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SDG 12 needs an oceanic interface: sand mining, saltwater intrusion (SWI) and coastal sustainability

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Abstract

The international development community has approached SDG 12 (Responsible Consumption and Production) through the lens of specific supply chains of consumer goods and services. For example, minerals from mines to markets; wood from forests to furniture; or food from farm to fridge, have been tracked in terms of their ecological profile in many of the SDG 12 targets. While such an approach can give us some idea of particular recycling or refurbishment opportunities, as well as waste-toenergy generation, it lacks a systems-oriented view on the interlinkages between socio-ecological systems of consumption and production. We argue that SDG 12 needs to be reimagined in terms of lateral impacts and connections in key sectors of resource extraction. Sand mining and saltwater intrusion (SWI) present an important example of how such a connection could be made between an anthropogenic activity in a coastal / marine environment and its ecological impact that could threaten food security. We present a review of research in this context that links these two seemingly disparate areas of academic inquiry. Focusing on the Mekong Delta we also consider how geospatial techniques could help to evaluate these connected impacts between sand mining and SWI and its consequential impacts on arable land and hence food availability and hunger. Considering a series of methodological challenges, we offer a way forward for measuring these impacts and charting a more integrative way forward for operationalizing SDG12 towards more sustainable environmental and social outcomes.

Introduction

Much of the current conversation around SDG12 has focused on material flows and the circular economy. While these are essential aspects of "sustainable production and consumption," it is important to have more lateral considerations of ecosystem services that might disrupt the attainment of SDG 12. In this vein, we consider how coastal environments, where much of the world's habitation remains concentrated, will have impaired agricultural productivity due to soil degradation. A major cause for impaired agricultural production and food security in these areas is sand mining for myriad industrial uses, which adds an additional connection with SDG12. When sand is mined in estuaries, there is a

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disruption in the groundwater hydrology in surrounding coastal areas which allows for saltwater to intrude further into coastal aquifers.

The ubiquitous issue of saltwater intrusion (SWI) in coastal ecosystems has sparked global concern but often this is seen as a localized hydrological problem [1–4]. However, a systems science perspective suggests that upstream impoundments and sand mining has a major connection with SWI, and this, in turn, is being amplified by sea level rise linked to climate change [5, 6]. Researchers are employing multifaceted approaches to comprehend the intersection of climate change, anthropogenic activities, and their impact on coastal ecosystems [7–11]. This understanding is crucial not only to mitigate the damage and safeguard the environment but also to adapt to changes that may prove irreversible. The escalation of SWISWI is amplified by sea-level rise, storm surges, land subsidence, drought, groundwater pumping and sand mining [12–14] (targets the SDG 12.2 - achieve the sustainable management and efficient use of natural resources) together pose a pressing threat to coastal ecosystems.

Among all other issues, sand mining presents a neglected nexus around SDG12 attainment and its linkages to coastal arability. Sand is ecologically connected to nature and nourishes biodiversity and the ecosystem. Strategically, sand is key to securing livelihoods through the construction of infrastructure and hence developing an industrial economy. However, poor governance and regulations from industry and institutions concerning extraction, sourcing, supply, and management affect the ecosystem and the long-term supply locally and globally [15–17]. In the present world, everyday life is tightly linked with the use of sand and sand products. As Vince Beiser wrote in his book, '*The World in a Grain: the Story of Sand and how it transformed civilization*'

> *"Sand is the thing that our cities are made out of… every concrete building that you see is basically just a huge pile of sand glued together with cement. All the roads that connect all those buildings — also made of sand. All the windows in those buildings are made from sand. The silicon that powers your computers, your cell phones, the chips in your electronics, that's also from sand. So basically, without sand, we have no modern civilization" [18].*

Each year, 50 billion metric tons of sand are unearthed, mostly for construction purposes, with an average of 18 kg per person daily; this rate of extraction is rising 6% annually [17]. Driven by demand and interest, this 70-billion-dollar industry [15] pushes unsustainable mining, causing irreparable environmental and ecosystem destruction through salt water intrusion. Most sand, up to 75%, drives concrete manufacturing for building structures of modern infrastructure development. Since 2010, the demand for silica sand increased from 180. 1 million metric tons to 303. 5 million metric tons in 2020, with China alone consuming over 80 million metric tons in 2020 (Table 1). The projection for 2025 is even higher; with 406 million metric tons of total global demand, China consumes 137 million metric tons alone. Incredibly, the demands that run everyday life cannot be satisfied with sand from the desert because wind-eroded sand is too rounded for effective interlocking material integrity for construction. Modern construction requires angular sand from the ocean floor and lakes, but fluvial sands from riverbeds have the best quality and are cost competitive [19]. Hence, we are stripping riverbeds, floodplains, and beaches to obtain usable sand. In the mid-1900s, sand mining was dominant in developed countries for construction and landfills, which extended to the fast-growing economies or developing nations over the last three decades, like China, India, and other parts of Southeast Asia [20]. Given the dominance of sand mining in Asia, we provide an example of impacts from one of the region's great riparian deltas – the Mekong – to consider monitoring and mitigation tools.

There is substantial empirical evidence on sand mining as a key influence in coastal saltwater intrusion. On the eastern coast of Odisha, India, massive sand mining is causing coastal erosion, which consequently favors SWI into the freshwater zone [21].

The Mekong Delta of Vietnam, a significant food supply zone for Southeast Asia, is continuously threatened by climate-induced stressors and SWI exacerbated through anthropogenic sand mining [22–24]. Moreover, studies show that dropping riverbed levels by groundwater withdrawal and sand mining can extend the salinity intruded area by 10–27% more than the current situation [9]. In Southern Sri Lanka, excessive sand mining is driving SWI into the two main rivers -- Nilwala and Ginganga – located on the coast of the Kaluganga river [25–27].

Sand mining instigates the shoreline to move in, thereby reducing the buffer zone around the riverbank, which can lead to water slides into the valley, resulting in flooding and further erosion [25, 27, 28]. Moreover, sand extraction from active sand bodies affects sand

Table 1 World Industrial Silica Sand Demand (In million metric tons, 2010–2025 – based on data from Freedonia Group research)

Year	Total (Million Metric tons)	China (Million Metric tons)	United States (Million Metric tons)	Other Asia/Pacific (Million Metric tons)
2010	180.1	56.3	31.2	29.4
2015	244.2	83.6	56.1	34.3
2020	303.5	109	72.5	42.1
2025	406	137	123.4	51

transportation to riverbeds, nearby coasts, or marine areas both in withdrawal places and downstream [16]. The process leads to soil erosion and infertility, threatening food production and traditional livelihoods [29]. There is also a long-term impact on the ecosystem viability of the region. For instance, river sand mining is interrupting fish movements, bird migration, and microbial diversity that is essential for nutrient cycling. Nearly 24 islands have disappeared in Indonesia since 2005; coral reefs have been destroyed in Kenya; and hundreds of acres of forest land have been ripped by aggressive miners to get sandy soil beneath in Vietnam [18].

Consequences of SWI manifest in various ways: expansion of barren farmland due to salinization; the encroachment of ghost forests and salt-tolerant invasive species; and decreased crop yields. These impacts lead to food losses, which have a dire and direct impact on farmer livelihoods and consumer supply chains. Hence, our current research targets SDG 12.3, which aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses [30–32]. This alarming trend also contributes to the expansion of coastal marsh areas, often encroaching upon productive farmlands, which has cascading effects on agriculture, coastal ecosystem services, human well-being, and the economy [7, 33] (hence fits into SDG 12.4 - achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment). Though cultivating crops on saline soil can yield high outputs with the help of alternative chemical additives, this solution has a flip side that affects water quality [34] (SDG 12.4). Striking a balance between agricultural productivity (output per unit of energy and materials inputs) and environmental integrity remains a challenge.

In delta regions worldwide that have been impacted, the documented alterations in SWI are primarily linked to anthropogenic actions, including alterations in hydrological cycles, erosion caused by dams upstream, sand mining, and groundwater extraction [9]. A recent study on the projections of salt intrusion in Mekong Delta under climatic and anthropogenic stressors showed that reducing sand mining and the amount of groundwater pumped can save up to 600,000 hectares of land from saline water [Fig. 1]. Additionally, the study underscores the Mekong Delta's vulnerability to sediment scarcity, projecting that by 2050, half of the delta may become saline due to sediment deficits. Remarkably, human activities, particularly riverbed erosion from sediment loss, have a greater impact on SWI in the first half of this century than climate change and rising sea levels combined. Global-scale research indicates that salt-affected soils are prevalent in diverse climate zones and continents. These soils cover an estimated global area ranging from approximately 8.31 to 11.73 million square kilometers, depending on the methodologies employed for assessing their extent [10].

Challenges to pursue SDG 12 in Coastal Areas

Navigating the pursuit of SDG 12 (Ensure sustainable consumption and production patterns) in the context of SWI poses a myriad of challenges that require careful consideration and innovative solutions. Here are five prominent challenges that arise in this specific field:

1. **Complex Interplay of Factors**: Addressing SWI involves understanding the intricate interplay between climate change, sea-level rise, land subsidence, and human activities. These multifaceted dynamics make it challenging to isolate individual causes and devise effective interventions that simultaneously mitigate impact and necessitate a holistic approach to sustainable consumption and production patterns.
2. **The Global Sand Mining Rush**. The rapid need for construction materials worldwide has led to sand mining operations which are causing a massive impact on coastal hydrogeology. Saltwater is able to intrude as layers of buffers get disrupted by massive sand mining operations, particularly in river deltas.
3. **Balancing Agricultural Productivity and Environmental Integrity**: The quest for higher crop yields on saline soil through chemical additives poses a dilemma. While this approach offers increased productivity, it threatens water quality and potentially triggers unintended ecological consequences. Striking the right balance between agricultural output and maintaining ecological equilibrium is a persistent challenge.
4. **Limited Technological and Scientific Capacity**: Applying Geographic Information Systems (GIS) technology and advanced mapping algorithms to monitor SWI demands technological and scientific expertise. In regions with limited resources, such as the global south and developing countries, accessing and deploying these advanced tools presents a significant hurdle, impeding effective monitoring and decision-making.
5. Implementing sustainable consumption and production patterns requires tailoring solutions to diverse geographical, environmental, socio-economic, and cultural conditions. What works effectively in one region might not be directly applicable elsewhere. Adapting strategies to fit local conditions while adhering to overarching sustainability principles is an ongoing challenge.

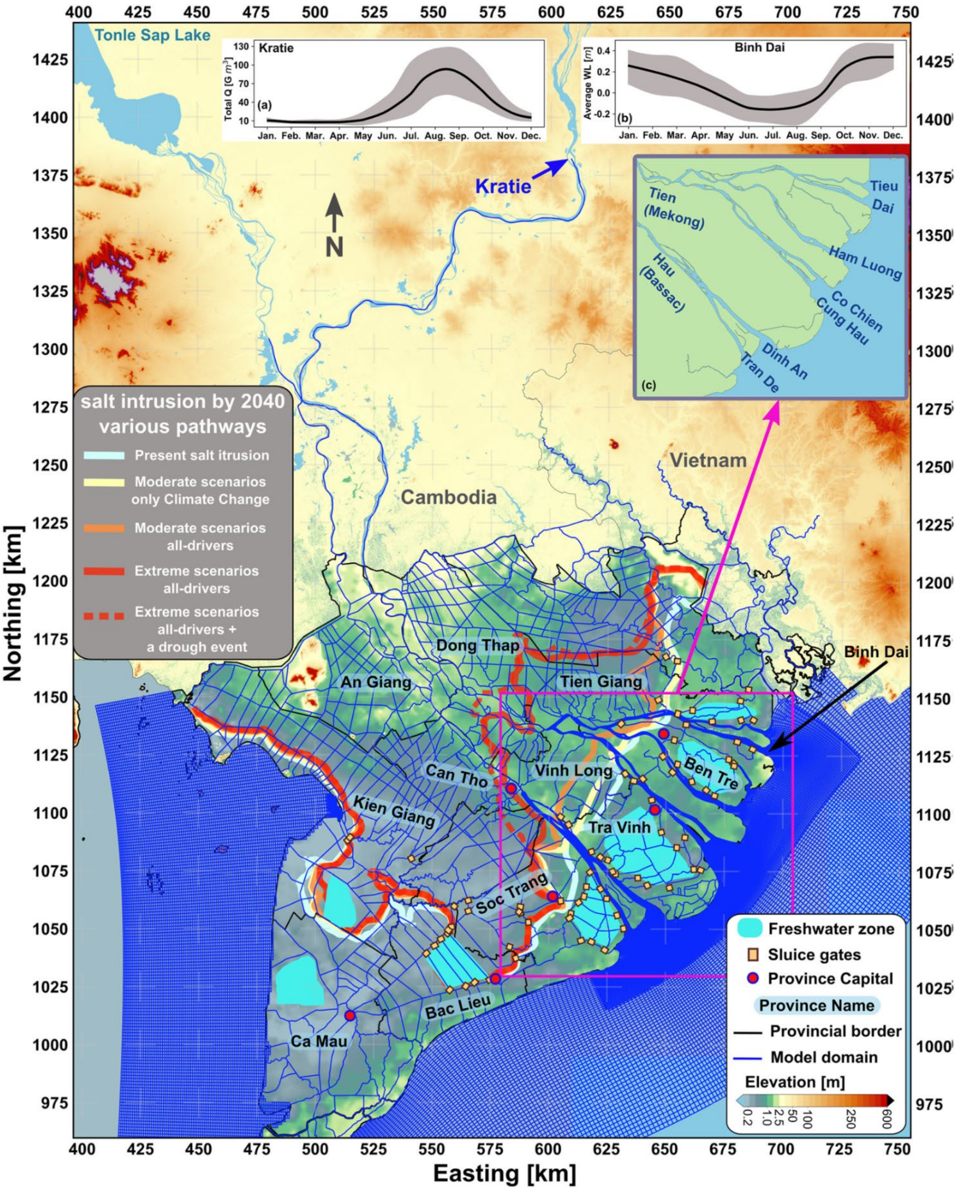

Fig. 1 Range of expected salinity intrusion changes in the Vietnamese Mekong Delta. Present and projected peak saline water intrusion (2 PSU contour lines) under scenarios of climate change (SLR and discharge variation under RCP scenarios), groundwater extraction-induced subsidence (M2 & B2) [35] and riverbed level incision due to sediment starvation (RB1 & RB3) laid over the digital elevation map of the VMD; [36] RCP4.5 + M2 + RB1 (moderate scenarios all drivers) defines a scenario with climate change-driven discharge variation and sea level rise combined with M2 land subsidence and RB1 riverbed level incision (likewise for scenarios all drivers); the surface water numerical model domain and the provincial map of the VMD (coord. system WGS84-UTM 48 N); Monthly variation of cumulative discharge in Kratie with mean and the envelope in gray (a) and monthly averaged water level in Binh Dai with the envelope in gray (b); Estuarine branches (c)

As climate change continues to reshape our planet, predicting the evolution of SWI patterns is a formidable challenge. Long-term planning requires anticipating how changing environmental factors will interact and affect the extent of intrusion, which is crucial for devising proactive mitigation and adaptation strategies.

Progress made

To address SWI as a complex issue, we developed a GIS app that empowers farmers and individuals to contribute valuable data to researchers. This data, in turn, assists GIS scientists in refining mapping algorithms that continuously track the scope and evolution of SWI's impact on coastal farmlands. The insights obtained from this mapping endeavor empower farmers with information about the past, present, and future states of their land, hence in turn facilitating profitable and sustainable farm management while respecting nature's harmony (SDG 12.8 - ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature).

Our GIS mapping algorithm utilizes freely available Sentinel 2 satellite data, accessible every five days worldwide, and operates on standard computers, bypassing the need for high computational power (and the associated technological costs). This approach is designed with global scalability in mind, particularly for regions with limited scientific and technological resources (SDG 12.A - support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production). The following four step.

1. **GIS Technology and Mapping Algorithms**: The development of a GIS app that enables farmers to contribute data for mapping SWI represents a significant advancement. This technology-driven solution empowers stakeholders to actively participate in addressing the issue.
2. **Sentinel 2 Data Utilization**: Leveraging freely available Sentinel 2 satellite observation data for mapping purposes is a substantial achievement. This data accessibility enhances our ability to monitor changes over time and track the extent of SWI's impact.
3. **Global Scalability**: The approach to GIS mapping algorithm design, considering global scalability, addresses the challenge of limited technological resources in developing regions. By utilizing standard computers and openly available data, this strategy facilitates wider adoption.
4. **Holistic Perspective**: The data should be considered within the context of a holistic understanding of the issue, considering interconnected factors and their implications. Connections to other SDGs should be considered through a network map.

With these four steps, we can ensure that farmers are able to benefit from technologies that may seem esoteric and disempowering to them. Social justice concerns about access to data can also be addressed therein.

Conclusions

In summary, while pursuing SDG 12 within the context of SWI presents challenges such as complexity of ecological variables, technological limitations, and the need for adaptation, progress has been achieved through technology-driven solutions. Data accessibility, harnessing local knowledge, and the incorporation of holistic approaches can ensure that we safeguard coastal ecosystems while promoting sustainable consumption and production patterns. The connection between sand mining and SWI highlights the importance of more lateral approaches to operationalizing SDG 12.

Abbreviations

PSU	Practical Salinity Unit
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SLR	Sea Level Rise
SWI	Saltwater Intrusion

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SA designed the article, MS, NS and SA collectively wrote the article.

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