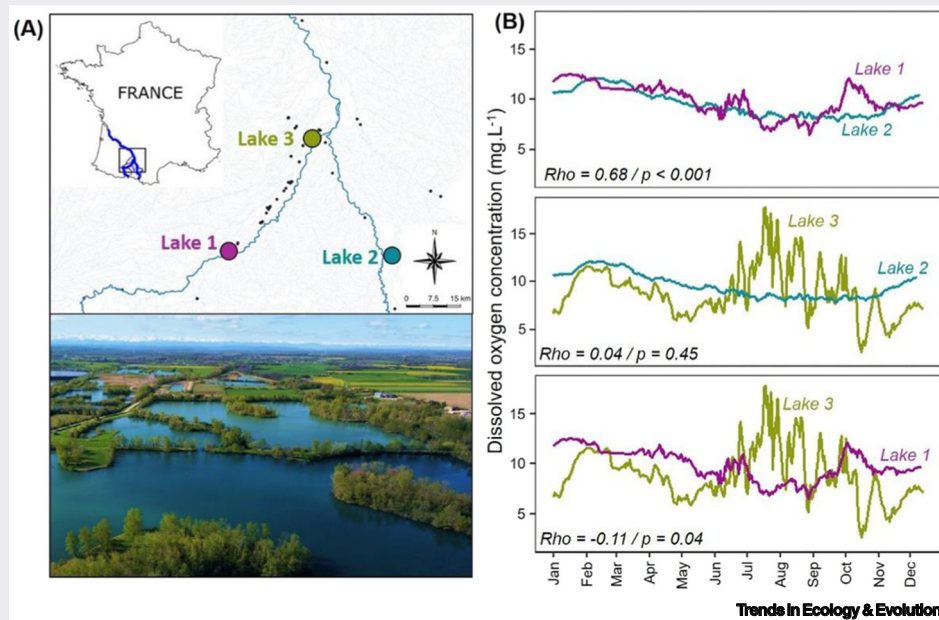


Figure 1. Different levels of ecosystem synchrony between lakes. (A) Geographical distribution of the three studied lakes and aerial picture of a network of gravel pit lakes in south-western France, and (B) temporal dynamic in daily dissolved oxygen concentrations monitored in the three studied lakes in 2023 using high frequency sensors. The correlation between each pair of lakes is provided in each panel.

Concluding remarks

Ecosystem synchrony is an emerging property to better understand coordinated ecosystem dynamics and quantify the multidimensional impacts of global environmental changes on ecosystem functioning. We propose that it opens new avenues of research into the causes and consequences of ecological dynamics operating across diverse environmental gradients (see [Outstanding questions](#)). From a theoretical perspective, ecosystem synchrony may shed light on the mechanisms driving ecosystem dynamics and their coordinated responses, ultimately improving our ability to understand ecosystem stability beyond local contexts and at finer temporal resolution than in previous studies. From more applied perspectives, ecosystem synchrony may help identifying the drivers and the persistence of ecosystem alterations. The level of ecosystem synchrony may depend on the nature of ecosystems, the amount of fluxes across them and the geographic bounds defined for their comparison, which could be more challenging to identify in specific instances (e.g., what strictly characterizes the limit between two forests?). As a consequence, the manner in which ecosystem synchrony (or asynchrony) promotes or deteriorates meta-ecosystem stability desires further inquiry.

Author contributions

All authors conceptualized this work. C.V. and J.C. drafted the first version of the manuscript. All authors contributed to discussions on article content and contributed to the editing and reviewing processes.

Acknowledgments

We are grateful to Shaopeng Wang, Stefano Larsen, and a third anonymous reviewer for their comments that greatly improved this manuscript. This work was funded by French Laboratory of Excellence project 'TULIP' (ANR-10-LABX-41; ANR-11-IDEX-002-02) through the EcoSync project and by the Office Francais de la Biodiversité (OFB) through the STABLELAKE project. This work is part of FUNELAKES (grant no. IRP 00020) and of the long-term Studies in Ecology and Evolution (SEE-Life) program of the CNRS.

Declaration of interests

No interests are declared.

References

- Diaz, S. *et al.* (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 366, eaax3100
- Oliver, T.H. *et al.* (2015) Biodiversity and resilience of ecosystem functions. *Trends Ecol. Evol.* 30, 673–684
- Pettorelli, N. *et al.* (2018) Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward. *Remote Sens. Ecol. Conserv.* 4, 71–93
- Odum, H.T. (1956) Primary production in flowing waters. *Limnol. Oceanogr.* 1, 102–117
- Lovett, G.M. *et al.* (2006) Ecosystem function in heterogeneous landscapes. In *Ecosystem function in heterogeneous landscapes* (Lovett, G.M. *et al.*, eds), pp. 1–4, Springer
- Erős, T. *et al.* (2020) Effects of nonnative species on the stability of riverine fish communities. *Ecography* 43, 1156–1166
- Heino, M. (1998) Noise colour, synchrony and extinctions in spatially structured populations. *Oikos* 83, 368
- Wilcox, K.R. *et al.* (2017) Asynchrony among local communities stabilises ecosystem function of metacommunities. *Ecol. Lett.* 20, 1534–1545
- Liebold, A. *et al.* (2004) Spatial synchrony in population dynamics. *Annu. Rev. Ecol. Syst.* 35, 467–490
- Moran, P. (1953) The statistical analysis of the Canadian Lynx cycle. *Aust. J. Zool.* 1, 291–298
- Seybold, E.C. *et al.* (2022) A classification framework to assess ecological, biogeochemical, and hydrologic synchrony and asynchrony. *Ecosystems* 25, 989–1005
- Lamy, T. *et al.* (2019) Species insurance trumps spatial insurance in stabilizing biomass of a marine macroalgal metacommunity. *Ecology* 100, e02719
- Walter, J.A. *et al.* (2024) Spatial synchrony cascades across ecosystem boundaries and up food webs via resource subsidies. *Proc. Natl. Acad. Sci. U. S. A.* 121, e2310052120
- Wang, S. *et al.* (2019) Stability and synchrony across ecological hierarchies in heterogeneous metacommunities: linking theory to data. *Ecography* 42, 1200–1211
- Hansen, B.B. *et al.* (2020) The Moran effect revisited: spatial population synchrony under global warming. *Ecography* 43, 1591–1602
- Wang, S. and Loreau, M. (2014) Ecosystem stability in space: alpha, beta and gamma variability. *Ecol. Lett.* 17, 891–901
- Moore, J.W. and Olden, J.D. (2017) Response diversity, nonnative species, and disassembly rules buffer freshwater ecosystem processes from anthropogenic change. *Glob. Change Biol.* 23, 1871–1880
- Vandvik, V. *et al.* (2020) Biotic rescaling reveals importance of species interactions for variation in biodiversity responses to climate change. *Proc. Natl. Acad. Sci. U. S. A.* 117, 22858–22865
- Chalise, D.R. *et al.* (2023) Spectral signatures of flow regime alteration by dams across the United States. *Earths Future* 11, e2022EF003078
- Loreau, M. *et al.* (2003) Meta-ecosystems: a theoretical framework for a spatial ecosystem ecology. *Ecol. Lett.* 6, 673–679
- Gravel, D. *et al.* (2010) Patch dynamics, persistence, and species coexistence in metaecosystems. *Am. Nat.* 176, 289–302
- Gounand, I. *et al.* (2018) Meta-Ecosystems 2.0: rooting the theory into the field. *Trends Ecol. Evol.* 33, 36–46
- Wang, S. *et al.* (2024) Towards mechanistic integration of the causes and consequences of biodiversity. *Trends Ecol. Evol.* 39, 689–700

Outstanding questions

What is the relative contribution of the different mechanisms by which perturbations affect ecosystem synchrony?

How is ecosystem synchrony influenced by the interactive facets of global change (i.e., cumulative, synergistic, antagonistic effects)?

Do the general level of ecosystem synchrony and its response to global change differ between ecosystem types and size (e.g., freshwater vs. marine or small vs. large lakes)?

What are the consequences of changes in the level of synchrony for meta-ecosystem stability?

Does the synchrony of different ecosystem functions differ within a local ecosystem?

24. Kinzig, A.P. *et al.* (2002) *The Functional Consequences of Biodiversity: Empirical Progress and Theoretical Extensions*, Princeton University Press
25. Schulze, E.-D. and Mooney, H.A. (2012) *Biodiversity and Ecosystem Function*, Springer
26. Van Der Plas, F. (2019) Biodiversity and ecosystem functioning in naturally assembled communities. *Biol. Rev. Camb. Biol. Rev.* 94, 1220–1225
27. Kominoski, J.S. *et al.* (2021) Understanding drivers of aquatic ecosystem metabolism in freshwater subtropical ridge and slough wetlands. *Ecosphere* 12, e03849
28. Houghton, R.A. (1987) Terrestrial metabolism and atmospheric CO₂ concentrations. *BioScience* 37, 672–678
29. Dornelas, M. *et al.* (2018) BioTIME: a database of biodiversity time series for the Anthropocene. *Glob. Ecol. Biogeogr.* 27, 760–786
30. Senf, C. (2022) Seeing the system from above: the use and potential of remote sensing for studying ecosystem dynamics. *Ecosystems* 25, 1719–1737
31. Donohue, I. *et al.* (2016) Navigating the complexity of ecological stability. *Ecol. Lett.* 19, 1172–118
32. O'Connell, C.S. *et al.* (2022) Utilizing novel field and data exploration methods to explore hot moments in high-frequency soil nitrous oxide emissions data: opportunities and challenges. *Front. For. Glob. Change* 5, 674348
33. Marcé, R. *et al.* (2016) Automatic high frequency monitoring for improved lake and reservoir management. *Environ. Sci. Technol.* 50, 10780–10794
34. Schindler, D.E. *et al.* (2010) Population diversity and the portfolio effect in an exploited species. *Nature* 465, 609–612
35. Carpenter, S.R. *et al.* (2011) Early warnings of regime shifts: a whole-ecosystem experiment. *Science* 332, 1079–1082
36. Wang, S. *et al.* (2017) An invariability-area relationship sheds new light on the spatial scaling of ecological stability. *Nat. Commun.* 8, 15211
37. Dallas, T.A. *et al.* (2020) Spatial synchrony is related to environmental change in Finnish moth communities. *Proc. R. Soc. B Biol. Sci.* 287, 20200684
38. Kahilainen, A. *et al.* (2018) Metapopulation dynamics in a changing climate: increasing spatial synchrony in weather conditions drives metapopulation synchrony of a butterfly inhabiting a fragmented landscape. *Glob. Change Biol.* 24, 4316–4329
39. Larsen, S. *et al.* (2023) Climatic effects on the synchrony and stability of temperate headwater invertebrates over four decades. *Glob. Change Biol.* 30, e17017
40. Yvon-Durocher, G. *et al.* (2012) Reconciling the temperature dependence of respiration across timescales and ecosystem types. *Nature* 487, 472–476
41. Ji, Y. *et al.* (2021) The lagged effect and impact of soil moisture drought on terrestrial ecosystem water use efficiency. *Ecol. Indic.* 133, 108349
42. Guichard, F. and Marleau, J. (2021) *Meta-ecosystem Dynamics: Understanding Ecosystems through the Transformation and Movement of Matter*, Springer International Publishing
43. Romero-Urbe, H.M. *et al.* (2022) Effect of degradation of a black mangrove forest on seasonal greenhouse gas emissions. *Environ. Sci. Pollut. Res.* 29, 11951–11965
44. Capon, S.J. *et al.* (2015) Regime shifts, thresholds and multiple stable states in freshwater ecosystems: a critical appraisal of the evidence. *Sci. Total Environ.* 534, 122–130
45. Dynamic time warping. In *Information Retrieval for Music and Motion* (Müller, M., ed.), pp. 69–84, Springer Berlin Heidelberg
46. Holmes, E.E. *et al.* (2012) MARSS: multivariate autoregressive state-space models for analyzing time-series data. *R. J.* 4, 11
47. Hopson, J. and Fox, J.W. (2019) Occasional long distance dispersal increases spatial synchrony of population cycles. *J. Anim. Ecol.* 88, 154–163
48. Pesendorfer, M.B. *et al.* (2020) Investigating the relationship between climate, stand age, and temporal trends in masting behavior of European forest trees. *Glob. Change Biol.* 26, 1654–1667
49. Reeve, J.D. (2018) Synchrony, weather, and cycles in southern pine beetle (Coleoptera: Curculionidae). *Environ. Entomol.* 47, 19–25
50. Defriez, E.J. *et al.* (2017) A global geography of synchrony for marine phytoplankton. *Glob. Ecol. Biogeogr.* 26, 867–877
51. Hegg, J.C. and Kennedy, B.P. (2021) Let's do the time warp again: non-linear time series matching as a tool for sequentially structured data in ecology. *Ecosphere* 12, e03742
52. Lottig, N.R. *et al.* (2017) Macroscale patterns of synchrony identify complex relationships among spatial and temporal ecosystem drivers. *Ecosphere* 8, e02024
53. Wallace, C.D. *et al.* (2019) Spectral analysis of continuous redox data reveals geochemical dynamics near the stream-aquifer interface. *Hydrol. Process.* 33, 405–413
54. Sheppard, L.W. *et al.* (2019) Synchrony is more than its top-down and climatic parts: interacting Moran effects on phytoplankton in British seas. *PLoS Comput. Biol.* 15, e1006744
55. Castorani, M.C.N. *et al.* (2022) Disturbance and nutrients synchronise kelp forests across scales through interacting Moran effects. *Ecol. Lett.* 25, 1854–1868
56. Lisi, P.J. and Hein, C.L. (2019) Eutrophication drives divergent water clarity responses to decadal variation in lake level. *Limnol. Oceanogr.* 64, S49–S59
57. Greenville, A.C. *et al.* (2016) Spatial and temporal synchrony in reptile population dynamics in variable environments. *Oecologia* 182, 475–485
58. Smith, B.E. *et al.* (2016) Bloom or bust: synchrony in jellyfish abundance, fish consumption, benthic scavenger abundance, and environmental drivers across a continental shelf. *Fish. Oceanogr.* 25, 500–514
59. Alp, M. *et al.* (2016) Phenological response of a key ecosystem function to biological invasion. *Ecol. Lett.* 19, 519–527
60. Gimenez, M. *et al.* (2023) Stocking practices shape the taxonomic and functional diversity of fish communities in gravel pit lakes. *Fish. Manag. Ecol.* 30, 603–614
61. Imbert, A. *et al.* (2024) Angling bait consumption and stable isotope niche of two cyprinids in different lake fisheries. *Freshw. Biol.* 69, 823–832
62. Nobre, R. *et al.* (2022) Small lakes at risk from extensive solar-panel coverage. *Nature* 607, 239
63. Gounand, I. *et al.* (2018) On embedding meta-ecosystems into a socioecological framework: a reply to Renaud *et al.* *Trends Ecol. Evol.* 33, 484–486