Dissipative Kerr solitons (DKSs) are optical pulses generated in Kerr nonlinear optical resonators, which rely on a double balance between the dispersion and the nonlinearity of the cavity medium as well as the continuous-wave (CW) parametric gain and cavity losses. DKSs generated in optical microresonators have recently attracted significant attention as a source of broadband, low-noise optical frequency combs with a number of unique properties such as chip-scale footprint, high repetition rates covering microwave to terahertz domains and complementary metal–oxide–semiconductor (CMOS) compatibility. The potential of microresonator-based DKSs has been demonstrated in a wide range of system-level applications, spanning from optical coherent communications to the calibration of astronomical spectrometers. In addition, such CW-driven nonlinear microresonators are of high fundamental interest, as they provide a test bench for the exploration of spatiotemporal light localization and dynamics of nonlinear systems.

Recent work has demonstrated that bright DKSs are able to form temporally ordered ensembles—soliton crystals. Their optical spectra are characterized by a set of strongly enhanced comb lines spaced by multiple free spectral ranges (FSRs) resulting from the regular arrangement of DKS pulses in the cavity. The formation of such structures was shown to be linked to the presence of avoided mode crossings (AMXs), which through the spectrally localized alterations of the microresonator dispersion changes the optical spectrum of a DKS state and induces a modulation on the CW intracavity background, leading to the ordering of DKS pulses in a crystal-like structure. Yet, to date, the dynamics of such soliton crystal states remains mainly unexplored. While several attempts were made to explore their defect morphology, stability chart, and the impact of Raman effects, there are a number of open fundamental questions regarding the conditions of their excitation, impact of the chaotic regimes and accessibility of defect-free states. It is also unknown whether soliton crystals reproduce the typical behaviour of DKS states—whether they feature similar switching mechanisms, or have enough robustness to form non-stationary states such as soliton crystal breathers.

Here we demonstrate the generation of perfect soliton crystal (PSC) states, which, strikingly, could be accessed in a deterministic fashion. More generally, we study the full range of dynamical properties of soliton crystals. First, we demonstrate that the formation process of these states strongly depends on the excitation pump power, which originates from two often-neglected operating regimes of the driven microresonator—spatiotemporal chaos (STC) and transient chaos (TC). Second, we show that soliton crystals can be reliably translated in the two-dimensional parameter space of the system (pump power and detuning). Using such translations, we experimentally investigate their behaviour in different stability regimes and demonstrate the switching of soliton crystals. Importantly, we establish a fundamental link between the soliton switching phenomenon and the regime of TC, which we prove to be responsible for DKS elimination. Finally, we present novel dynamical phenomena appearing in soliton crystals, including the observation of soliton crystal melting, disordering and recrystallization.

Perfect soliton crystals

Despite a broad variety of soliton crystal states, here we mainly focus on their simplest and most ideal representatives—PSCs. A PSC is a set of DKSs distributed evenly on the resonator circumference, whose number \( X \) equals the maximum number of solitons that the resonator can accommodate under given pumping conditions (Fig. 1a). In contrast to soliton crystal states with defects, the behaviour of PSCs is unperturbed by missing or shifted pulses. Besides their simplicity, the PSC states bear several important features relevant for both fundamental research and applications. First, due to the high regularity of the intracavity pulses, the PSC states...
Fig. 1 | PSCs in Si3N4 microresonators. a, An illustration of the PSC consisting of X pulses formed in the CW-driven nonlinear optical microcavity. b, Optical micrographs of Si3N4 microresonators with different FSRs of 20 GHz, 200 GHz and 1,000 GHz (left), and PSC states generated in each device (right). c, Left: the set-up scheme used for the generation and characterization of DKS crystal states: a tunable external-cavity diode laser with a centre wavelength of 1,550 nm is used as a seed. EDFA, erbium-doped fibre amplifier; FPC, fibre polarization controller; VNA, vector network analyser; EOM, electro-optical phase modulator; PD, photodiode; OSC, oscilloscope; ESA, electrical spectrum analyser; OSA, optical spectrum analyser. Right: an optical micrograph of a 100 GHz Si3N4 microresonator device shown in c under the same conditions of pump power and effective detuning. The inset shows the system response measurement using a VNA-based scheme in both states. The positions of the soliton and cavity resonances are indicated with the letters S and C, respectively. d, Optical spectra of the soliton crystal state (blue) and single-soliton state (red) stabilized in a Si3N4 microresonator. d, Optical spectra of the soliton crystal state (blue) and single-soliton state (red) stabilized in a Si3N4 microresonator. The native repetition rate of ~100 GHz Si3N4 microresonator. e, Measured integrated dispersion of the Si3N4 microresonator shown in c (circles) and fitting curves for the fundamental transverse electric (TE; dashed red) and transverse magnetic (TM; dashed blue) modes families. The calculated group velocity dispersion term \((\Delta \nu^2/2\alpha)\) for the TE mode used for DKS formation is ~1.2 MHz. f, Repetition rate beatnote measurements in the single-soliton state and the PSC state shown in d. The native repetition rate of -100 GHz is undetectable in the PSC state.

can be used as high-purity, ultrahigh-repetition rate soliton combs, reaching a mode spacing of several terahertz (which is challenging for small microresonators due to bending losses and limitations on the dispersion control). The second advantage of PSC states is that the comb power is distributed in a few lines (supermodes), separated by X FSRs, giving them an X enhancement in comparison to the single-soliton state excited under the same conditions (see Fig. 1a,d). In experiments, we employ Si3N4 microring resonators with various FSRs of 20, 100, 200 and 1,000 GHz (Fig. 1b), fabricated with two different fabrication processes—a subtractive and a photonic Damascene process. In these devices, we repeatedly observed the formation of PSC states with different numbers of regularly arranged solitons (see Fig. 1b). A typical set-up for DKS excitation shown in Fig. 1c includes an additional electro-optical modulator and a vector network analyser (VNA) to measure the cavity response and probe the DKS state. Figure 1d shows a particular PSC state with X = 15, generated in a 100 GHz microresonator (blue) and the single-soliton state (red) generated in the same device under exactly the same conditions (pump power and effective detuning). Despite an apparent similarity of the PSC states to primary combs, we unambiguously prove the soliton formation in a PSC state with the cavity response measurements (inset of Fig. 1d), which show a clear double-resonance response indicating the coexistence of DKS pulses with CW background. A key feature of the generated PSC states is the complete suppression of all the other comb lines apart from the supermodes (see Fig. 1f), which indicates high regularity of the DKS pulse arrangement and the absence of defects. Furthermore, we could not detect the native-FSR beatnote of ~100 GHz electronically in the PSC states, and the observed difference between constructively interfering comb modes and the noise floor established by an optical spectrum analyser was at least 60 dB (Fig. 1d).

Generation of soliton crystal states

We next focus on understanding the conditions of the generation of soliton crystals. It was experimentally demonstrated that soliton crystals can appear as a result of microresonator mode interactions, which through the AMXs induce a modulation on the intracavity CW background, leading to the ordering of the DKS pulses. We point out, however, that to the best of our knowledge all current microresonators inevitably contain AMXs, which, even in a quasi-single-mode case, can result from the interaction between fundamental modes. Thus, in principle, every microresonator system should be able to generate a crystal state, because a necessary requirement for crystallization is satisfied. Since soliton crystals have rarely been reported so far, it is reasonable to assume that there exists another ingredient, which enables the formation of soliton crystals, which has not yet been understood.

In the experiments, we observed that the generation of soliton crystal states is typically achieved at relatively low pump powers, while the same standard procedures of soliton excitation (forward tuning) at high pump powers can lead to the formation
of only multiple-soliton states with a structured spectrum and irregular soliton arrangements. We observed this consistently in various microresonators, with only a difference in the actual threshold value ($P_\text{th}$) distinguishing these two scenarios. To illustrate this behaviour, we used four different pump powers ($P_1$ to $P_4$) and carried out 100 pump laser sweeps over the cavity resonance in one of our 100 GHz devices. At each pump power, the success rate of generated PSC states was counted through the statistics of the recorded soliton steps. Figure 2d,e shows the histogram of such success rates for measured pump powers revealing the existence of a clear threshold for deterministic PSC formation at around 0.25 W. Strikingly, for both experimental power values below the threshold ($P_1 = 0.15$ W and $P_2 = 0.20$ W), the system has a long soliton step, which is reproduced with a 100% success rate (see Fig. 2f). On this step, the system always stabilizes in the same PSC state shown in Fig. 2f, making the process deterministic. In contrast, reproducing an experiment at higher pump power $P_4 = 0.25$ W (above the threshold), we can observe that soliton steps are stochastically distributed, thus reducing the success rate of the PSC generation. At a high pump power well above the threshold ($P_5 = 0.8$ W), the number of generated solitons is purely stochastic (see Fig. 2e), and is moreover well below the soliton number in the PSC state ($X = 15$).

To reproduce the observed behaviour in simulations and understand the underlying physics, we use the perturbed Lugiato–Lefever equation (LLE) with the parameters corresponding to our experimental Si$_3$N$_4$ device (see Supplementary Information for details).
Numerically we also observed the existence of a threshold pump power (~0.25 W, very close to the experimental value), which separates two different generation scenarios. In the first one, below the threshold, every simulation ends in the same PSC state, as shown in Fig. 2b. The process does not depend on the initial conditions and reveals determinism and robustness of the generation procedure available for the PSC states below the $P_{sw}$. In contrast, the simulation result very quickly becomes stochastic for pump powers above the threshold. Depending on the initial conditions and scan parameters, the system forms soliton crystals with defect(s) or—only in rare cases—the PSC. At high enough powers, no soliton crystal formation is observed. The resulting intracavity waveform is a typical multiple-soliton state, consisting of several sparsely spaced DKS pulses, as shown in Fig. 2c. Even though the pulses can still maintain long-range ordering (being bound to the modulated background), the characteristic signatures of soliton crystal states—supermodes—are degraded.

We found that the observed behaviour can be linked to the stability diagram of the LLE (Fig. 2a). The system has multiple regions with different stability properties, including modulation instability (MI), stable stationary DKS, breathers, STC and TC, which we map for our system in the second set of simulations (see Supplementary Information). We note that the LLE can be reduced to the dimensionless form for the normalized intracavity waveform $\Psi(\tau, \theta)$:

$$\frac{d\Psi}{d\tau} = \frac{1}{2} \frac{d^2\Psi}{d\theta^2} + |\Psi|^2 \Psi = (-i + \zeta_0)\Psi + if$$

(1)

where $\theta$ is the dimensionless longitudinal coordinate and $\tau$ is the normalized time. The dynamics of the system in this case will be described by only two control parameters: normalized detuning $\delta$ and normalized pump amplitude $f$, defined as:

$$f^2 = \frac{8g\eta \bar{P}_m}{\kappa^2 \hbar \omega_0}, \quad \zeta_0 = \frac{2\delta \omega_0}{\kappa}$$

(2)

where $\kappa$ denotes the total resonator linewidth ($Q=\omega_0/\kappa$, loaded quality factor), $\eta=\kappa_{int}/\kappa$ is the coupling coefficient, $\bar{P}_m$ is the pump power, $\omega_0$ is the pumped resonance frequency and $\delta \omega = 2\delta \omega_{int} = \omega_0 - \omega_0$ is the detuning of the pump laser from this resonance, counted positive for a red-detuned laser. The nonlinearity is described via $\chi = \hbar \omega_0 c n_2/\eta^2 \nu_{gs}$, indicating the Kerr frequency shift per photon, with the effective group refractive index $n_2$, the nonlinear refractive index $\chi$, and the effective optical mode volume $\nu_{gs}$. Thus, the obtained stability diagram and the following discussion can be directly generalized to any Kerr nonlinear microresonator system using dimensionless parameters ($f, \delta$). We also note that attempts to simulate the stability chart for soliton crystals were made recently, but the investigation of its complex structure and chaotic regimes was incomplete.

By comparing experimental results and simulations of forward scans with the stability diagram, we found that two instability regions—STC and TC—play a major role in the formation of soliton crystal states. We discovered that the excursion of the system through any of these regions reduces the probability of generating PSCs or soliton crystals with a low number of defects. First, in the region of STC, which has its lower boundary at $P \approx 0.25 W$ ($f \approx 3$), the intracavity waveform experiences fluctuations in the instant number of pulses due to its complex chaotic behaviour. Such fluctuations do not guarantee that the number of seed pulses, at the moment when the DKS state is stabilized, will match the number of potential ‘sites’ introduced by the background modulation. This stochasticity results in fundamental indeterminism in the final DKS state, which can be either a PSC or soliton crystal with defects.

The second region—TC—appears above $f \approx 4$ for PSC states, and follows the region of STC for a forward tuning procedure. A prominent feature of this region is that the system there does not have inhomogeneous attractors and converges to the trivial, flat solution. This convergence, however, is not immediate and its character and duration depend on the initial conditions. Importantly, any pulsed solution including a DKS state or PSC will gradually (pulse-wise) decay to a CW background, while the pump and effective detuning of the state are maintained within the TC region (see Supplementary Information).

The effects of both regions explain our experimental observations and presence of threshold power. Since the generation procedure of the DKS state for powers below $f \approx 3$ ($P_{sw} \approx 0.25 W$) avoids the STC, the system deterministically lands in a PSC state. On the other hand, above the threshold ($f \approx 3$), the final number of pulses in a DKS state becomes stochastic, and as in experiments the probability of obtaining a PSC decreases. At high pump powers $f > 4$, when the system experiences the cumulative effect of both STC and TC regions, the formation of the PSC is prohibited due to the impact of TC, which ‘clears’ the cavity and limits the maximum soliton number of the generated DKS states.

Our results establish a critical role of the pump power in the generation process of soliton crystals and PSC states. They provide a simple generation approach ($f < 3$) for deterministic access to PSCs in any microresonator system, which we successfully realized in a diverse set of microresonators (see Fig. 1b). In particular, we were able to generate a PSC consisting of 87 DKS pulses in a 20 GHz microresonator with supermode power enhancement of almost 40 dB.

**Switching of soliton crystal states**

After deriving the conditions for the faultless and deterministic generation of PSC states, we focus on their dynamical properties. We do so by monitoring and, importantly, translating the soliton crystal state, once generated, in the two-dimensional parameter space of the system (pump power, effective detuning). Indeed, we experimentally verified that PSC states are robust with respect to the power- and detuning-translations within the soliton existence area, which allows one to explore different dynamical regimes of soliton crystals by implementing arbitrary complex routes of PSC state transfer in power, detuning or both. We use this translation method to investigate the switching process of soliton crystal states. Although the switching (pulse-wise reduction of the soliton number) was demonstrated for multiple-soliton states, it has never been reported for soliton crystal states. Here, first, we experimentally realize the soliton crystal switching, and second—more fundamentally—discover an origin of this process.

We constructed complex routes consisting of three consecutive stages (see Fig. 3a): (1) PSC generation with forward tuning at a power below $P_{sw}$, (2) PSC state translation to a new power $P'$, (3) backward tuning of the state to induce switching. Implementing such routes for various $P'$ in the same 100 GHz device from the previous section, we observed that the switching of PSC states becomes possible above a pump power $P_{sw} \approx 0.6 W$ ($f \approx 4$). Below $P_{sw}$, the system does not show any switching behaviour, and the PSC state directly seeds MI (a similar effect was observed in fibre cavities). Above $P_{sw}$, as the pump power is increased, the number of available switchings increases until the system is able to reach a CW solution before the transition to the MI state (above ~1 W ($f \approx 5$)). In most cases at intermediate power, the direct MI seeding can still be observed, but happens after several switchings. Figure 3c shows an example of such behaviour, where the system was switched from a PSC state with 15 DKS pulses to a single-soliton state, and then seeded MI.

To verify this behaviour in simulations, we used the same LLE as in the previous section, and implemented backward tuning procedures of PSC states at various powers. Similarly to the experiments, we observed that the PSC state starts to experience switching behaviour above the pump power of 0.55 W, which is very close to the experimentally obtained $P_{sw}$. Comparing this threshold to the stability diagram obtained for the PSC states, one can see that it essentially

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**Equations:**

1. $\frac{d\Psi}{d\tau} = \frac{1}{2} \frac{d^2\Psi}{d\theta^2} + |\Psi|^2 \Psi = (-i + \zeta_0)\Psi + if$
2. $f^2 = \frac{8g\eta \bar{P}_m}{\kappa^2 \hbar \omega_0}, \quad \zeta_0 = \frac{2\delta \omega_0}{\kappa}$
Fig. 3 | Controllable translations and switching of PSC states. a, A simulated stability chart of the LLE shown in Fig. 2a. The dark blue dotted line traces the complex experimental routes for the controlled PSC state evolution: (1) generation (below the TC region), (1–2) power and detuning translation to a higher pump power \( P' \), (2–3) backward tuning (into the TC region) to induce switching. The grey dotted line indicates the route when the backward tuning is implemented at too low power and the system does not enter the TC region, such that no switching is induced. b, Experimental results showing the number of switchings available to the PSC state at different pump powers. The states are unswitchable (grey attempts) below a threshold power of \( P_{th} = 0.6 \) W, and are switchable above (green attempts). The horizontal axis shows the number of available switchings. CMI, chaotic MI; SS, switching to a single-soliton state. c, An experimental trace of the generated light during the continuous switching of a PSC state to a single-soliton state. The insets show the optical spectra of the corresponding states. d,e, Simulations of the intracavity waveform evolution during backward tuning of the PSC at non-switchable pump power (d) and at switchable pump power (e). In the first case, the system directly seeds MI, while in the second case the system first decays to a flat solution (CW) via multiple-soliton states, marked as MS.

Fig. 4 | Controllable translations and switching of PSC states. a, A simulated stability chart of the LLE shown in Fig. 2a. The dark blue dotted line traces the complex experimental routes for the controlled PSC state evolution: (1) generation (below the TC region), (1–2) power and detuning translation to a higher pump power \( P' \), (2–3) backward tuning (into the TC region) to induce switching. The grey dotted line indicates the route when the backward tuning is implemented at too low power and the system does not enter the TC region, such that no switching is induced. b, Experimental results showing the number of switchings available to the PSC state at different pump powers. The states are unswitchable (grey attempts) below a threshold power of \( P_{th} = 0.6 \) W, and are switchable above (green attempts). The horizontal axis shows the number of available switchings. CMI, chaotic MI; SS, switching to a single-soliton state. c, An experimental trace of the generated light during the continuous switching of a PSC state to a single-soliton state. The insets show the optical spectra of the corresponding states. d,e, Simulations of the intracavity waveform evolution during backward tuning of the PSC at non-switchable pump power (d) and at switchable pump power (e). In the first case, the system directly seeds MI, while in the second case the system first decays to a flat solution (CW) via multiple-soliton states, marked as MS.

We would also like to bring the readers’ attention to two recent studies\(^{13,14}\), which experimentally demonstrated the generation of soliton crystal states and DKS switching in hydrex microresonators, and whose observations can be explained using the understanding of PSC generation and switching developed in the present work (see Supplementary Information).

Dynamics of soliton crystal states

Next, we report a rich panel of peculiar dynamical phenomena that can be found in PSC states. We highlight three of them, which were observed using the different PSC transformations shown in Fig. 4a: reversible melting and recrystallization of the PSC state, switching between PSC states and the formation of PSC breathers.

First, we demonstrate that a PSC state can be consistently restored after its excursion to the MI region. This corresponds to a complete destruction of the regular soliton arrangement—‘soliton crystal melting’, and its reassembling, when the system is brought back to the region of stable DKS—‘soliton recrystallization’ (route A–B–A in Fig. 4a). The PSC state (A) was tuned backward until reaching MI (A–B), and then forward (B–A) to the initial position. We trace the system evolution during this procedure by measuring the optical spectrum. For the major part of the stable DKS region, the system maintains a typical PSC spectrum. It starts to develop additional lines apart from the supermodes as the system approaches the MI region, indicating the appearance of variations in the relative positions of DKS pulses, while maintaining the overall long-range ordering. The effect is similar to the introduction of disorder in the crystal lattice of solids. Once the system reaches MI, the spectrum changes to the typical spectrum of a noisy comb and the system acquires strong intensity noise. In this state, stable DKS pulses cannot exist in the system, and the intracavity waveform is chaotic. Reverting the tuning direction and bringing the system...
Fig. 4 | Diverse dynamics of PSC states. a, A simulated stability chart of the LLE shown in Fig. 2a. Three experimental evolution routes of the initial PSC state (A) are marked with different colours. b, Experimental observation of PSC melting and recrystallization. The route is shown as A–B–A in a, and passes below STC and TC regions. The detuning was reduced linearly until the system reached MI, and then increased to the starting value, as shown in the top plot. The middle map shows the evolution of the optical spectrum of a PSC state during excursion to the MI regime (crystal melting) and then back to the PSC (recrystallization after melting). The bottom plot shows three spectra at different stages, from left to right: initial PSC state, disordered soliton crystal state, and MI at the corresponding stages of the tuning route. c, Switching between PSC states. The route is shown as A–E–F in a. Optical spectra of the initial PSC state with \( X = 15 \) and the final PSC state with \( X = 13 \), obtained ‘on the fly’ by power translation and switching from the initial state. d, Optical spectra of the stable (blue) and breathing (red) PSC states. Both states maintain strict regularity of the DKS pulses. e, Evolution of the total intensity noise spectrum as the PSC is tuned into the breathing region. The appearance and reduction of the sharp tone, corresponding to the breathing frequency, can be observed. The spectra with larger detuning have darker colour; the traces are shifted vertically by 5 dB each for better visualization of the evolution. Resolution bandwidth (RBW) of the measured traces is 10 kHz.

back to the initial state (B–A), the system can be restored back to the initial PSC state, where the DKS pulses are again crystallized in the form of an equidistant lattice (see Supplementary Information for simulations of this procedure). We note that the interconversion between certain soliton crystal states and MI was also recently accessed in a non-deterministic fashion21, and was linked to the chaotic behaviour in the MI state.

Second, we demonstrate that the system can be switched from one PSC state to another with a distinct number of intracavity pulses (route A–E–F in Fig. 4a). In our experiments, it was enabled by a proper choice of the pump power for switching, which led to the transition from a PSC with \( X = 15 \) to the one with \( X = 13 \) (Fig. 4c). We attribute this dynamic to the change in the modulation of the CW background caused by the cavity cooling after switching. Since the positions and strength of the modal crossings are sensitive to the temperature of the system22,23, the removal of the DKS pulses can induce a new binding potential with a different number of sites.

Third, we experimentally demonstrate the formation of PSC breathers, which correspond to simultaneous oscillations in the amplitude and duration of all DKS pulses forming the PSC state. For this, we brought the PSC state to the breathing region (route A–C–D in Fig. 4a), where the characteristic indicators of breathing DKS states were observed, including the triangle-shaped optical spectrum and the appearance of the narrow breathing tone, whose frequency was close to the estimated effective detuning and was decreasing as the detuning decreased (see Fig. 4d,e)24.

Discussion

We demonstrated platform-independent on-demand generation of PSCs, which provide strong enhancement of the supermodes and can be of high use for the development of chip-scale optical frequency combs with ultrahigh-repetition rates beyond several terahertz. In addition, such states can provide a convenient microwave-to-terahertz link, enabling the stabilization of terahertz signals with standard radiofrequency equipment.
Furthermore, taking into account the two important thresholds that we derived for the generation of PSC states \( f_n \approx 3 \) and their switching \( f_n \approx 4 \), one can in principle construct deterministic routes to access any soliton state available in the system.

We also emphasize that our results, showing the impact of chaotic regions on the formation and switching processes of solitons states, as well as the translation methods we developed to study the complex dynamics of the system, can be extended to all DKS states, including less temporally organized multiple-soliton states or single DKSs. We believe that a clear understanding of the effect of chaotic regimes of the CW-driven nonlinear cavity on the formation and general dynamics of the DKS states, which we formulated in the current work, will help to uncover and explain other DKS phenomena in optical microcavities and establish connections to recent theories and observations\(^{1,3,5,21,23} \).
Methods

Optical microresonators. Si$_3$N$_4$ integrated microring resonators with an FSR of $\sim 100$ GHz and Q-factors $\sim 10^6$ (linewidth $\kappa \approx 150 \text{ - } 200$ MHz) were fabricated using the photonic Damascene process$^{25}$. To achieve single-mode operation and suppress the effect of AMXs$^{38}$, a 'filtering section' was added to the microresonator$^{26}$. Similarly, the photonic Damascene process was employed for the fabrication of the 200 GHz and 1 THz devices used for the verification of the results presented in the paper, and in particular for demonstrating the platform-independent generation of PSCs. In addition, 20 GHz microresonators (for which we demonstrated a large soliton crystal consisting of 87 regularly spaced solitons) have been fabricated with subtractive process.

Data availability

The data used to produce the plots within this paper are available at https://doi.org/10.5281/zenodo.2809645. All other data used in this study are available from the corresponding authors on reasonable request.

Code availability

The code used to produce the plots within this paper is available at https://doi.org/10.5281/zenodo.2809645.

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