Rapid seaward expansion of seaport footprints worldwide

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Abstract

As global maritime traffic increases, seaports grow to accommodate and compete for higher volumes of trade throughput. However, growth trajectories of seaport footprints around the world have gone unmeasured, likely because of a lack of readily available spatio-temporal data. Here, we use geospatial analysis of global satellite imagery from 1990–2020 to show that 65 seaports among the world's top 100 container ports, as ranked by reported throughput, have been expanding rapidly seaward. Collectively, these seaports have added approximately 978 km^2 in gross port area in three decades through coastal land reclamation. We also find that the relationship between footprint expansion and throughput volume is highly variable among seaports. Understanding patterns of seaport expansion in space and time informs global assessments of critical infrastructure and supply chain vulnerability to climate-driven hazard. Seaport expansion also sets up complex trade-offs in the context of environmental impacts and climate adaptation.

Introduction

Seaports are essential to flow of global trade[1]: approximately half of all global trade, by value, is maritime[2]. For such valuable infrastructural assets, seaports are precariously exposed to coastal natural hazards. Recent research has shown that seaport and maritime supply chain exposure to multiple climate-driven natural hazards is geographically heterogeneous, with hotspots of risk concentrated in cyclone corridors[3,4,5,6]. But even for seaports where the current risk of disruption from natural hazards is relatively low[3], functional risk to seaport infrastructure and operations is expected to increase before 2050[4,7]. In general, this intensification of future risk may be exacerbated by two underlying drivers. One is sea-level rise and changes in climate-related forcings more generally, which, by compounding the potential landward reach of extreme sea levels, will tend to shift coastal flooding regimes toward more frequent, higher-magnitude events[7,8,9]. The other is global maritime traffic, which is projected to grow by between two and 12 times its current volume by mid-century[10]. Of these two drivers, the latter likely imparts a more immediate effect on the global distribution of seaport risk[11]. As greater maritime trade volume demands more seaport infrastructure and accommodation space in existing and new locations, the sector must expand the physical area available for operation[7,12] – and so seaports get bigger.

While regional and global analyses of risk to seaport infrastructure and international trade networks are becoming more powerful, nuanced, and detailed[2,3,4,13], current assessments treat the spatial footprints of seaports as static quantities, and do not account for seaport expansion, typically seaward, over time **(Fig. 1)**[14]. Spatio-temporal patterns of change in seaport footprints affect routes of global trade as seaports compete for throughput[12], inform the dynamics and implications of climatic risk[3,4], physically reshape coastlines where exposure to hazard impacts is already high[8,15,16], and are associated with detrimental environmental consequences for coastal ecology[17,18,19,20,21]. Reports of coastal land reclamation related to port expansion, specifically, tend to be geographically focused[22,23,24]. Thus far, trajectories of seaport footprint growth around the world have gone unmeasured, likely because of a lack of readily available spatio-temporal data on seaport areas[4,7].

Here, we measured annually over three decades (1990–2020) patterns of seaward expansion in 65 of the world's top 100 container ports as ranked by throughput[25] (**Fig. 2**), using a recently published method for quantifying spatial footprints of coastal land reclamation from satellite imagery in Google Earth Engine[14] (**Fig. 1**; see Methods). Coastal land reclamation involves the engineered conversion of a nearshore subaqueous or intertidal environment to subaerial dry land or an enclosed water body[14,26]. A seaport complex may expand seaward to accommodate changing requirements for a host of operational reasons (e.g., new or larger vessel berths, terminal accessibility and logistics, storage area, onsite production), but also because there may be no option or availability to expand inland, given terrain or conflicts with existing land uses[22,27,28,29].

Our remote-sensing method uses as its baseline a 1990 composite coastline from an annual dataset of global surface water[30]. Coastal land-reclamation activities after 1990 emerge as seaward-directed relocations of the global surface-water coastline over time. To differentiate "seaports" from ports in riverine and inshore settings, we mapped the Lloyd's List[25] of the 100 largest container ports by reported container throughput in 2020, and identified 89 container ports located on an open-water coastline. From those 89 sites, we excluded 24 seaports where total seaward-directed changes were smaller than 1 km^2 (see Methods). A list of the container ports excluded from our analysis is provided along with the data for the results presented here (see Data Availability).

Seaward expansion greater than 1 km^2 since 1990 does not reflect the full spatial footprint of any given seaport complex. Determining from remotely sensed data landward expansion and patterns of change in the total footprints of seaport area across coastal and terrestrial spaces requires a different analytical approach. Nor does our method differentiate among specific uses of seaport-related space, such as terminal facilities, storage, industry, or other integrated layouts[4,13,14]: the seaward footprints that we measure must be interpreted as a partial gauge of gross port area. Imagery from Google Earth and Planet Basemap, and targeted queries in OpenStreetMap, corroborate that the seaward growth we measure at these 65 sites is associated with expansion of seaport complexes.

Results

We find that since 1990, 65 seaports among the world's top 100 container ports by reported throughput in 2020[25] have expanded their spatial footprints seaward through coastal land reclamation by a total of 978 km^2 **(Fig. 2)**. This sum is large (~22%) relative to the current estimated area of port terminals worldwide (~4,500 km^2)[4]. These 65 seaports also represent a significant segment of the global port sector. According to UNCTAD, 798.9 million TEUs (industry-standard "twenty-foot equivalent units") of containers were handled worldwide in 2020[31], of which the top 100 container ports processed 632.2 million TEUs (79%)[25]. The 65 container seaports in our analysis moved 500 million TEUs in 2020: 79% of the total volume among the top 100 container ports, and 63% of the overall volume of maritime container trade worldwide.

Two thirds (43) of the 65 seaports in our analysis are in Asia, and collectively reclaimed 871 km^2 (89%) of the total seaward expansion we measured **(Fig. 2)**. Twenty-one of those seaports are in China, and account for 627 km^2 (63%) of seaward expansion. The port of Tianjin alone has reclaimed more than 183 km^2 (18%), more than triple the area reclaimed by the port of Singapore, which has expanded by the second-largest extent. These outliers make the majority of seaport expansions seaward appear modest: approximately half (32) of the 65 seaports identified have reclaimed less than 5 km^2. But in relative terms, even this growth is meaningful. All but seven of the 65 have at least doubled their seaward area since 1990; 39 have quadrupled it; 12 have expanded it by an order of magnitude.

Beyond ranked totals, time series of spatial growth in individual seaports reveal a variety of patterns and pulses of seaward expansion **(Fig. 3)**. Although spatial scales of expansion among these seaports span three orders of magnitude, the time series exhibit some qualitatively similar characteristics. For example, the time series are punctuated by one or more step-changes in area, indicative of major expansions. Marked seaward reclamation early in the time series produces an asymptotic curve (concave down: e.g., ports of Algeciras, Taicang); rapid expansion late in the time series produces a more exponential curve (concave up: e.g., ports of Colombo, Yingkou). Pronounced growth through the middle of the time series produces a sigmoidal curve (e.g., ports of Barcelona, Jinzhou); punctuated growth at the beginning and end of the time series produces a more cubic curve (e.g., ports of King Abdullah, Laem Chabang). Most of the time series express variations on these curve shapes, including some seaports with sustained periods of effectively linear growth (e.g., ports of Busan, Incheon). While seaports in China and greater Asia constitute the majority of our sample, no particular time-series shape appears specific to a given region. The majority of these 65 seaports show trends of substantial seaward growth within the past 10 to 15 years.

The regional distribution of seaward expansion among container seaports in our results **(Fig. 2)** aligns broadly with the regional distribution of trade dominance globally. According to the Lloyd's List[25], in 2020, 25 ports in China absorbed almost 40% of the container volume among the top 100 container ports, and 25 ports across the rest of Asia routed an additional 28%. The 21 seaports in China in our analysis handled 237 million TEU, or 38% of volume among the top 100 container ports in 2020; 22 other major seaports across Asia handled an additional 160 million TEU (25%). But our analysis also shows other regional patterns relevant to trade dominance. For example, 10 seaports in Northern Europe and eight in the Middle East had 8.6% and 5.6% shares, respectively, of reported volume among the top 100 container ports in 2020. While three of those seaports in Northern Europe (3% volume share) have expanded seaward a total of ~29 km^2 (3%) since 1990 – and most of that in Rotterdam alone – all eight of those seaports in the Middle East have collectively reclaimed ~49 km^2 (5%).

While the handful of seaports responsible for the most seaward reclamation since 1990 are also the largest by container throughput in 2020, a more inclusive roster of seaports yields a scattered relationship between seaward reclamation and container throughput **(Fig. 4a)**. Past work relating port area to handled tonnage in 1990 for 27 ports around the world fit a linear relationship[7,32], but our results indicate a more complicated dynamic. First, comparing rank by total reclaimed area versus rank by container throughput in 2020 suggests that a number of seaports among the top 100 container ports are pushing to grow relative to their counterparts **(Fig. 4b)**: we find 29 seaports (45% of those in our analysis) with an outsized reclamation signature (above the 1:1 reference line) relative to their container throughput. Second, a partial phase space described by seaward expansion and container throughput demonstrates a variety of trajectories among individual seaports over time **(Fig. 5)**. For 43 of the 65 seaports in our sample (a subset determined by data availability), we show reported container throughput as a function of seaward reclamation area annually between 2011 and 2020 **(Fig. 5)**. This reversal of the axes in **Fig. 4** and previous work[7,32] is deliberate, to explore seaward expansion as a potential driver of trade volume. In many cases, container throughput increases with seaward expansion, suggesting that reclamation can serve a key means by which seaports may capture volume share and thereby climb up the global rankings. But these data also show plenty of exceptions to that correlation. For example, newly reclaimed land is not immediately ready for use[14]: there is a lag between reclamation and the infrastructure installation necessary to handle higher trade volumes, which some of these trajectories may reflect. Moreover, expansion does not guarantee *ipso facto* greater trade capture, nor does a larger seaport footprint itself ensure that a given throughput volume is sustained. Seaport expansion and container throughput are steered by political, policy, and market forces illegible to this analysis. Given the variety we see in these reclamation and trade volume trajectories, we echo recent cautions against invoking "simple scaling relationships [between seaport area and trade volume] across countries"[4]. Indeed, even a scaling relationship for one seaport may be a poor predictor for another.

Discussion and Implications

Our analysis is intended to synthesise and quantify a collective pattern of seaward expansion among a majority of the largest container seaports in the world **(Fig. 3)**. Port expansion is typically discussed in broad terms or at the scale of case studies[22,23,24], but the globally distributed pattern in our results is notable for its apparent ubiquity, transcending national-scale differences in policy and regulatory contexts. We also show that while a positive relationship between expansion and container throughput volume is generally evident **(Fig. 4a)**, as others have found[7,32], that relationship may be less straightforward at the scale of an individual seaport **(Fig. 5)**. Trade volume through a given seaport depends on market dynamics, which can go up or down, but seaport expansion is a ratchet that can only advance. For any given seaport, expansion thus enables and assumes a precarious model in which its market share – or the volume of the market itself – will continue to grow. Moreover, although growth in global maritime traffic is a fundamental driver of seaward expansion among container seaports[7,10,12], it is not necessarily the only driver, especially in coastal urban centres straining at the edges of their available real estate[14,22,28,29].

Partial phase spaces like the one we explore **(Fig. 5)** are useful windows into dynamical systems, but our study is unlikely to help a given seaport authority profile the dimensions of its infrastructural vulnerability. The logistical, policy, ecological, environmental, hazard-exposure, and climate-adaptation ramifications of seaward seaport expansion are inevitably case-specific. Our work does, however, contribute to a wider discourse regarding emergent patterns of coastal risk around the world, of which the infrastructure of maritime trade is an intrinsic component. For example, the spatio-temporal footprints of seaward seaport expansion that we measure are a further documentation of ocean sprawl: "the rapid proliferation of hard artificial structures…in the marine environment"[19], with deleterious consequences for marine sedimentary habitats, biodiversity, and ecological connectivity[18,19,20,21]. The spatial extent of ocean sprawl and anthropogenic coastal hardening is still being assessed[33] and its proliferation forecast[34]. Our findings, and related efforts to quantify coastal land reclamation globally[14,26], reflect only a component of ocean sprawl, but are indicative of its unprecedented pace and coevolution with socio-ecological and socio-economic risk[34,35,36].

How seaports and maritime supply chains will adapt to future climate change is an open question[5,6,7,12,37,38,39] with material implications[40,41]. A recent conceptual experiment considered the volume of material needed to raise 100 US seaports by two metres, and found that such retrofitting would require 704 million m^3 of fill – a quantity equivalent to the total estimated volume of sand delivered by all beach nourishment projects in the US since 1972[42]. Not all fill material used in land reclamation is sand, but sand (with particular granular characteristics) is the essential ingredient in concrete, and surging demand for construction-grade sand has triggered a deepening environmental crisis related to sand mining[43,44,45]. Because the geography of suitable fill material is heterogeneous, the projected scale of construction required for seaport adaptation and expansion globally could result in an unprecedented "worldwide race for adaptation resources"[40,41]. Coastal reclamation itself is an ancient engineering technology, yet the current scale, rate, and global extent of coastal reclamation is a novel phenomenon[14]. Furthermore, new regional hotspots of seaward seaport expansion may develop, if, for example, China's national Belt and Road Initiative increases and converts on its investments in seaports around the African continent[46,47,48], where signatures of coastal land reclamation are already visible[14].

The analysis we employ here is not limited to container seaports, and could be directed toward other seaport types[4]. To unpack patterns and consequences of seaport expansion seaward, future research might examine the layered and nuanced context of market movements, investment policies, climate adaptation, and operational sustainability at the case-study scale. Another avenue of inquiry might take advantage of increasingly powerful tools for Earth observation to gain a comprehensive perspective of seaports as dynamic sites of intensive anthropogenic coastal modification, bellwethers of coastal risk, and, potentially, of infrastructural climate-proofing.

Methods

To select seaports for our analysis we used the Lloyd's List[25] report of the 100 largest container ports globally, based on reported container throughput in 2020. We differentiated seaports from riverine and inshore ports by mapping them and confirming their industrial land use in OpenStreetMap[49]. We identified 89 container ports located on an open coastline.

We then applied a recently published open-source method for quantifying spatial footprints of coastal land reclamation from satellite imagery in Google Earth Engine, described in detail in ref.[14] (see also Code Availability). We measured annual patterns of seaport reclamation using the 30 m resolution Global Surface Water (JRC-GSW) dataset from 1990 through 2020[30] and its Yearly Water Classification History (v1.4), including "no water" and "seasonal" bands, in Google Earth Engine[14]. Seaport expansion by reclamation **(Fig. 1)** registers as lateral changes in water surface at the coastline, or "lost permanent water surfaces"[38]. We recorded the area of these seaward-shifting footprints at annual intervals, relative to a 1990 benchmark coastline: in 1990, seaward expansion is assumed to be zero; we thus measure non-zero seaward expansion from

1991. Because the image-processing technique underpinning the JRC-GSW dataset uses pixel-scale annual composites, and because coastal reclamation processes are designed to reduce tidal effects on construction[50], we did not apply a tidal correction. Nor did we treat the resulting expansion data with any manual post-processing (e.g., pixel correction, interpolation, smoothing). The time series for some seaports include excursive, uncorrected data points that are likely artefacts of the automated analysis. To explore their effects we also undertook a parallel, intensively manual post-processing method of pixel correction, interpolation, and smoothing, and found that the automatic and manual methods delivered only a ~1% difference in global total area of seaward expansion in 2020. Manual post-processing might therefore affect the time series for a given seaport in detail but not in absolute shape. Here we present the automated measurements because we find them to be a sufficiently accurate representation of seaward expansion, and because they are reproducible.

Delineating an approximate analytical region-of-interest for each seaport was a manual process. We began by querying land-use polygons in OpenStreetMap (e.g., industrial area, industrial land use, terminal islands, etc.) in the vicinity of each seaport. However, such polygons in OpenStreetMap are themselves composites, and do not necessarily reflect the current footprint of a given seaport. We therefore iteratively checked the OpenStreetMap footprint of each seaport against output from the Google Earth Engine analysis for visualising coastal land reclamation[14] to draw a bounding polygon large enough to accommodate the apparent extent of the seaport in 2020. The landward edges of each polygon get clipped to the 1990 composite shoreline by the Google Earth Engine analysis. The bounding polygons for the 65 seaports that we examine in this work are provided with the analytical code (see Code Availability).

Of the 89 container seaports we investigated, 24 seaports returned total areas of seaward expansion smaller than 1 km^2 (equivalent to ~1100 30 x 30 m pixels of lost permanent water surface). In the interest of a conservative survey, we excluded these 24 seaports from consideration. The remaining 65 seaport are associated with seaward expansion greater than 1 km^2 since 1990. Seaward expansion greater than 1 km^2 since 1990 does not reflect the full spatial footprint of a given seaport complex, which may include land reclaimed prior to 1990, and/or extend landward. To corroborate that the seaward growth we measured at these 65 sites is associated with expansion of seaport complexes, we used compilations of recent images (2018–2020) in Google Earth and Planet Basemap to make visual assessments of seaport space relative to the areas returned by our automated process in Google Earth Engine. Our method does not differentiate among specific uses of seaport-related space (e.g., terminal facilities, storage, industry, or other integrated layouts[4,14]), which makes the seaward extents that we observe a partial measure of gross port area.

Given that: (1) the time series for some seaports include artifactual data points, (2) most of the time series are nonlinear, (3) major reclamation projects can register as abrupt jumps in seaward seaport area, and (4) the scale of seaward expansion among these seaports collectively spans three orders of magnitude, we estimated series variability in the following way. Missing data points within a given time series were filled by linear interpolation. Using a three-year sliding window, we detrended each three-point sub-series and calculated its standard deviation (in km^2). For each seaport, we report the mean of theses sliding standard deviations, and also report that mean as a percentage of the total seaward reclamation in 2020 (Fig. 3). We find 53 of the 65 seaports have a mean sliding standard deviation less than 1 km^2, and 61 seaports less than 2 km^2. For 47 seaports, the mean sliding standard deviation represents less than 5% of their total reclaimed area in 2020, and does not exceed 10% for any seaport in our sample. All 65 mean sliding standard deviations in our analysis sum to ~42 km^2, or approximately 4% of the total seaward expansion we calculate for 2020. Again, standard deviation here is not strictly a measure of excursive artifacts from the automated data-extraction process, since large reclamation initiatives register in the time series as abrupt jumps in seaward area; cleaning erroneous returns (whether high or low) for a given year at a given seaport would need to be done manually, from the relevant imagery. Note also that variability we estimate pertains to the time series in our analysis, which is separate from considerations of pixel-scale uncertainty in the underlying Global Surface Water (JRC-GSW) dataset[30]. Our calculations of time series variability are included in the analytical code that accompanies this work (see Data Availability).

Records of TEU throughput between 2011–2020 for 43 of these 65 seaports were compiled from archived Lloyd's List reports.

Data Availability

Study data are available at ref.[51].

Code Availability

Code for calculating seaport area using Google Earth Engine is available at https://github.com/dhritirajsen/Seaport_reclamation. Code for generating the analyses presented in this article are available at ref.[51] and https://github.com/envidynxlab/Seaports.

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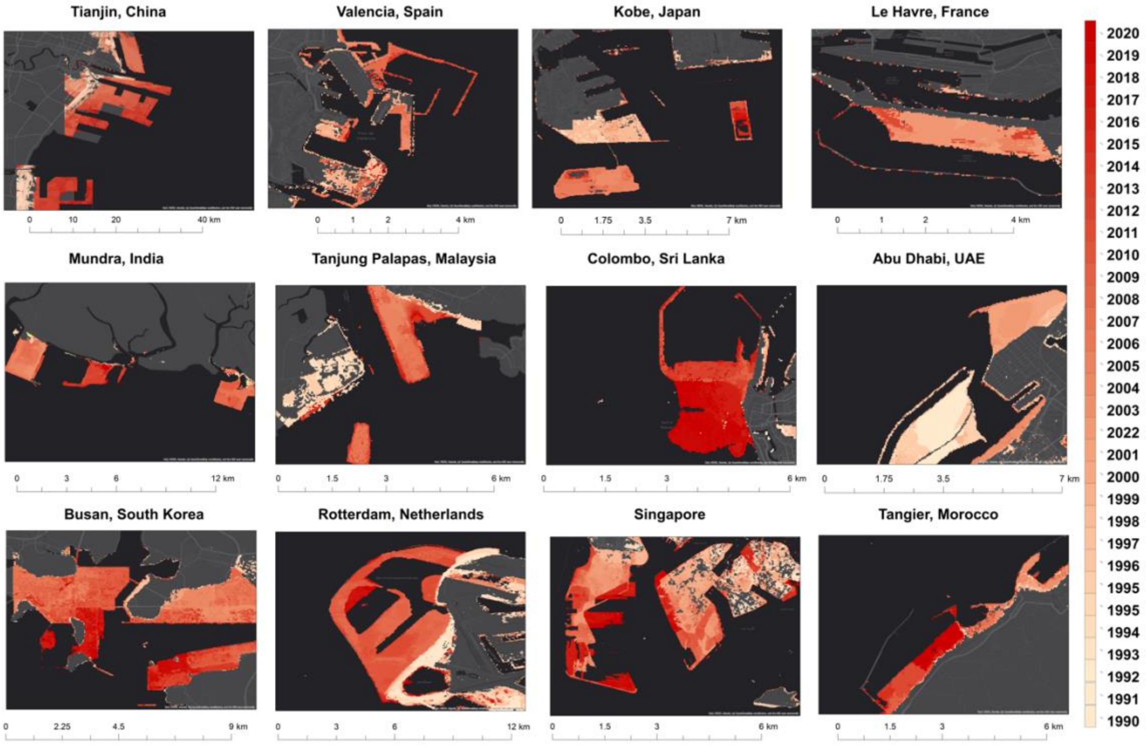

Figure 1: Examples of seaport expansion seaward with coastal land reclamation. Spatio-temporal patterns of expansion in selected container seaport footprints around the world, 1990–2020. Light shades delineate earlier reclamation, dark shades more recent works.

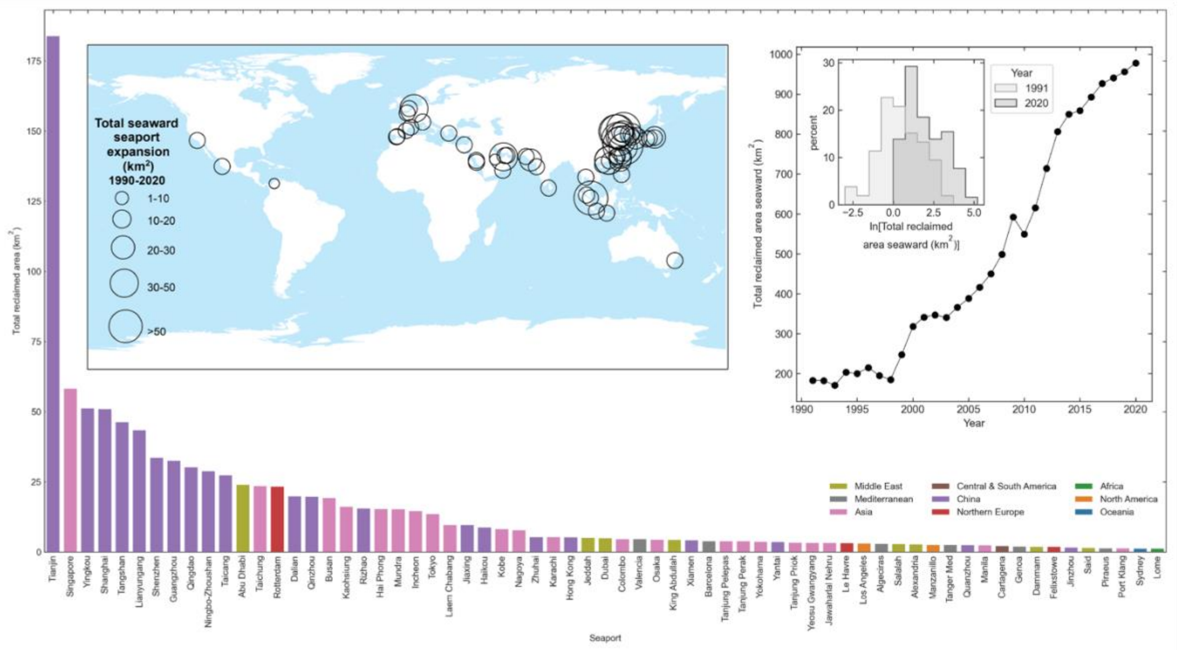

Figure 2: Geographic distribution and magnitudes of seaport expansion seaward among major container seaports. Bar plot shows total area (km^2) of seaward expansion between 1990 and 2020 for 65 of the world's top 100 container seaports by reported trade volume in 2020[25]. Regions are those defined by Lloyd's List[25]. Inset map shows their geographic distribution; circle size indicates the relative magnitude of total seaward expansion. Inset plots shows an annual time series of the total seaward-directed change in area for these 65 seaports between 1990 and 2020, and their comparative distributions of seaward area (in log scale) in 1991 versus 2020.

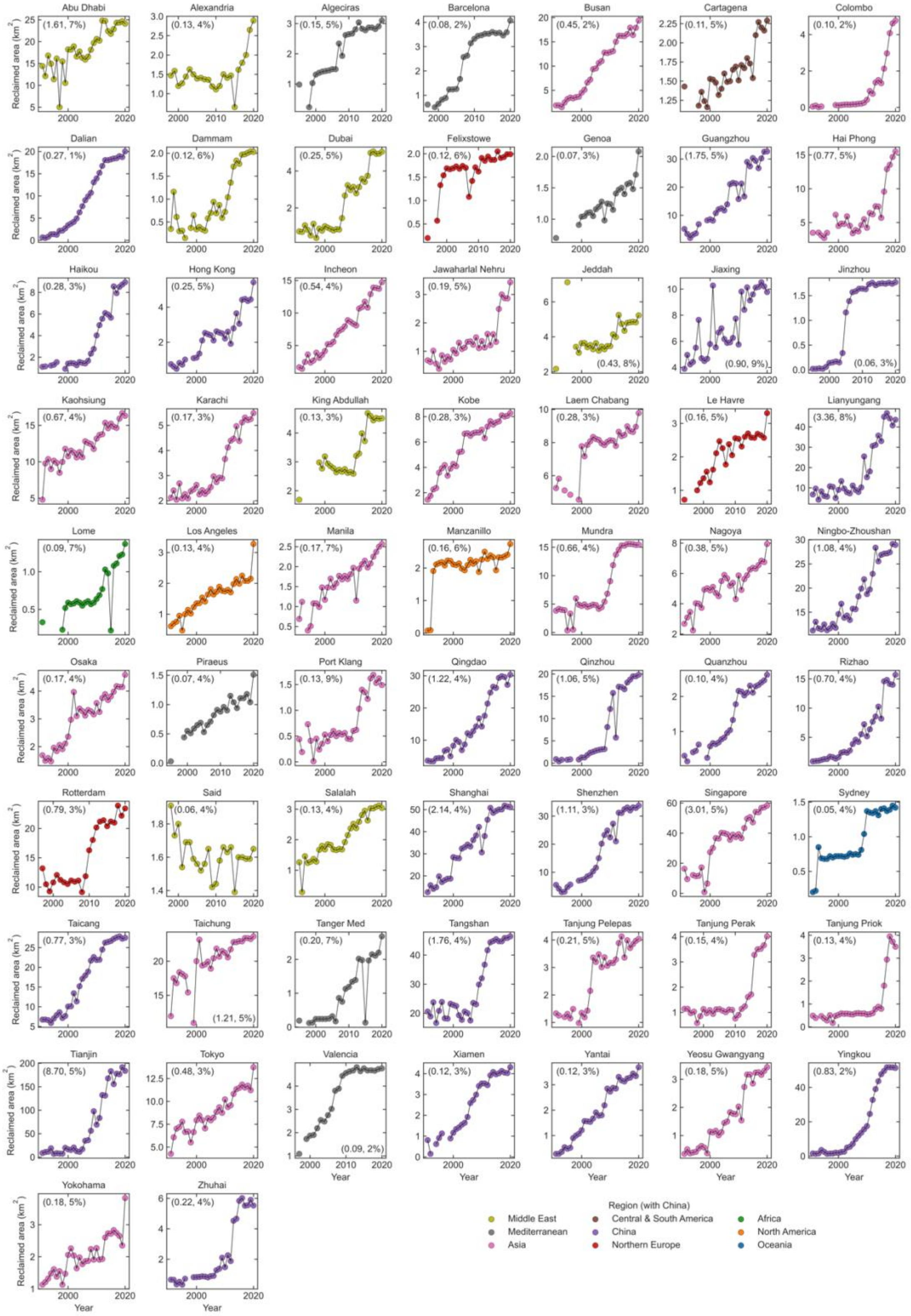

Figure 3. Annual time series of seaport expansion seaward. Subplots document expansion seaward, in km^2 (left axis) between 1990 and 2020 for 65 of the world's top 100 container seaports by reported trade volume in 2020[25]. Subplots are arranged in alphabetical order. Colour indicates region, with China denoted independently. Gaps indicate missing data. Parenthetical values in each subplot report the mean running standard deviation (in km^2) for the series (see Methods), and that value as a percentage of the total reclaimed area for that seaport in 2020, respectively. Note that the scale of the vertical axis differs among subplots.

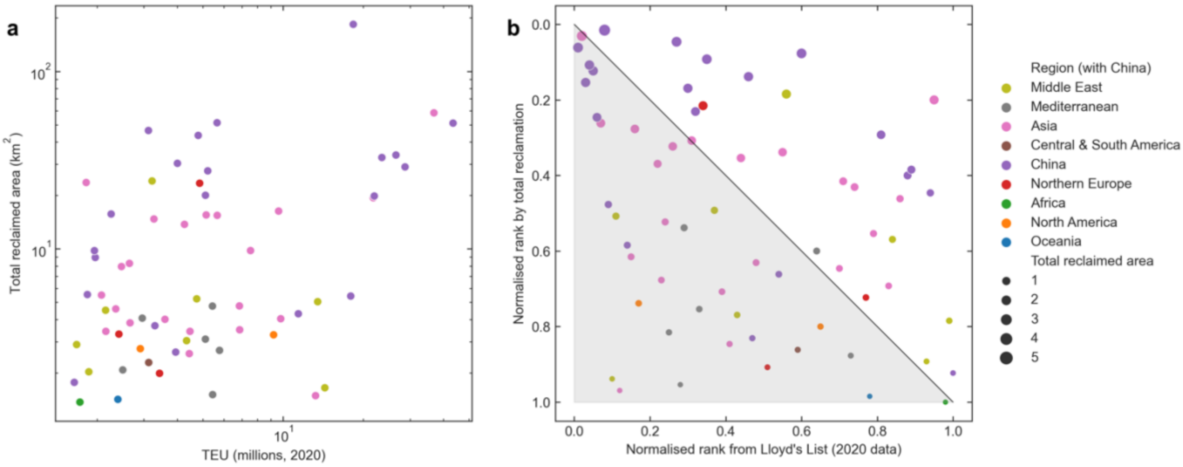

Figure 4. Relationship between total seaward expansion and reported container throughput in 2020. (a) Scatterplot, in log-log scale, of total reclaimed area seaward (km^2) between 1990–2020 and reported container throughput (millions TEU) in 2020 for 65 of the world's top 100 container seaports[25]. Colour indicates region, with China denoted independently; marker size is uniform. Convention of axes is consistent with ref.[16]. **(b)** Scatterplot of normalised seaport rank by total seaward expansion (as in Fig. 2) versus normalised rank by reported container throughput in 2020[25]. Axes convention is such that top-ranked seaports by both metrics (largest expansion, greatest throughput) cluster at upper left. Marker size represents relative magnitude of total seaward expansion. Reference line indicates hypothetical 1:1 correlative relationship, in relative terms, between seaward expansion and container throughput.

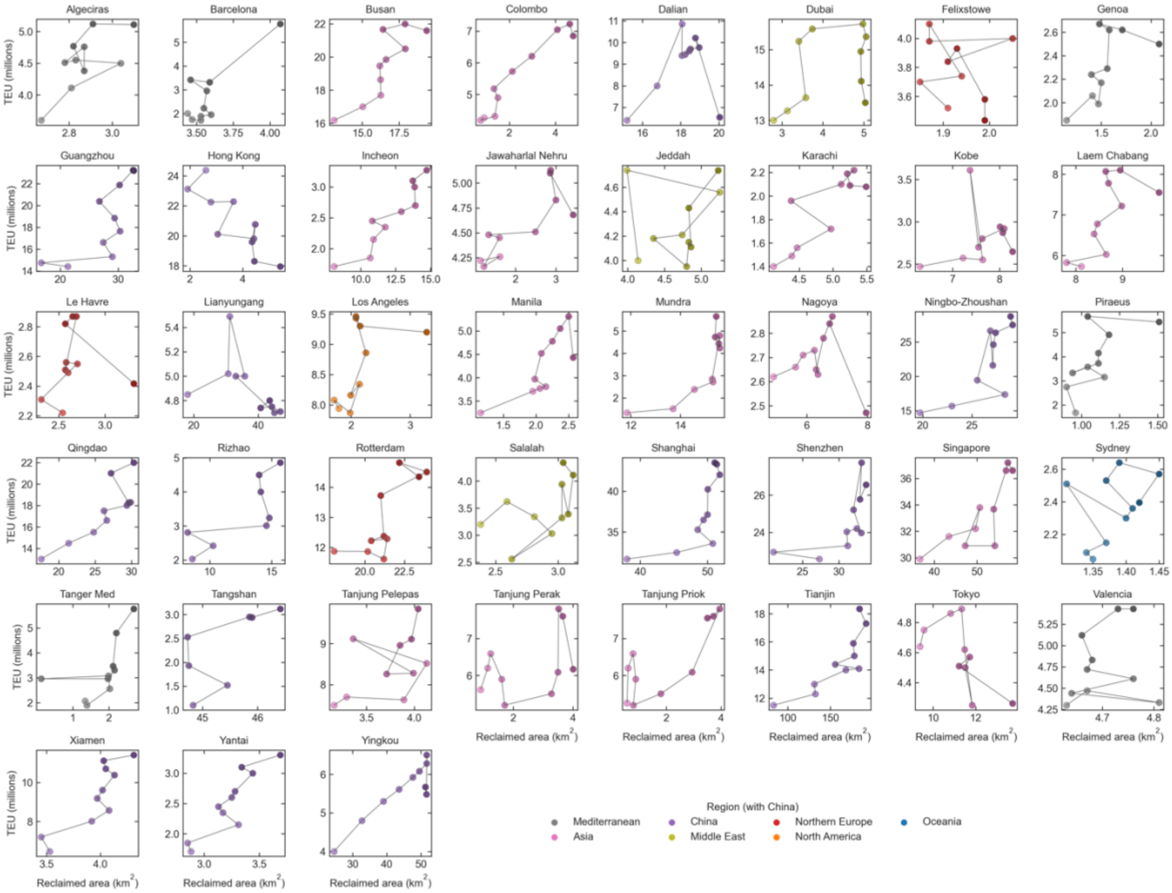

Figure 5. Trajectories of container trade volume relative to seaport expansion seaward. Subplots show partial phase space defined by container trade volume (TEU millions) and seaport expansion seaward (km^2) between 2011 and 2020 for 43 of the world's top 100 container seaports by reported trade volume in 2020[25]. Subplots are arranged in alphabetical order. Marker colour indicates region, with China denoted independently; marker value indicates year, advancing from light (2011) to dark (2020).