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COASTAL VULNERABILITY ASSESSMENT BASED ON MULTIPLE BIO-GEOPHYSICAL HAZARDS: A CASE STUDY IN LA UNION, PHILIPPINES

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ABSTRACT

This study focuses on the coastal vulnerability of La Union, Philippines, a province located along the western coastline in the northern island of the country. Using the Coastal Vulnerability Model in the Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST), the research assesses the spatial distribution of exposure to flooding and inundation due to extreme weather events in La Union. The results reveal varying levels of vulnerability, with a substantial proportion of the coastline categorized as very low to low exposure. However, moderate and high exposure areas are also identified, indicating specific locations with heightened risks. Two scenarios, (i) with and (ii) without natural habitats, are compared to quantify the influence of habitats on coastal vulnerability. The study emphasizes the importance of natural habitats, such as mangroves, in providing coastal protection. Moreover, the need for targeted interventions, adaptive management, and sustainable development practices to mitigate climate change's impacts and protect coastal communities and ecosystems in La Union, Philippines, is being highlighted as an important strategy to enhance resilience against natural coastal hazards. This is the first study that employs the InVEST suite of models in assessing coastal vulnerabilities in the Philippines.
Keywords: Bathymetry, Coastal Erosion, Inundation, Sea-Level Rise, Topography

INTRODUCTION

Climate pressures on coastal areas have become unprecedented throughout the years as these areas face constant jeopardy from natural hazards such as storm surges, tropical cyclones, and floods (Al Ruheili & Boluwade, 2023). In fact, projections indicate that risks to coastal areas will escalate in the twenty-first century due to the combined effects of rising sea levels, the expanding presence of human development in flood-prone coastal regions, and other climate change-induced events (Tiggeloven *et al*., 2020). This, in turn, yields cascading effects ranging from flooding and coastal erosion to the destruction of critical ecosystems, such as mangroves and coral reefs. This intensification of risks to coastal communities resulted in increased coastal vulnerability, which, in a more precise definition, refers to the susceptibility of coastal communities to the detrimental impacts of climate change. Anthropogenic activities and climate change have already significantly degraded approximately 60 % of global ecosystems, with the continuation of this threat anticipated in the future as climate change advances (Pereira *et al*., 2010). As such, coastal regions around the world are becoming increasingly vulnerable to these effects, putting both human populations and valuable ecosystems at risk, especially in countries like the Philippines (Yusuf & Francisco, 2009).

In the Philippines alone, the extent of mangroves has witnessed a substantial decline from an estimated 400,000-500,000 hectares in the 1920s to approximately 120,000 hectares in 1994 (Primavera, 2000). This decline can be attributed to the overexploitation of mangroves and their conversion into agricultural lands, salt ponds, and commercial settlements (Garcia *et al*., 2014). As a result, the loss of a protective buffer provided by coastal ecosystems and natural habitats increases the vulnerability of coastal populations and infrastructure to natural hazards. It has become essential to adopt an ecosystem-based management approach to address this issue (O'Higgins *et al*., 2019). Addressing climate change, monitoring human impact on ecosystems and societies, and applying sustainable practices are essential for facing present and future challenges (Yang *et al*., 2020). All of these are covered by the targets of the Sustainable Development Goals (SDG), particularly SDG14 (Life on Water) by the United Nations, thus promoting strong sustainability in such areas (Neumann *et al*., 2017).

The prevailing increase in coastal vulnerability emphasizes the roles of natural habitats in mitigating coastal risks and hazards and is among the major approaches in coastal sustainability and resiliency programs. Being a precursor for this science-based approach, there is a developing research interest in the methods that assess coastal vulnerability. There have been a number of models that have been developed to evaluate the effects of sea level rise, erosion, and inundation (Gornitz *et al*., 1990; Cooper & McLaughlin, 1998; Hammar-Klose & Thieler 2001; Marzouk *et al*., 2021; Parthasarathy, 2021) based solely on either geophysical characteristics or qualitative assessments of natural habitat. However, relatively few models consider both the geophysical and natural habitat characteristics of a region to map the relative vulnerability of coastal areas to erosion and inundation. This gap was filled by the Coastal Vulnerability Model of the Integrated Valuation of Environmental Services and Trade-offs (InVEST) software (Sharp *et al*., 2020). The model produces a qualitative index of coastal exposure to erosion and inundation and ranks them from low to moderate to high exposure. For instance, the coastal vulnerability considers a range of variables including sea-level rise predictions, coastal elevation, natural habitats e.g., mangroves, corals, etc., and human density to assess the risks associated with climate change for coastal regions. Recently, the InVEST Coastal Vulnerability Mode has been widely utilized and applied in numerous studies due to the robust framework for evaluating the susceptibility of coastal regions to erosion and other hazards making it a valuable resource for coastal management, policy development, and decision-making processes. For instance, Hopper & Meixler (2016) applied InVEST model to spatiotemporally evaluate coastal vulnerability and the role of natural habitats in attenuating coastal vulnerability in Jamaica Bay, New York in different time scenarios: past (1609), present (2015), and future (2080). Similarly, a study conducted by Sajjad *et al*. (2018) demonstrated that about a quarter of mainland China's coastline faces high vulnerability to coastal hazards, impacting over

5 million residents. The study projects the doubling of these numbers by 2100, thereby underscoring the imperative to establish corresponding measures. It also implies the importance of natural habitats as they have the potential to reduce this vulnerability by up to 45 % thereby providing a critical baseline for developing strategies to address these challenges and fortify coastal resilience. On a more recent note, a study by Ai *et al*. (2022) also utilized the same model to establish high coastal vulnerability in the northern coast of Jiaozhou Bay, in contrast to its southern and eastern counterparts, which display relatively lower vulnerability levels. The juxtaposition between the north-south coastal vulnerability in the Jiaozhou Bay coast can be attributed to the type of coastline, elevation, distance to the continental shelf, and urban development.

In a prior study conducted by Berdin *et al*., (2004) in La Union, Philippines, coastal erosion vulnerability mapping was performed to investigate the factors contributing to coastal erosion. The study utilized geophysical characteristics and socioeconomic data by employing mapping and surveys in involved coastal communities. The Coastal Vulnerability Index (CVI) method, as outlined by McLaughlin *et al*. (2002), was employed to map the vulnerability. To update and enhance the understanding of coastal erosion vulnerability in La Union, it is our goal to integrate InVEST Coastal Vulnerability Model. By incorporating this model, the study can benefit from its comprehensive assessment of vulnerability based on various factors such as wind and wave exposure, and sea-level rise projections. The InVEST model provides a robust framework for evaluating the susceptibility of coastal regions to erosion and other hazards caused by extreme weather events. By employing the InVEST Coastal Vulnerability Model, the study herein can further refine the understanding of coastal erosion dynamics and inform effective coastal management strategies. In hindsight, the Coastal Vulnerability Model can help inform decision-making processes for policymakers and resource managers seeking to mitigate and adapt to the effects of climate change. Hence, the objectives of this study are to (i) determine the vulnerability of the coastal areas of La Union, Philippines and (ii) compare the coastal vulnerability between two coastal scenarios (with vs. without natural habitat). This study assumes that the coastal areas in La Union, Philippines exhibit significantly lower vulnerability to erosion and inundation in scenarios where natural habitats (e.g., mangroves, coral reefs, and seagrasses) are preserved, as compared to scenarios where these habitats are absent or degraded, as evaluated using the InVEST Coastal Vulnerability Model.

METHODS

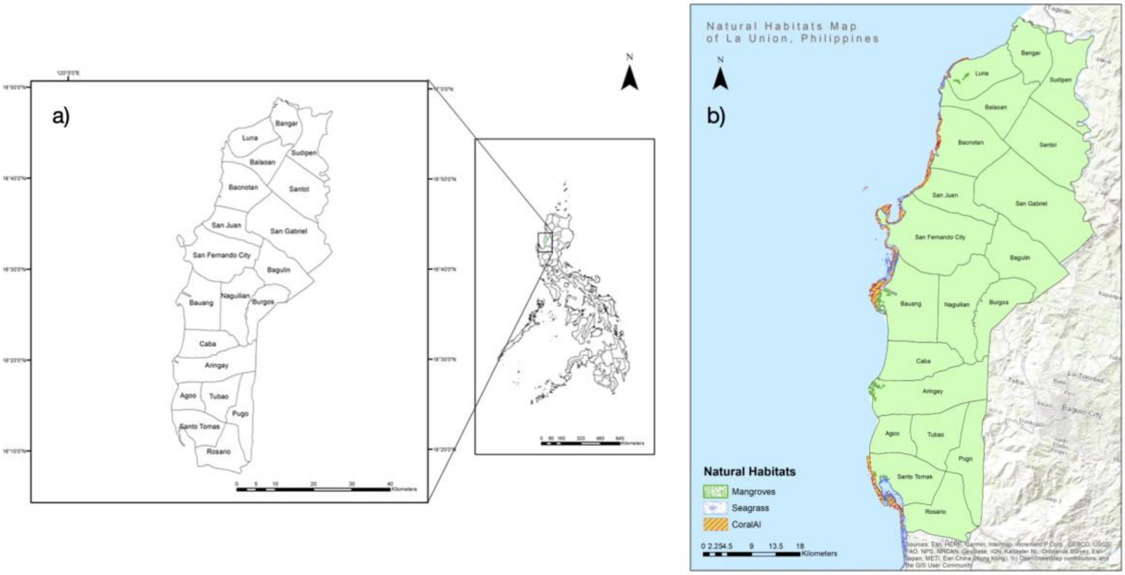
Study Area

La Union (Fig. 1A) is a province located in the Northwestern coast of the Ilocos Region of the Philippines, situated along the country's western coastline. Predominant winds are coming from the northwest direction with a speed ranging from 2 – 6 m/s during normal conditions with significant height of less than 1 m are generated. At 10 to 20 m/s, wave heights could reach over 3 m (Berdin *et al*., 2004). There are a total of 20 municipalities in La Union, where 12 of them are coastal areas facing the West Philippine Sea.

The geography of the province of La Union is predominantly a hilly terrain that rises from the western coastal area eastwards to the Cordillera Mountain Range (Balaoro-Banzuela *et al*., 2023). Its coastline stretches through the province with an estimated length of 114.70 km to 155.4km (DENR-R1, 2019), encompassing 11 municipalities with 94 coastal barangays, estimating to 185, 038 inhabitants in these coastal communities (Salmo *et al*., 2015). The province also covers the natural coastal habitats of mangroves, coral reefs, and seagrass. As of 2021, La Union has 644.973 ha of areas assessed for corals (DENR-R1, 2021) within the jurisdiction of the following municipalities: Balaoan (58.647 ha), Bacnotan (59.309 ha), Luna (39.575 ha), San Fernando City (364.496 ha), San Juan (12.431), and Bauang (110.515 ha). The coral reefs of La Union are part of the greater Lingayen Gulf embayment, encompassing its eastern section known as Sector III which is characterized by nearshore and fringing reefs (Deocadez *et al*., 2003). Additionally, mangrove covers in the province are estimated to be around 120 (DENR-R1, 2021) – 150 ha (PENRO, 2020). These lands are declared as protected areas or parks in the province as per Provincial Ordinance No. 352-2021, also known as the Environmental Code, found in Article B, section 3.3B.04, Chapter 3.3; this includes the Bauang Mangroves, San Fernando City Mangrove Swamp, Immuki Island of Balaoan, and the Agoo-Damortis Protected Landscape and Seascape. Furthermore, data from 2017–2018 show that there are around 64 – 148 ha of seagrass (DENR-R1, 2021) within the jurisdiction of La Union; some study reports presence along the Agoo-Damortis Protected Landscape and Seascape on its cove together with some mangroves (Mamhot *et al*., 2018). The La Union Provincial Government considers the development and protection of mangrove lands, along with other natural coastal habitats, as a priority due to their provision of various ecosystem services to coastal communities. This is particularly crucial since a significant portion of the population depends on fishing as a livelihood (Aduana-Alcantara *et al*., 2023). Nevertheless, the increase in aquaculture activities contributes to the loss of mangrove lands, resulting in a decrease in fish availability. This, in turn, leads to the adoption of destructive fishing practices as a means of adaptation, which further damages coral reefs and seagrass ecosystems (Philreefs, 2003).

The wave climate in La Union is influenced by seasonal monsoon patterns, resulting in varying sea and swell characteristics throughout the year. During the dry season from November to April, La Union experiences its peak surfing conditions. The northeast monsoon, known locally as the "amihan," brings consistent swells, with wave heights often reaching between 8 to 10 feet. Both beginners and experienced surfers favor this season due to the reliable wave patterns. On the other hand, the southwest monsoon, or "habagat," influences this season, bringing varied surf conditions. While there are still surfable waves, they tend to be smaller and less consistent than in the dry season. Additionally, this period is characterized by higher humidity and the possibility of tropical storms and monsoons. Within its boundaries, La Union encompasses several protected areas and natural reserves that are vital for biodiversity conservation and sustainable reef-to-ridge management (Balaoro-Banzuela *et al*., 2023). Mangroves, coral reefs, and seagrass beds are among the significant natural habitats found along the coastal areas of La Union. Despite its thriving economy and tourism industry, La Union is not immune to environmental challenges, including those posed by climate change (Capili *et al*., 2005; Ngilangil *et al*., 2013; Ngilangil *et al*., 2018). The coastline of the study area features sandy beaches along gentle coastal plains. Under normal conditions, wind speeds range from 2 to 6 m/s, generating waves with significant heights of less than 1 meter. However, when wind speeds increase to between 10 and 20 m/s, wave heights can exceed 3 meters (Berdin *et al*., 2004). Over the last decade, the province has experienced significant impacts from typhoons, flooding, and landslides, thus highlighting the need for effective risk management and adaptation strategies. La Union's coastline experienced a downward trend in vegetation, spanning 289.42 sq. km in 2021 compared to 412.31 sq. km in 1990. This trend coincides with a steady increase in urban area by 111.96 sq. km and agricultural land by 303.91 sq. km as of 2021 (Rivera *et al*., 2024).

Fig. 1: (A) Study Area of La Union Province, Philippines, with its respective municipalities. (B) Distribution of mangroves, seagrass, and coral reefs on the coastline of La Union



Data preparation and inputs

The study compiled several data requirements (Table 1) for InVEST Coastal Vulnerability Model (Table 1), including the Area of Interest (AOI) of La Union, Landmass, WaveWatchIII, Bathymetry, Digital Elevation Model (DEM), Continental Shelf Contour, Habitats (mangroves, coral reefs, and seagrass) table, and population density (Fig. 1B). First, the AOI was used to clip all the global datasets to focus on the study area. Next, the DEM was derived from the Shuttle Radar Topography Mission or SRTM at 30m resolution. The elevation data is required to run the model to determine regions with higher elevation that are at lower risk of inundation. AOI and DEM were downloaded from the DIVA-GIS country-level data (https://diva-gis.org/gdata). Moreover, the landmass data was derived from the GADM (https://gadm.org/data.html) which outlines the coastal region of La Union to estimate the exposure index of the AOI. Wavewatch III is a model developed by the National Oceanic and Atmospheric Administration (NOAA) to capture the large-scale ocean waves 7-day model with a 5-day hourly forecast at approximately 50 km or 0.5-deg resolution. WaveWatch III was used to estimate the relative contribution of wave energy to coastal exposure. Although the model provides forecasts, the analysis relied on hindcast data derived from reanalysis datasets to ensure historical consistency. Another important variable used is the continental shelf contour for mapping the edges of the continental shelf. The WaveWatchIII and continental shelf contour data were sourced from InVEST default sample data. Further, bathymetry data were downloaded from the General Bathymetric Chart of the Oceans' (GEBCO) global gridded dataset that has digitized depth points that extend beyond the AOI as a requirement of InVEST software. The habitat data, specifically for mangroves, coral, and seagrasses, were downloaded from Allen Coral Atlas (https://www.allencoralatlas.org/). These 3 natural habitats were chosen due to the availability of the data in La Union province. All these datasets were projected in the same coordinated system (WGS84 UTM 57N) using the ArcMap 10.7 software as preparation for input in the InVest software to calculate the coastal exposure index.

Table 1: Data specifications

Data	Source	Data type
Digital Elevation Model (DEM)	SRTM	Raster
WaveWatchIII	NOAA	Vector
Bathymetry	GEBCO	Raster
Landmass	GADM	Vector
Habitats	Allen Coral Atlas	Table

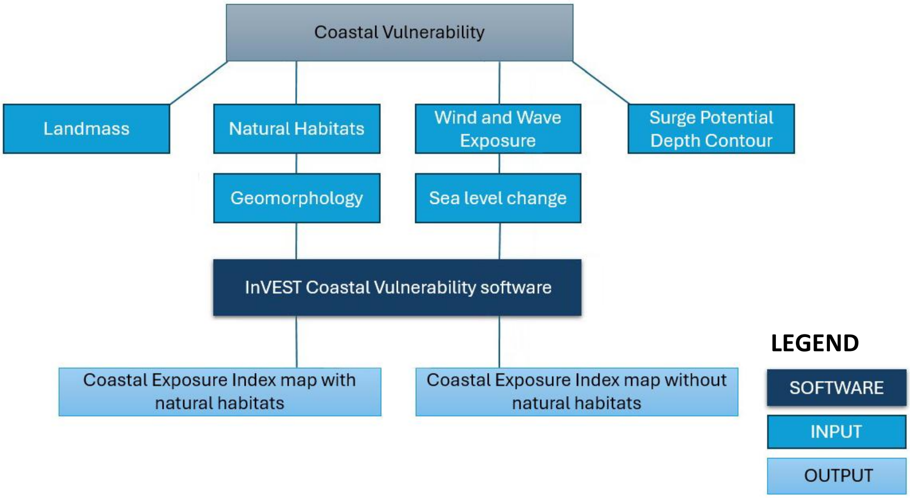
Coastal vulnerability assessment using InVEST pipeline

The coastal risk assessment was done with InVEST 3.11.0 Workbench (Fig. 2), an open-source software that was downloaded from the Natural Capital Project website of Stanford University (https://naturalcapitalproject.stanford.edu/software/invest). The InVEST Coastal Vulnerability model is an index-based tool used to evaluate the relative risk of coastlines to erosion and inundation and acknowledges the role of natural habitats such as mangroves in providing coastal protection. The coastal vulnerability index is constructed using bio-geophysical variables including geomorphic characteristics, sea-level rise, bathymetry, topography, and relative wind and wave forces which are qualitatively ranked based on the methods of Gornitz (1990) and Hammar-Klose & Thieler (2001) which is a mixture of user- and model-defined criteria. The primary output of the coastal vulnerability model is a geospatial dataset (points) that are plotted at user-defined intervals along the shoreline in the coastal region of interest. The computation of exposure index EI for each shoreline segment was done using the following formula:

$$EI = (R_{Relief} \cdot R_{Habitats} \cdot R_{WindExposure} \cdot R_{WaveExposure} \cdot R_{Surge})1/5$$

The model then assigned ranks from Rank 1 – 5 (the higher the value, the higher the exposure) to the bio-geophysical variables. Moreover, the Coastal Vulnerability was done with the following settings in InVEST Workbench: model resolution= 500, maximum fetch distance=1000, elevation averaging radius = 5000 in unit meters (m). The output file (geopackage) was then exported to ArcMap 10.7 for a detailed classification using a defined interval with the following classification scheme: 1 (very low exposure), 2 (low exposure), 3 (moderate exposure), 4 (high exposure), and 5 (very high exposure) for detailed visualization (Fig. 2). In principle, the static modeling process behind the application of Coastal Vulnerability in InVEST is based on (i) the calculation of a vulnerability index for different coastal segments, combining the relative importance of various risk factors, (ii) objective identification of high exposure areas, the protective role of coastal habitats, and potential socioeconomic impacts, and (iii) output maps that will serve as the baseline that guide decision-making on risk mitigation.

Fig. 2: Schematic Representation of the InVEST Coastal Vulnerability Model in InVEST 3.11.0 Workbench



Habitat protection scenarios

This study also analyzed the role of habitats in safeguarding coastal areas. In the InVEST Coastal Vulnerability Assessment model, scenarios are generated to evaluate how different factors influence the vulnerability of coastal areas by using habitat layer data. The model particularly focuses on comparing scenarios "with" and "without" coastal habitats to highlight the protective role of natural features like mangroves, coral reefs, and dunes. These scenarios offer a clear comparison of risks with and without natural defenses, helping stakeholders appreciate the value of coastal ecosystems in mitigating climate and storm-related hazards. During the modeling processm key components of the scenario modeling include two conditionsL (1) the 'with habitat' scenario, where habitats reduce wave energy by a certain percentage, reflecting their protective effects, and (2) the 'without habitat' scenario, where this wave attenuation is remove. In terms of geomorphology, the model considered that the physical features of the coast are static across scenarios unless explicitly changed. Sea level rise and storm surge remain constant in both scenarios, evaluate the impacts of increased vulnerability under habitat loss for this study. Under the "with habitats" scenario, the InVEST model incorporated the presence and characteristics of various habitats, such as mangroves, coral reefs, and seagrass beds, which are known to provide natural protection against coastal hazards to acknowledge their significance for better recommendations of coastal planning.

RESULTS

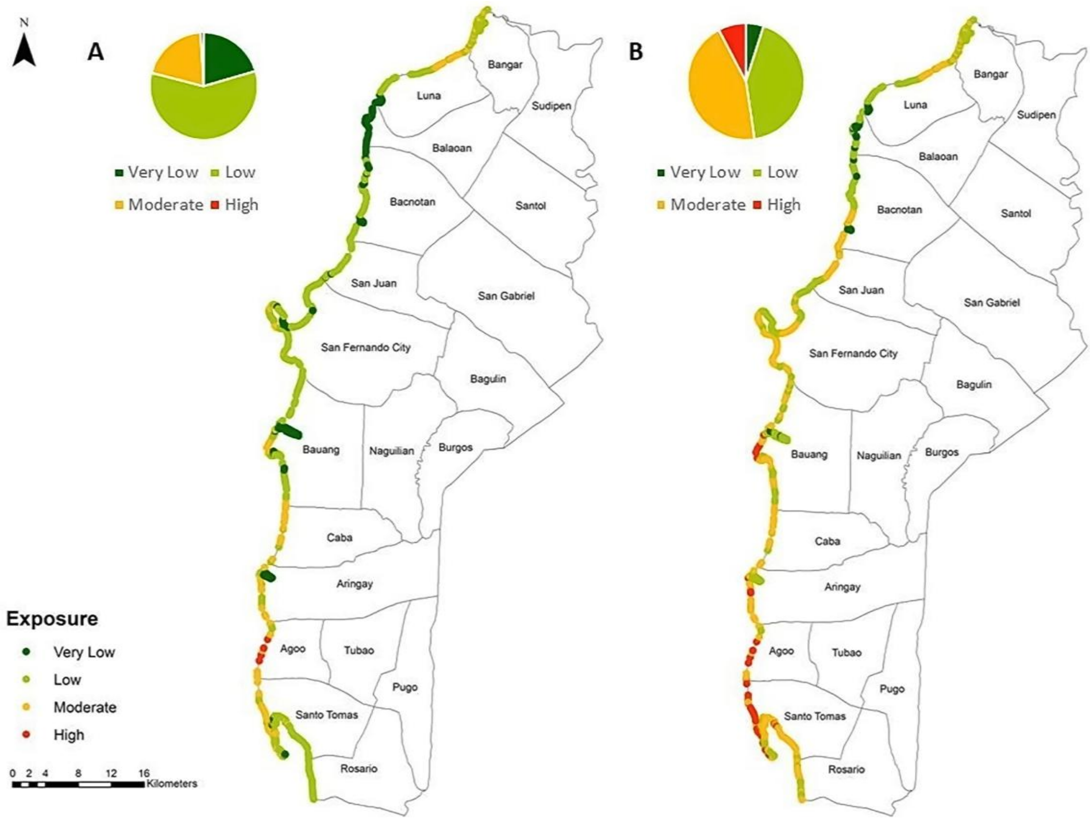
Exposure Index in La Union

In this study, the InVEST model was used to create an exposure map (Fig. 3) to analyze the spatial distribution of coastal vulnerability in La Union. A total of 405 points were mapped along the coastline, with exposure values ranging from 1 (very low) to 5 (very high) (Fig. 3A) based on the input model resolution, landmass, and area of interest. The analysis revealed that 20.5 % of the points were categorized as Very Low Exposure, indicating minimal risk of coastal flooding. The majority, 58.51 %, were classified as Low Exposure, reflecting relatively low vulnerability. Another 20 % were classified as Moderate Exposure, indicating a moderate level of risk, while only 0.98 % fell into the High Exposure category, representing areas with elevated flooding and inundation risks. Among the municipalities, Agoo's coastline showed the highest proportion of High Exposure points, indicating significant vulnerability. Meanwhile, Bauang, Caba, Aringay, Santo Tomas, San Juan, Luna, and Bangar exhibited Moderate Exposure. In contrast, Bacnotan and Balaoan had predominantly Very Low Exposure points, suggesting minimal susceptibility to coastal hazards.

Habitat Roles and Scenarios

In the InVEST Coastal Vulnerability Model, the role of habitats is crucial in determining the model's output to assess coastal vulnerability. The model considers the characteristics and distribution of habitats along the coast, recognizing their significance in providing natural protection and ecosystem services. The study analyzed two scenarios: the "with habitats" (Fig. 3A) and "without habitats" (Fig. 3B) scenarios. In the "with habitats" scenario, the presence and distribution of natural habitats, such as mangroves, coral reefs, and seagrass beds, were considered along the coastal areas of La Union (Fig. 1B). These habitats have long been recognized for their ability to act as natural buffers, providing valuable coastal protection against hazards. Conversely, in the "without habitats" scenario, there was a noticeable increase in the extent of coastal areas exhibiting high exposure. In the “without habitats” scenario (Fig. 3B), the absence of these natural habitats leads to a heightened vulnerability to coastal hazards. Our results revealed a drastic increase of coastal vulnerability among the costal areas in comparison to the “with habitat” scenario (Fig. 3A). Specifically, 4.93 % of the areas had very low exposure, indicating a minimal risk level. Additionally, 42.71 % of the areas fell under the low exposure category, signifying a relatively lower susceptibility to coastal hazards (Fig. 3B). However, a significant proportion, 44.69 %, exhibited moderate vulnerability. Notably, 7.65 % of the areas demonstrated high exposure, indicating a heightened risk of flooding and inundation.

Fig. 3: Exposure index map of La Union "with natural habitats" (A) and "without natural habitats" (B) scenarios with their distribution as depicted by the pie charts found on the upper left



DISCUSSION

Exposure Patterns in the coastline of La Union

The assessment of exposure patterns in La Union, utilizing the InVEST model and a comprehensive set of biophysical variables, provides valuable insights into the spatial distribution of coastal vulnerability. The generated exposure map, which also serves as the map for the "with habitat" scenario (Fig. 3A), based on 405 points generated in the InVEST software along the coastline, showed significant findings that can inform decision-making processes and coastal management strategies. Primarily, the distribution of exposure levels to segments to erosion and inundation caused by storms in La Union demonstrates varying degrees of susceptibility to coastal erosion and inundation in severe weather conditions based on the InVEST model. Our results showed that a substantial proportion of the coastline, comprising 79.01 % of the points, falls within the Very Low and Low Exposure (areas in the more northern part of La Union) categories, which suggests a relatively lower risk of coastal hazards in these areas (Sharp *et al*., 2020). However, it is crucial to remain cautious even in areas classified as Very Low or Low Exposure. While the risk may be relatively lower, it does not imply complete immunity from coastal hazards. Extreme weather events induced by changing climate can still pose threats, albeit at reduced levels (Sharp *et al*., 2020). Besides that, there are other threats, including sedimentary imbalance, sea-level rise, natural habitat destruction, and tectonic events (Rangel *et al*., 2015; Bonaldo *et al*., 2019; Limbo-Dizon and Dagamac, 2023) that contribute to such coastal hazards. The presence of Moderate Exposure areas in La Union, constituting 20 % of the points, signifies a moderate vulnerability to flooding and inundation. These locations require focused attention and appropriate interventions to mitigate potential risks. Understanding the specific factors contributing to moderate exposure is essential for tailoring local adaptation strategies to address the identified vulnerabilities effectively. Moreover, identifying high-exposure areas (Fig. 3A), encompassing only 0.98 % of the points, highlights specific locations with a higher risk of flooding and inundation. Such areas demand immediate action and targeted measures to protect the coastal community, infrastructure, and ecosystems. The relatively small proportion of points classified as High Exposure emphasizes the overall resilience of the La Union coastline. However, it is crucial to prioritize these high-risk areas and allocate resources strategically to minimize potential impacts.

Among the coastal municipalities in La Union, Agoo stands out with the highest percentage of Highest Exposure points. This indicates a greater vulnerability to coastal hazards in Agoo compared to other municipalities. Similarly in the previous CVI Study by Berdin *et al*. (2004), Agoo also had the highest exposure to coastal erosion even though a long seawall was priorly built. This high exposure can be attributed to reduction of Agoo's coastline due to the 7.8 magnitude earthquake in 1990 (Berdin *et al*., 2004). The identification of Agoo as a high-risk area provides an opportunity for local authorities and stakeholders to focus their efforts on implementing adaptation strategies and enhancing community resilience. Moreover, our study showed that the river mouths of Bauang and Aringay had the lowest exposure which in fact, in contrast to the prior CVI study in 2004 that categorized these two river mouths with the highest coastal erosion exposure. This could be explained by the increase of mangrove reforestation programs around these two river mouths as efforts to conserve and rehabilitate mangroves may have increased (Aduana-Alacantara *et al.,* 2023). Furthermore, several municipalities, including Bauang, Caba, Aringay, Santo Tomas, Luna, San Juan and Bangar, exhibit moderate exposure along their coastlines. Similarly, these areas should also be closely monitored and prioritized for targeted interventions. In contrast, Bacnotan and Balaoan have been identified as municipalities with Very Low Exposure coastlines. Despite having low exposure, the coastal communities in Bacnotan are still vulnerable to flooding and storm surges during typhoon season (Ngilangil, 2018) which can be explained by having localized flooding due to heavy rainfalls and inadequate drainage and flood management (Alabanza *et al*., 1989).

Nonetheless, while these areas are less vulnerable to immediate coastal hazards, it is important to note that exposure patterns can change over time due to various factors such as sea-level rise and storm events. Due to its geographic location, La Union is no stranger to several natural hazards. It is reported in the province' Provincial Disaster Risk Reduction and Management Plan (PDRRMP) for 2017-2022 that the province is considered a flood prone area; susceptible to tidal surge and inundation brought by storms and super typhoons that hit the Philippines. The whole province experienced flooding due to typhoon Pepeng (International Name: Parma) in October of 2009. Although the flooding events reported in the PDRRMP are commonly attributed to the overflowing of the province's river systems, they do acknowledge storm surges as the cause of flooding because most of the municipalities presented in their flood hazard map are in the coastal areas mentioned in the results. Additionally, storm surge events in the province also affect as far as the interior municipalities of San Gabriel, Naguilan, and Sudipen. On their storm surge susceptibility maps, 1 meter of storm surge will affect nine coastal municipalities: Agoo, Aringay, Bacnotan, Bangar, Bauang, Caba, Luna, San Juan, Sto. Tomas and the City of San Fernando. Flooding alone affects the population of at least 93,140 people, 54% of the province's total road network, 26 schools, and 8 hospitals. (PENRO, 2022). Moreover, La Union still needs to address its shortcomings in risk management plans, specifically in (i) training/equipment, (ii) community simulation exercises, and (iii) limited knowledge of coastal communities in the role and impacts of climate change and anthropogenic activities on disaster hazards to overall enhance resilience. Hence, continuous monitoring and adaptive planning are necessary even in areas classified as having low exposure.

Roles of natural habitats in coastal protection and other ecosystem services

The distribution of natural coastal habitats such as mangroves, coral reefs, and seagrass (Fig. 1A) in coastal areas may play an important role in providing coastal protection and contributing to the overall resilience of the region to climate change and sea level rise (Cahoon *et al*., 2021; McLeod & Salm, 2006; van Zanten *et al*., 2014; Ondiviela *et al.,* 2014). Fig. 3B significantly showed the increase in coastal vulnerability doubles in the "without natural habitat" scenario. This model affirms that habitats act as natural buffers and offer numerous ecosystem services that help mitigate the impacts of coastal hazards (Arkema *et al*., 2017), especially in the province of La Union where it experiences an average of 3 typhoons per year (Provincial Risk Disaster and Management Plan, nd) Firstly, mangroves, with their dense root systems and intricate structures, serve as a physical barrier against waves, storms and erosion (Othman, 1994; Pennings *et al*., 2021). Despite the ecosystem services and economic value, the mangroves provide, challenges in rehabilitation and protection are still ongoing in La Union, hence, adequate strategies for ecological awareness and land management should be implemented (Salmo III *et al*., 2015; Aduana-Alcantara *et al*., 2023).

Second, coral reefs attenuate wave energy by breaking up incoming waves and reducing their force before reaching the shore (Hardy & Young, 1996). Moreover, coral reefs also provide physical barriers that prevent coastal erosion and maintain sediment balance (Reguero *et al*., 2018). Consequently, these reefs are also not safe from issues and threats such as overfishing, siltation, and pollution which are long-standing challenges in the provincial waters of La Union (Aduana-Alcantara *et al*., 2023). Encroachment and destructive fishing are the main causes of habitat degradation in these areas of La Union (Arceo *et al*., 2020; Aliño, P., nd).

Lastly, seagrasses also act as a buffer and dampen wave action (Terrados & Borum, 2004; Beth Schaefer & Nepf, 2022). One characteristic of seagrasses is that it stabilizes the sediments and prevents erosion by trapping and binding sediment particles (Cabaço *et al*., 2008). However, it is alarming that seagrass habitats are being depleted at critical rates (McLeod *et al*., 2011). Considering the presence or absence of habitats provide valuable insights into the influence of these natural features on coastal vulnerability, which then emphasizes the need for strategic coastal management and the implementation of habitat-focused strategies to mitigate risks (Ngoile & Horrill, 1993; Nichols *et al*., 2019).

In addition to these natural habitats' physical role, they offer a wide range of ecosystem services that further enhance coastal resilience. For instance, mangroves, coral reefs, and seagrass provide habitats for a diverse range of marine species, supporting biodiversity and promoting ecological balance (Nagelkerken *et al.,* 2008; Van Katwijk *et al*., 2009; Knowlton *et al*., 2010). Furthermore, these habitats act as carbon sinks also known and recognized as blue carbon, sequestering and storing significant amounts of carbon dioxide from the atmosphere that enhances coastal resilience by reducing the impacts of ocean acidification (Kinsey & Hopley, 1991; Bouillon *et al*., 2008; Duarte, 2010; Andreeta *et al*., 2014). A study even suggested that carbon stocks in seagrass ecosystems are higher than those found in terrestrial ecosystems (Duarte *et al*., 2013) Overall, considering the significant role of natural habitats in coastal protection, continuous conservation and protection of mangrove forests such as the Agoo-Damortis Protected Landscapes and Seascapes should be prioritized by the Department of Environment and Natural Resources (DENR) (Aduana-Alcantara, 2023).

InVEST Coastal Vulnerability Model Limitations and Future Directions

The InVEST Coastal Vulnerability model (Fig. 2) has several limitations that need to be acknowledged and understood by its users. Firstly, the model simplifies the complex and dynamic interactions of coastal processes that may overlook key factors contributing to coastal vulnerability such as socioeconomic factor (urbanization and infrastructure development, economic activities, access to early warning systems). Second, the model does not account for specific coastal features, such as storm surges or wave dynamics in the nearshore region. Next, the model does not consider the quantity and quality of habitats and assumes that the quality and condition are equal. Next, the model does not predict the response of a region to specific storms or wave conditions, and it does not consider large-scale sediment transport pathways that may exist in the region of interest. Lastly, proper model calibration is required in order to generate better vulnerability maps (Zhang *et al*., 2021). While the InVEST Coastal Vulnerability Model has gained prominence as a practical and accessible framework for evaluating exposure to coastal hazards, it is essential to recognize that it belongs to a broader spectrum of ecosystem service (ES) modelling tools. As described by Kareiva *et al*. (2011) in *Natural Capital: Theory and Practice of Mapping Ecosystem Services*, InVEST represents the first of three tiers of ES modelling tools. These tiers vary by complexity, data requirements, computational intensity, and their level of ecological or socio-economic integration. Furthermore, although the model considers the manifold factors related to soil, topography, and bathymetry, the caveats of the model manifest in its inability to integrate anthropogenic factors beyond population density, such as recreational and fishing activities, especially considering that the municipality of San Juan expects a significant tourist influx annually. Eyewitness accounts of the third and last authors have reported rising sea levels along the coastlines of the municipality throughout the years, particularly in areas designated for tourist activities.

InVEST Coastal Vulnerability is a valuable tool for screening and identifying areas of concern at a strategic level. However, its limitations highlight the need for: (i) high-quality and context-specific input data, (ii) complementary tools or models for detailed process-based analysis, (iii) greater transparency in model operations to reduce its "black box" perception and (iv) iterative use with stakeholder input to ensure relevance and accuracy. While InVEST provides a starting point, its results should be integrated with other methodologies and local expertise for robust coastal management and planning (Mukhopadhyay *et al*., 2024). Despite the said limitations, the InVEST Coastal Vulnerability Model provides accessibility with its user-friendly interface to model coastal vulnerability at a regional and even a country-wide scale. Future directions for the InVEST Coastal Vulnerability model include refining and expanding its capabilities to address some existing limitations. For instance, incorporating more detailed and site-specific data on storm surge, wave dynamics, and sediment transport processes can enhance the accuracy of the model's predictions. Additionally, incorporating the quantity and quality of habitats into the model can provide a more realistic assessment of their contribution to coastal protection and resilience which is not a feature of InVEST Workbench 3.11.0 yet. Another avenue for future research is to integrate the model with climate change scenarios to assess the potential impacts of sea-level rise, increased storm intensity, and other climate-related factors on coastal vulnerability which were not included in this study due to data availability for La Union. Adding these variables would allow for a more comprehensive understanding of future risks and the identification of adaptation strategies to enhance coastal resilience in La Union.

CONCLUSION

This study offers a comprehensive assessment of coastal vulnerability along the coastline of La Union, with the InVEST Coastal Vulnerability model identifying 79.01 % of the coastline as having Very Low and Low Exposure to coastal hazards. This indicates that most of La Union's coast is less susceptible to coastal threat damage. However, the municipality of Agoo emerged as a critical area with the highest exposure, suggesting a critical need for targeted interventions. Natural habitats, such as mangroves, coral reefs, and seagrasses, greatly reduced coastal vulnerability. The scenario analysis revealed that the absence of these habitats led to a sharp increase in coastal exposure, particularly in areas previously deemed low risk. This finding underscores the crucial role of these ecosystems in coastal protection and their inclusion in vulnerability assessments. By identifying areas most at risk and the protective role of natural habitats, this research provides essential insights for policymakers and local government units (LGUs) to develop effective and sustainable coastal management practices. Adaptive strategies that preserve natural habitats and mitigate risks in highly exposed areas, such as Agoo, are vital to enhancing coastal resilience.

InVEST Coastal Vulnerability model offers feasible projections to analyze ecosystem benefits to aid coastal management strategy (Ballesteros & Esteves, 2021), sustainable development, and adaptation to climate change among the coastal communities of developing countries such as the Philippines, where climate change has been having serious impacts, Moreover, the use of this model urges for a more natural way to mitigate the impacts of natural hazards such as protecting and restoring the natural habitats (Wedding *et al*., 2022), i.e. mangrove restoration, coral reef rehabilitation, and coastal protection, in the province of La Union.   However, to ascertain such a projection, a proper calibration step for the “blackbox’ model outputs from InVEST is still recommended (Mukhopadhyay *et al*., 2024). Nevertheless, by highlighting the vulnerability of exposed coastline areas in an urgently needing coastal communities of La Union, effective risk management and strategies can be implemented by the local government units to avoid the unnecessary loss of lives and damage to infrastructure that could happen in the not-so-distant future. It is, therefore, important to provide ample resources and educate the major stakeholders in these identified vulnerable coastal communities of La Union.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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