Rapid seaward expansion of seaport footprints worldwide

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Over recent decades, seaports around the world have been expanding seaward through land reclamation at a scale and pace that geospatial analysis of global satellite imagery is now revealing. Understanding patterns of seaport growth is necessary to accurately estimate risk to seaport infrastructure from future coastal hazards. What the global trend in seaport expansion may mean for climate adaptation is a complicated open question.

Seaports are essential to flow of global trade[1]: approximately half of all global trade, by value, is maritime[2]. However, for such valuable infrastructural assets, seaports are precariously exposed to marine natural hazards. Recent research has shown that seaport exposure to multiple climate-driven natural hazards is geographically heterogeneous, with hotspots of risk concentrated in cyclone corridors[3,4]. But even for seaports where current risk of disruption from natural hazards is relatively low[3], functional risk to seaport infrastructure and operations is expected to grow in the coming century[4,5]. In general, this intensification of risk may be exacerbated by two underlying drivers: rising extreme sea levels[5,6], and a projected increase in global maritime traffic by between 2 and 12 times its current volume[7].

While natural-hazard analyses of risk to seaport infrastructure and international trade networks are becoming more powerful, nuanced, and detailed[2,3,4], current assessments treat the spatial footprints of seaports as static quantities, and do not account for seaport expansion, typically seaward, over time[8] **(Fig. 1a)**. Spatio-temporal patterns of change in seaport footprints affect routes of global trade as seaports compete for throughput[9], inform the dynamics and implications of relative risk (risk per unit seaport area)[3], physically reshape coastlines where exposure to hazard impacts is especially high[6,10,11], and reflect intensive seaward expansion in coastal cities experiencing high rates of subsidence[12]. Thus far, trajectories of seaport footprint growth around the world have gone unmeasured.

Here, we calculated the spatial footprints of seaports annually over three decades (1990–2020) using a new method for quantifying coastal land reclamation from satellite imagery in Google Earth Engine[8]. We find that of the top 100 seaports globally, as ranked by their throughput in 2020[13], 68 have expanded their spatial footprints through coastal reclamation since 1990 **(Fig. 1b)**. Collectively they account for nearly 1000 km^2 of new coastal land, and over 20% of the estimated total port area on the planet (~4500 km^2)[3]. Of these 68 expanded seaports, 22 are in China, and account for 643 km^2 of coastal reclamation (65% of total reclamation globally). Tianjin alone has reclaimed more than 183 km^2 since 1990 (18% of total reclamation globally) – more than triple the area reclaimed by Singapore, which has expanded by the next highest total. These outliers make the majority of seaport expansion appear modest: approximately half of the

68 seaports identified have reclaimed less than 5 km^2. But in relative terms, even this growth is significant. All but six of the 68 have at least doubled their seaward area since 1990; more than half have quadrupled it; almost a quarter have expanded it by an order of magnitude. In the extreme, Dalian, in China, now has a seaward footprint nearly 190 times its size in 1990.

Beyond ranked totals, time series of spatial growth reveal a variety of patterns and pulses of seaport expansion. Given that distribution of real spatial scales among these seaports spans three orders of magnitude, to more easily compare their patterns of growth we normalised the trajectory of each seaport by its total reclaimed area in 2020 **(Fig. 2a**; individual time series for each seaport in units km^2 are shown in **Fig. S1)**. Some seaports describe effectively linear growth, expanding seaward at an effectively steady rate; many are punctuated by two or more step-changes in size, reflecting series of major expansions. Trajectories that lie well above the 1:1 reference line reflect seaports that underwent significant reclamation early in the time series; those well below the 1:1 reference line indicate seaports that have grown more recently at especially rapid rates. The majority of seaports show trends of substantial growth within the past 10 to 15 years **(Fig. S1)**.

Although a handful of the largest seaports by throughput are also responsible for the most reclamation, comparing rank by throughput versus rank by total reclaimed area shows mid-tier and smaller seaports among the global top-100 pushing to grow, with patterns of recent expansion that outstrip their larger counterparts **(Fig. 2b)**. Some of those smaller but rapidly expanding seaports appear particularly exposed to coastal hazard and cyclones[3] **(Fig. 2b)**. Notable among all top-100 seaports is Shanghai, which ranks first in throughput, fourth in total reclamation area, has experienced significant recent growth, and reflects the highest exposure to coastal and cyclone hazard **(Fig. 2b)**.

Reclamation activities may result from a number of different economic and political drivers, which this analysis does not differentiate. However, for 45 of these seaports – a subset determined by data availability – we show throughput volume (in terms of industry-standard "twenty-foot equivalent units", or TEU) as a function of total reclamation area annually between 2011 and 2020 **(Fig. 2c;** individual time series for each seaport are shown in **Fig. S2)**. Newly reclaimed land visible in a satellite image is not immediately productive: there is a lag between reclamation and the infrastructure installation necessary to handle higher trade volumes. Nevertheless, these data demonstrate that, in general, throughput volume tends to increase with total reclaimed area. For seaports other than the very largest, reclamation appears to be a key means of climbing up the global rankings. But these data also show wide variety in the relationship between reclamation and trade volume, and we echo recent work that cautions against invoking "simple scaling relationships [between seaport area and trade volume] across countries"[3]. Indeed, even such a scaling relationship for one seaport may be a poor predictor for another.

The spatio-temporal patterns of seaward expansion that we show for seaport footprints fit within the global trend in ocean sprawl – "the rapid proliferation of hard artificial structures…in the marine environment"[16]. Coastal reclamation is only possible by installing hard artificial structures at the shoreline. While coastal reclamation itself is an ancient engineering technology, the scale, rate, and global extent of coastal reclamation is a new and evolving phenomenon[8]. Time series of seaport expansion – for these and the hundreds of expanding ports not included among the top-100 by throughput[2,3,4,8] – may inform and refine approaches to forecasting future expansion of coastal infrastructure[17,18]. Moreover, until recently, leading global digital elevation models were derived from Earth observation data that predated much of the seaport document we present here[19]. As new, high-resolution global datasets of coastal elevation become available[20,21] – and as analytical tools and techniques make it easier to determine elevation change from existing satellite catalogues, such as InSAR[12] – researchers will be able to more accurately and comprehensively assess patterns of coastal vulnerability to future natural hazards[10,11]. For urbanised settings like seaports, where asset exposure is not only densely concentrated but also competitively driven to intensify, any future-proofing plans for climate adaptation[22] will inevitably hinge on better vulnerability assessment.

Methods

We used the Lloyd's List (2021)[13] report of the 100 largest container ports globally, based on reported trade volume in 2020. To differentiate seaports from riverine and inshore ports, in Google Earth Engine (GEE) we delineated the Low Elevation Coastal Zone (land below 10 m elevation) from the Multi-Error-Removed Improved-Terrain DEM[23] and mapped the location of each port in Open Street Map using OSMnx[24]. This yielded an initial set of 82 seaports located at the coastline.

Our analysis of reclamation area followed the method described in ref.[8]. To identify and measure annual patterns of seaport reclamation, we used the 30 m resolution Global Surface Water (JRC-GSW) dataset from 1990 through 2020[25] and the Yearly Water Classification History (v1.4), including "no water" and "seasonal" bands, in GEE[8]. Seaport reclamation **(Fig. 1)** registers as changes in water surface at the coastline. Because reclamation processes are designed to reduce tidal effects on construction[26], we do not apply a tidal correction. Raw measurements of reclamation area from raster data may be affected by clouds and other artefacts, so we smoothed the 30-year time series of reclamation area for each seaport with a Savitzky–Golay filter, consistent with other Landsat-derived analyses[27]. We report both raw and smoothed measurements in the companion dataset[28]. Coastal reclamation areas smaller than 1 km^2 (approaching the limit of spatial resolution) were excluded. The remaining 68 seaports are the subset analysed here. We overlayed high-resolution base maps from Planet and Google Earth to confirm evidence of recent reclamation between 2018 and 2020 for selected seaports.

Data Availability

Study data are available at ref.[28].

Code Availability

Code for calculating seaport area using Google Earth Engine is available at https://github.com/dhritirajsen/Mapping_Coastal_land_reclamation. Code for generating the figures in this article are available at https://github.com/envidynxlab/Seaports.

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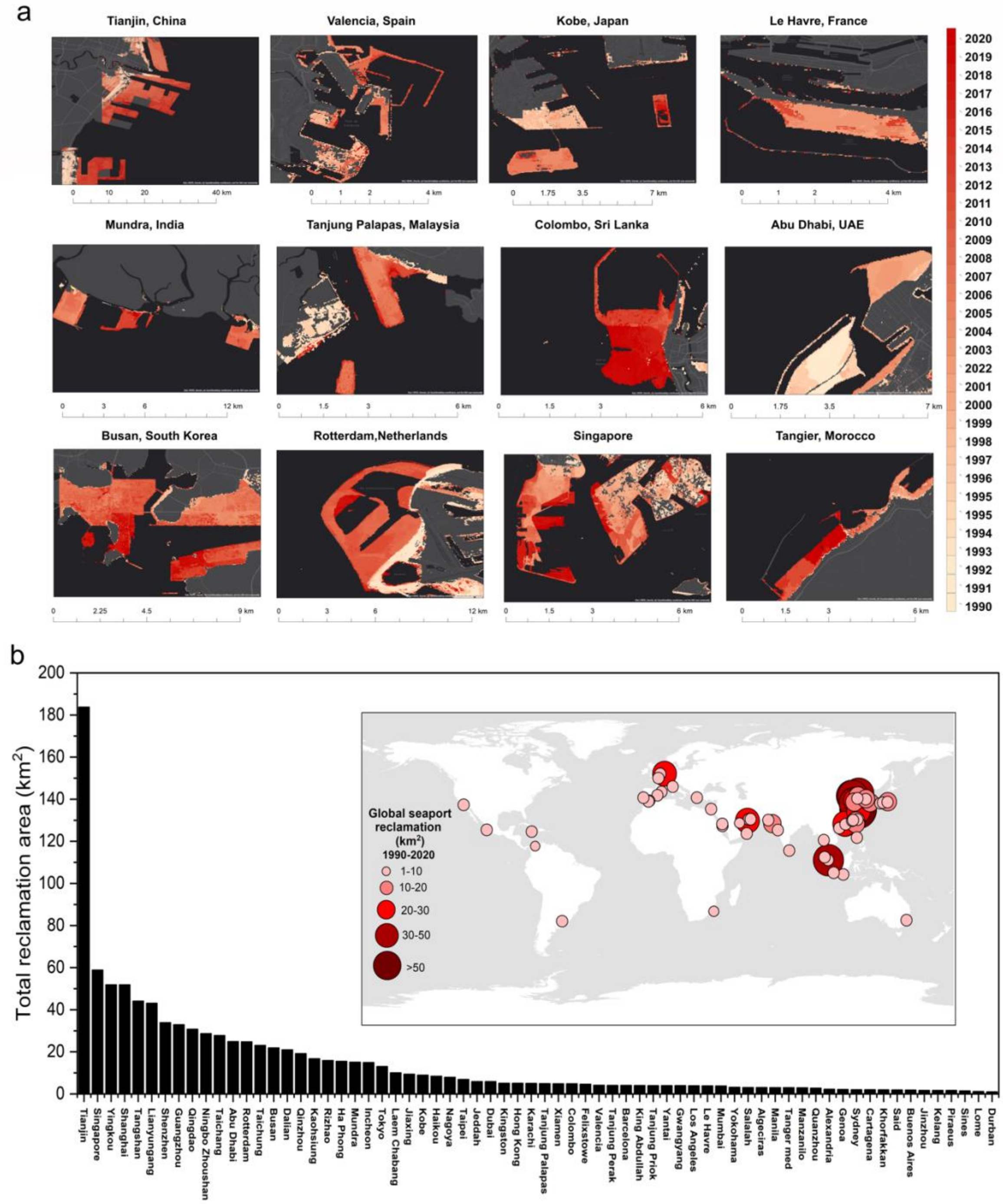

Figure 1: Seaport expansion with coastal land reclamation. a, Spatio-temporal patterns of expansion in selected seaport footprints around the world, 1990–2020. Light shades delineate earlier reclamation, and dark shades more recent works. **b**, Total reclamation area 1990–2020, from highest to lowest, for 68 of the world's top 100 seaports by trade volume, mapped in inset.

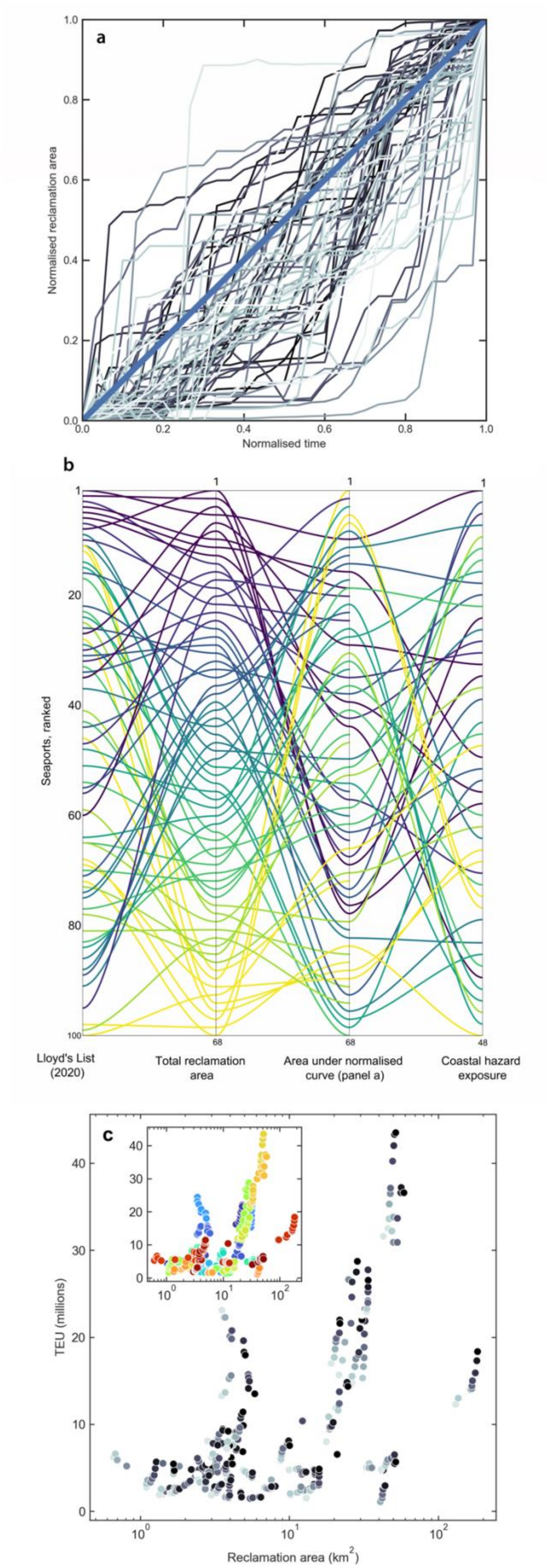

Figure 2: Patterns and trends in seaport expansion. a, Comparative time series of cumulative reclamation area for 68 seaports, each normalised by its total reclaimed area in 2020. Note that the time series for some seaports begin after 1990. Series are coloured by total reclamation area in 2020 (shown in Fig. 1b), where darker shades denote larger areas, and vice versa. Blue line marks 1:1 reference. **b**, Parallel-coordinates plot of seaports ranked by: Lloyd's List rank by trade volume in 2020; total reclamation area in 2020; total area underneath curve of normalised time series shown in panel (**a**), organised from smallest area to largest to emphasise seaports with new and significant relative growth; and estimated risk from coastal and cyclone hazard, from ref.[3], for 48 of the 68 seaports in this analysis. **c**, Trajectories of seaport trade volume[14,15] relative to reclamation area, 2011–2020 (light to dark); inset shows same trajectories coloured by seaport.

SUPPLEMENTARY INFORMATION

Rapid seaward expansion of seaport footprints worldwide

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This file includes two supplementary figures **(Figs. S1, S2)**.

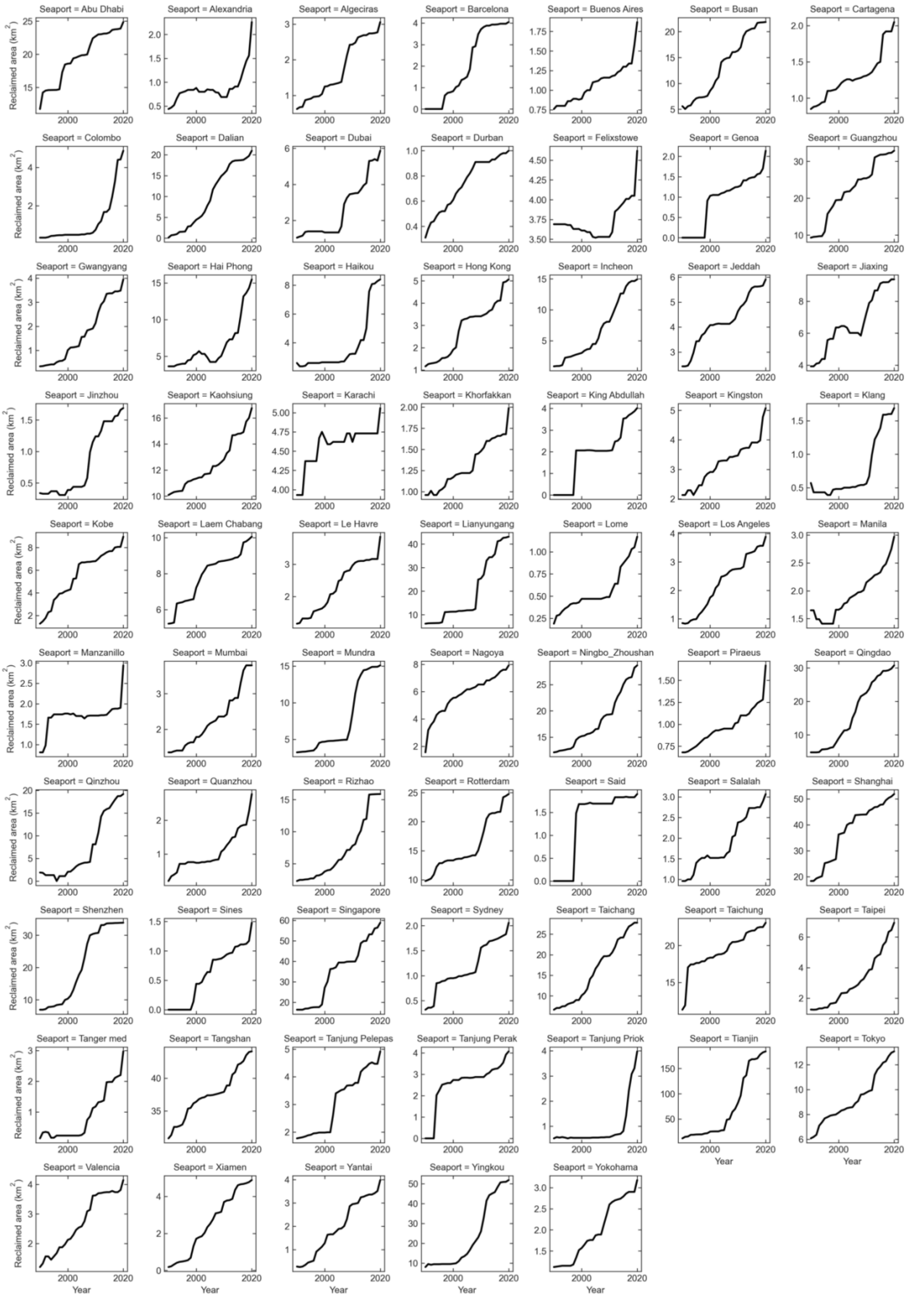

Figure S1. Time series (smoothed) of total reclamation area, 1990–2020, for 68 of the world's top 100 seaports by throughput. Note that scale of y-axis differs among plots.

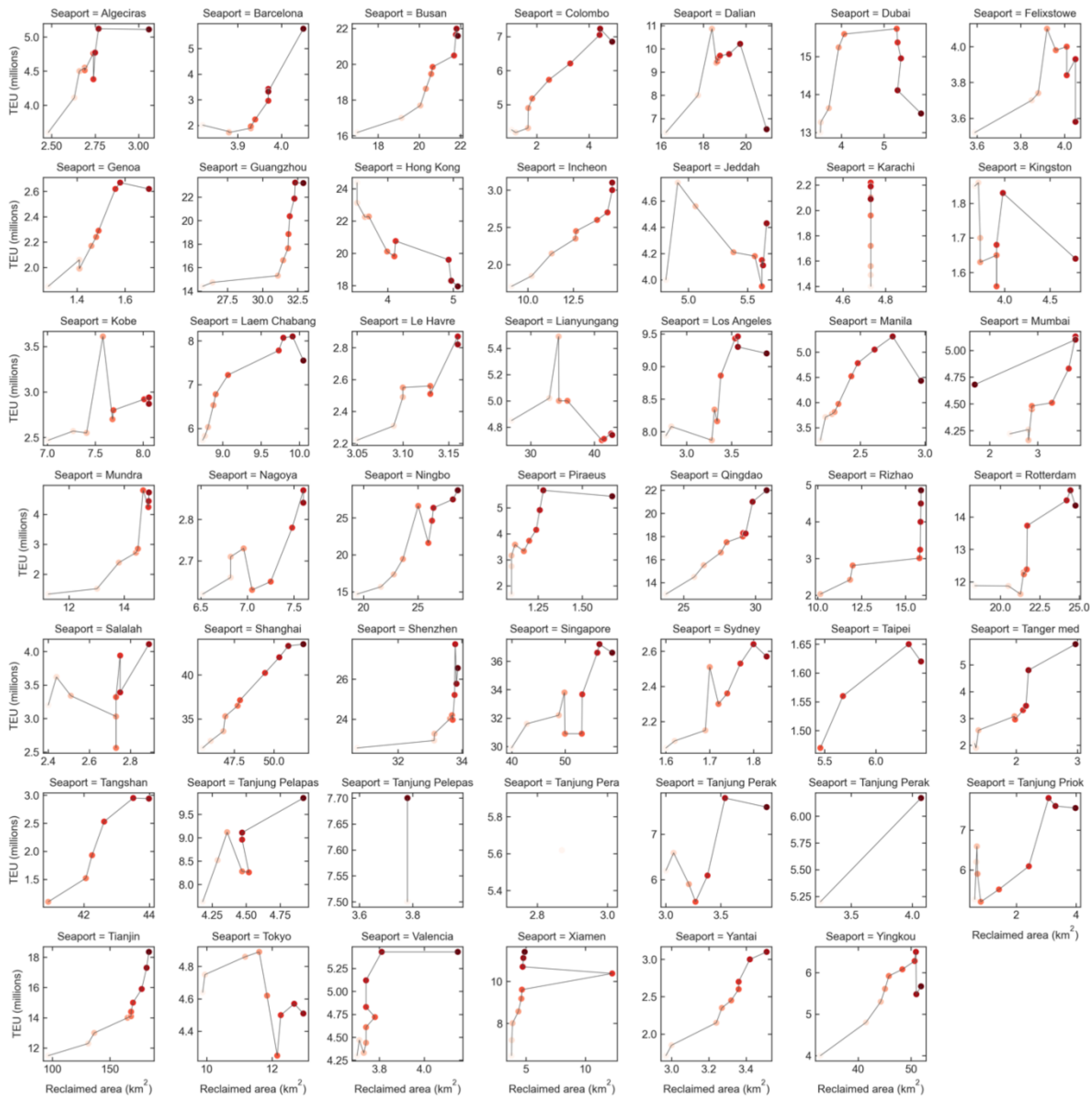

Figure S2. Trajectories of trade volume (millions TEU) relative to total reclaimed area (km^2), 2011–2020 for 48 of the global top-100 seaports by throughput. Marker colour indicates year, from 2011 (lightest) to 2020 (darkest). Total reclamation area is from the smoothed time series. Data for TEU volumes are sourced from the United Nations Conference on Trade and Development (https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=13321) and the World Shipping Council (https://www.worldshipping.org/top-50-ports), cited as refs.[14,15] in the main text.