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OPINION

The overlooked sustainability trade-offs of port adaptation at scale

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Introduction

Seaports host a high density and value of infrastructure and industry, covering an area of around 5.4 million km^2 globally [1]. Due to climate change, and in particular rising sea levels, physical damages and operational downtime may increase considerably [1,2]. Much of the infrastructure built over the last decades did not consider climate change in its original design [2], requiring adaptation to maintain functionality. Over the years, port administrators have recognized the climate challenges ahead [3,4] and moved it up on the sustainability agenda [5]. However, adaptation at the global scale will require huge materials footprints, could make existing port assets become obsolete, and may cause further harmful interference in the natural environment. Despite the growing attention of the need to adapt ports, we argue that the sustainability trade-offs of port adaptation at scale should be explored accordingly, as this may result in environmental limits to adaptation. In this opinion piece, we synthesize the existing evidence on the sustainability trade-offs associated with climate adaptation, and propose three key avenues for future research.

Evidence of adaptation planning

Broadly speaking, there are three types of strategies for adapting ports to sea level rise and changing weather extremes; accommodate, defend and retreat.

Accommodating port facilities entails adapting port infrastructure to new design levels. Elevating port terminals is the most widely considered adaptation option and implies artificially raising the port terminals, or part of them. For instance, one study estimated that elevating United States ports by two meters would require 60 – 80 USD billion [6], while elevating 53 large ports in the Asia-Pacific with 1.6 and 2.3 meter would need 30 – 50 USD billion [7]. Other accommodating options include increased dredging, upgrading drainage works, elevating access roads, nature-based solutions, and improved tie-down systems for cranes.

Defending a port entails the construction of coastal or riverine protection infrastructure, such as breakwaters, storm barriers, embankments, flood walls or locks [8]. A number of studies have evaluated the need to retrofit breakwater structures or build new protective infrastructure, such as Esteban et al. [9] for ports in the Tokyo

Bay and Sierra [10] for 47 ports in Spain. In the latter case, breakwaters could not be upgraded at a reasonable cost, emphasizing (financial) limits to adaptation.

Retreat strategies encompass a complete relocation of existing port facilities, or alternatively partial reallocation of port activity from one port or terminal to another. Cases of planned retreat are not yet considered to the best of the authors' knowledge. Still, since retrofitting existing terminals could be too expensive, a gradual shift towards inland terminals, other freight modes (e.g., rail, road), or, in case of limited available land, seaward expansion of terminals to cope with climate change may be considered. This is corroborated by earlier findings of Becker *et al*., where the majority of surveyed ports (58%) responded that sea level rise of one meter or more would cause problems for operations [2].

Sustainability trade-offs of port adaptation at scale

Adapting ports to climate change inevitably results in sustainability trade-offs, due to both the environmental footprint of adaptation solutions and their negative impacts on the local environment. Limited research has attempted to quantify the environmental impacts of port adaptation or explored solutions to navigate these trade-offs, especially when considering the aggregate impacts of many ports undertaking adaptation strategies simultaneously. Such activities will be resource- and cost-intensive, resulting in their own adaptation emissions footprint.

As a starting point, *accommodating* ports will require large amounts of material resources, in particular concrete, aggregates, and sand. One estimate suggests that the dredged material needed to elevate ports in the United States by two meters would be around 700 million m^3 [6]. Considering that United States ports cover less than 10% of the global port area [1], the need for dredged material globally would be around 7 billion m^3 to cope with sea level rise long-term. For context, this would be equal to 35 times the amount of dredging that was needed for the expansion of the Suez Canal in 2015 (~200 million tonnes). On top of that, changing water levels and wave climate can alter the need for maintenance dredging of navigation channels. On the one hand, higher water levels may reduce the need for maintenance dredging, though the rate of sea level rise is unlikely to outpace the need for regular maintenance dredging. On the other hand, deeper water depths can elevate wave heights and tides, which alongside changes in the wave direction, can increase the rate of sedimentation. Dredging operations have known environmental impacts, i.e., emitting greenhouse gasses (both CO_2 and methane), disturbing marine ecosystems, and causing harmful contamination of the environment [11]. One study has called for a better quantification of the ecosystem-based carbon footprint of port projects [12]. This would entail quantifying the impacts on the carbon storage and sequestration functioning of blue carbon ecosystems, either directly imposed by the engineering project or indirectly by altering hydrological or sedimentation dynamics.

In a similar fashion, *defensive* strategies require vast amounts of materials. Becker *et al*. estimated that to adapt 221 seaports to two meters of sea level rise, 148 million m^3 of concrete, 125 million m^3 of stone and 110 million m^3 of sand would be required [8]. This study stressed the potential challenge in mobilizing such vast amounts of materials. While globally, the materials needs of port adaptation may seem small compared to the total material production (mainly for construction), locally it can create competition for resources, in particular sand, silt and stone. Moreover, resource production will have an indirect effect on carbon emissions and other environmental impacts (e.g., water footprint). Understanding these wider environmental impacts, and designing alternative adaptation strategies to minimize the environmental impacts is therefore imperative.

Evidence suggests that financial or technical constraints exist with respect to port adaptation [2]. The *retreat* of port terminals can result in terminals becoming obsolete as a result of climate change, or being replaced with new terminal expansion projects. The retreat of port terminals can have significant environmental implications. First, such brownfield sites often have limited potential for re-use given their highly polluting environment, alongside environmental impacts associated with razing and disposing of existing infrastructure. However, brownfield sites can also be seen as opportunities for redevelopment of new industrial activities. For instance, in the United Kingdom, a former oil and gas fabrication yard was redeveloped into an offshore wind manufacturing facility [13]. Second, port retreat may also initiate further port expansion to compensate for lost port areas. Port expansion is already the dominant driver of coastal land reclamations globally [14], with the top-100 container ports alone adding almost 1000 km^2 of new port areas between 1990 and 2020 through coastal land reclamations [15]. Land reclamations have large environmental footprints in terms of materials and associated environmental impacts, and hence widespread port terminal retreat may impose large stress on local ecosystems.

The way forward

Seaports globally will face pressing challenges to adapt to a changing climate. Despite this widespread recognition, we argue that the sustainability implications of adaptation at scale are still unexplored, which may pose additional adaptation constraints. Here, we propose three main research avenues that intend to improve our understanding of the large-scale environmental impacts of port adaptation.

First, there is limited understanding of the global or regional adaptation needs, both in terms of investments and materials, and how this may differ geographically and under different climate scenarios. These need assessments serve as a starting point for quantifying the environmental footprints of port adaptation, and identifying the potential challenges of mobilizing these environmental resources.

Second, as highlighted in this paper, activities to protect, accommodate, or retreat ports will result in greater disturbances affecting the coastal zone, and associated resource demands and emissions footprints. This increased activity will, in turn, have global implications for climate change. As such, better insights in the environmental trade-offs of adaptation can help spark innovative ideas to cope with climate change while minimizing, or even benefiting, the environment. For instance, to widen the Houston Ship Channel, as part of the Galveston Bay flood protection plan, dredged materials are used to create artificial barrier islands with restored wetlands. These solutions show that port developments to protect against climate change can also be a window of opportunity to embed nature in design, which can have benefits both locally and globally.

Third, as sustainability becomes increasingly important for ports globally, both to decarbonize and to reduce environmental impacts, port adaptation will inevitably create frictions in sustainability governance. As a result, aside from technical and financial limits to adaptation, there may also be environmental limits to adaptation in geographies with strict environmental regulations. It may prove more efficient to consolidate port activities or even shut down some ports entirely, as opposed to investing to adapt every one of the world's 3,800 ports. Insights are needed into how port adaptation should be governed and enacted from a broader sustainability perspective to ensure local and national governments can achieve their sustainability and adaptation ambitions.

Author contributions

Conceptualization: Jasper Verschuur, Austin Becker.

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References

1. Verschuur J, Koks EE, Li S, Hall JW. Multi-hazard risk to global port infrastructure and resulting trade and logistics losses. Commun Earth Environ. 2023;4(1). https://doi.org/10.1038/s43247-022-00656-7
2. Becker A, Inoue S, Fischer M, Schwegler B. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Climatic Change. 2011;110(1–2):5–29. https://doi.org/10.1007/s10584-011-0043-7
3. UNCTAD. Port Industry Survey on Climate Change Impacts and Adaptation. UNCTAD Res Pap No 18. 2017. Available: http://unctad.org/en/PublicationsLibrary/ser-rp-2017d18_en.pdf
4. Lin Y, Ng AKY, Zhang A, Xu Y, He Y. Climate change adaptation by ports: the attitude of Chinese port organizations. Maritime Policy & Management. 2020;47(7):873–84. https://doi.org/10.1080/03088839.2020.1803430
5. ESPO. ESPO Environmental Report 2023. Brussels; 2023. Available: https://www.espo.be/media/ESPO Environmental Report 2023.pdf.
6. Becker A, Hippe A, Mclean E. Cost and Materials Required to Retrofit US Seaports in Response to Sea Level Rise: A Thought Exercise for Climate Response. JMSE. 2017;5(3):44. https://doi.org/10.3390/jmse5030044
7. ARE. Climate Costs for Asia Pacific Ports. 2018. Available: https://asiareengage.com/wp-content/uploads/2022/12/APACportsclimatecosts.pdf
8. Becker A, Chase NTL, Fischer M, Schwegler B, Mosher K. A method to estimate climate-critical construction materials applied to seaport protection. Global Environmental Change. 2016;40:125–36. https://doi.org/10.1016/j.gloenvcha.2016.07.008
9. Esteban M, Takagi H, Shibayama T. Adaptation to an increase in typhoon intensity and sea level rise by Japanese ports. Clim Chang Adapt Plan Ports. 2016. p. 117–32.
10. Sierra JP. Economic Impact of Overtopping and Adaptation Measures in Catalan Ports Due to Sea Level Rise. Water. 2019;11(7):1440. https://doi.org/10.3390/w11071440
11. Manap N, Voulvoulis N. Data analysis for environmental impact of dredging. Journal of Cleaner Production. 2016;137:394–404. https://doi.org/10.1016/j.jclepro.2016.07.109
12. Nieuwkamer R, Kox MAR, Fiselier J, van Wieringen DRG, Tonneijck FH, Cronin K. Reducing the ecosystem-based carbon footprint of coastal engineering. 2022.
13. Snieckus D. Scotland's Nigg steel yard reborn for offshore wind in emerging "North Sea 2.0" era. In: Recharge. 2021.
14. Sengupta D, Choi YR, Tian B, Brown S, Meadows M, Hackney CR, et al. Mapping 21st Century Global Coastal Land Reclamation. Earth's Future. 2023;11(2). https://doi.org/10.1029/2022ef002927
15. Sengupta D, Lazarus ED. Rapid seaward expansion of seaport footprints worldwide. Commun Earth Environ. 2023;4(1). https://doi.org/10.1038/s43247-023-01110-y