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The environmental burdens of special economic zones on the coastal and marine environment: A remote sensing assessment in Myanmar

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ABSTRACT

Special economic zones (SEZs) play a pivotal role in the development of many emerging economies. However, often SEZs are located in remote locations in authoritarian states where independent environmental assessment is difficult. Few studies assess the environmental impact of SEZs and, as a result, limited empirical evidence is available. This article fills the gap by developing a method for assessing the direct and indirect environmental impacts of SEZs using high-resolution satellite data and a machine learning algorithm to examine the rate and pattern of environmental changes. The method is developed through the study of SEZs in Myanmar. Land covers were quantified using very high resolution imagery orthorectified satellite images through Random Forest in Google Earth Engine. The results of the study indicate that the development of the SEZs come at the cost of valuable resources such as mangroves, forests, and agricultural lands. The impact on forests and mangroves is particularly significant. During the SEZ construction, mangrove and forest saw 35% and 12% decline respectively. The increase in area of development after SEZ construction was 83%. The methodological approach developed here may serve as a framework for studies of SEZs in inaccessible locations around the world.

1. Introduction

Special economic zones (SEZs) are unusual parts of the world economy in terms of law, institutions, and economic functions (Chaisse and Dimitropoulos 2021). SEZs are geographically delimited areas created to facilitate industrial activities through fiscal and regulatory incentives and infrastructure support (UNCTAD 2019). Such zones carve out jurisdiction as a subset of the overall state jurisdiction for the purposes of enacting different laws and regulations that are more trade and investment friendly (Zeng 2021). Since the year 2000, SEZs have mushroomed in developing countries to attract foreign direct investment (FDI), accelerate industrialization and create jobs (Aiyer 2017). There are 5400 SEZs in 147 economies around the world. Asia is home to three quarters of them (UNIDO 2015). They have been a core element of the economic development strategy of the Association of Southeast Asian Nations (ASEAN) and currently all ASEAN member states have SEZs (Aggarwal 2022).

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As part of an export-oriented development strategy, the zones commonly include industrial mega-areas that accommodate large-scale infrastructure, deep-sea ports, logistical infrastructure for oil and gas, hotels and tourism, and industrial complexes (Aggarwal 2022). They are primarily defined by a specific regulatory regime and a dedicated governance mechanism designed to relieve customs and tariffs and reduce the burden on businesses from permits, licenses, employment laws, and land access. In return, host governments expect investors to create positive spillover effects, such as facilitating innovation, boosting employment, raising exports, and diversifying the economy. The global experience of SEZs have been mixed, with some countries achieving successful economic outcomes, while others struggle to overcome market failures, institutional constraints, and social and environmental costs (Aggarwal 2022; Zeng 2021).

The lax regulatory regimes of SEZs often raise concerns about environmental, social, and human rights standards, as well as possible conflicts over land rights (Brussevich 2020). Several SEZs have failed to yield the expected economic benefits while having severe adverse impacts on the environment and local communities (Adunbi 2019; Aritenang and Chandramidi 2020; Chaisse and Ji 2020). On the other hand, while SEZs can be hotspots for environmental mismanagement, they can also provide opportunities for implementing environmental policies specifically designed to regulate industries within the zones. Also, certain environmental advantages may ensue from the introduction of foreign financial resources and environmental technologies that are otherwise not readily available (Richardson 2004). However, according to the “race to the bottom” literature, most SEZs have a net negative impact on the environment and local communities (Richardson 2004; UNIDO 2015; ZENG and DOUGLAS, 2012). Despite this contradiction, existing studies focusing on the direct and indirect impacts of SEZs have been rare (World Bank, 2017). Particularly, the magnitude and intensity of SEZ impacts on the environment remain understudied.

SEZs tend to be located in remote regions. As such, SEZ-related information and data are generally scarce, making it difficult to assess the environmental consequences of such zones. Many SEZs are also located in countries where there is limited scope for independent environmental assessment due to authoritarian rule, corruption, and/or secrecy surrounding deals with foreign investors. Recent improvements in access to satellite data and computing platforms for machine learning have greatly improved the ability to comprehensively assess SEZs in any location in the world in near real time (Ali et al., 2020; Jensen et al., 2019). This article demonstrates how these technologies can be applied to provide evidence related to the environmental impacts of SEZs. The method is tried out on the Kyaukpyu SEZ in Myanmar. Myanmar is an authoritarian country and the Kyaukpyu SEZ is a flagship project of China’s Belt and Road Initiative (BRI) located in an inaccessible part of Myanmar. This is precisely the type of case where independent access can be limited and a remote sensing approach can be useful.

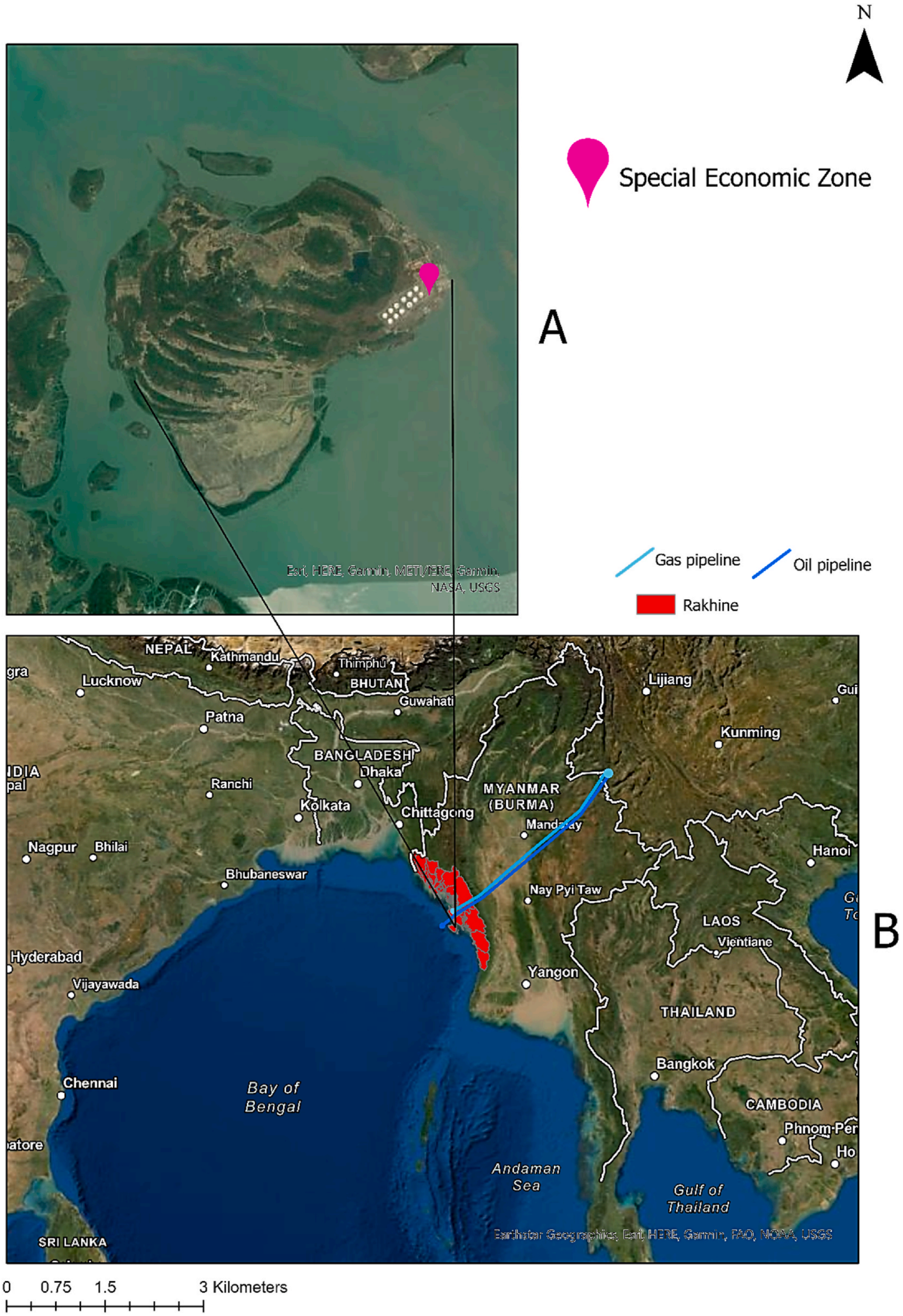
From 2010 onwards, Myanmar was navigating its economic transformation and a partial loosening of military rule. SEZ development was prioritized as a critical element of the country’s industrialization (Oxfam 2017). The three most notable ongoing SEZ projects are the Kyaukpyu SEZ in the rural but strategically important Rakhine State, which is also the largest SEZ in Myanmar, the Thilawa SEZ on the outskirts of Myanmar’s former capital Yangon, and the Dawei SEZ in the Tanintharyi Region. Tanintharyi is a long narrow southern territory of Myanmar bordering the Andaman Sea to the west and Thailand to the east.

Although they are expected to encourage economic growth and reduce poverty, all three SEZ projects continue to face local opposition, particularly the Kyaukpyu and Dawei SEZs. The International Commission of Jurists (2017) has reported that SEZs in Myanmar are linked to human rights violations and environmental abuses (Donateo 2017). Although Myanmar’s SEZ law adopted in 2014 reaffirms the applicability of environmental regulations to SEZ development, it does not clearly delineate responsibilities between developers and the state (DICA 2014). The law also does not conform with international human rights standards (MCRB 2018).

Kyaukpyu SEZ is the backbone project of the China–Myanmar Economic Corridor (CMEC) established under the Belt and Road Initiative (BRI) (Dutta 2018). It is China’s flagship BRI project in Myanmar (Mark et al. 2020). The BRI could affect 24 million people in Myanmar who live in the BRI corridors, as river-related infrastructure development, deforestation, and changing land use can induce flooding, sedimentation, and water pollution (Helsingen et al., 2018). Kyaukpyu is the terminal point of China’s USD 2.5 billion oil and gas pipelines, which provides an alternative energy transportation route from the Middle East to China, thereby reducing China’s dependence on the Malacca Strait and South China Sea (Sternagel 2018). Kyaukpyu SEZ currently includes five main projects: oil and gas pipelines, oil terminals, deep seaports, an industrial park, and a railway connecting China and Myanmar. Thanks to the SEZ, a once remote and isolated region now hosts new industries and logistics. Besides social impacts, the large-scale project damages the surrounding ecosystem due to the irreversible environmental impacts resulting from the construction and operation of energy infrastructure and ports. Although the environmental impacts of the SEZs are well-known among the local population, systematic empirical evidence remains absent or inconclusive. China’s BRI projects “are likely to transform Myanmar’s economy at different scales and influence the allocation of economic benefits and losses among actors,” carrying also substantial environmental risks if left unchecked and without proper monitoring (Mark et al., 2020).

To date, scientific investigations are scant regarding the adverse impacts of SEZs on the environment and livelihoods. There is also a lack of analysis of the environmental impact of China’s BRI projects in Myanmar. Although a diverse literature is available on the economic rationales and impacts of SEZs internationally, studies focusing on their environmental impacts through land-use-land-cover changes (LULCCs) have been rare. Most studies on SEZs around the world have investigated their economic success, market competitiveness, and institutional implications (Adunbi 2019; Anwar et al., 2016; Aritenang and Chandramidi 2020; Chaisse and Ji 2020; Naeem et al. 2020; Wang 2013). Several studies have assessed SEZs’ social impacts with a particular focus on land and labor rights (Brown 2019; Brussevich 2020; Laungaramsri and Sengchanh 2019; Naeem et al., 2020; Sampat 2015). Some studies have focused on the environmental management of SEZs, water quality in surrounding areas, and sustainable zone selection (Chen et al., 2011; Turgel et al., 2019).

This article aims to close this gap by examining the environmental and land-use impacts of the Kyaukpyu SEZ. In addition, the study briefly reviews the two other major SEZs in Myanmar. This article is the first to provide scientific evidence on the terrestrial and



Esri, HERE, Garmin, METI/ERE, Garmin, NASA, USGS

Earthstar Geographics, Esri, HERE, Garmin, FAO, NOAA, USGS

Fig. 1. Study area map. Map (A) shows the location of Maday island, and the pink location symbol shows the example of special economic zone (SEZ) operations. Map (B) presents the location of Rakhine state and the oil and gas pipelines trespassing through Myanmar. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

maritime environmental impacts of an SEZ in Southeast Asia. We seek to address critical issues such as the rate and pattern of LULCC in the SEZ development area and the maritime traffic changes in the surrounding waters by using very high-resolution satellite data and a machine learning algorithm. The case of Myanmar is particularly interesting because of its geopolitical significance, unique political and economic characteristics, and environmental vulnerability. This study's can provide insights into the environmental consequences of SEZs on terrestrial and marine ecosystems and implications for maritime security. Furthermore, the methodological approach developed in this article may serve as a framework for studies of SEZs around the world.

2. Material and methods

2.1. Study area

The primary study area is the Kyaukpyu SEZ on Maday Island, Kyaukpyu Township, off the coast of Rakhine in Western Myanmar. Fig. 1 shows the location of the study area. The region has a predominantly rural population mainly dependent on subsistence farming and fisheries (Oxfam 2017). No survey record on air quality is available for either Kyaukpyu or Ramree Island as a whole, and atmospheric environmental assessment is therefore not impossible based on the available data. However, the air quality is worsening, and the emission sources are estimated to be industrial facilities, marine vessels, inland transportation, and burning of waste (Myanmar Environment Institute, 2017). Although marine water quality assessment was conducted on Maday Island for oil and gas development projects, the data are not publicly available (see Fig. 2).

Most parts of Kyaukpyu Township and Maday Island are covered with open forest, followed by agricultural land. Although mangroves make up approximately 16% of the total forest area, no designated protected mangrove area exists in Kyaukpyu. The total area of the SEZ covers 35 villages with a population of approximately 20,000 inhabitants. The satellite imagery in this study covers the entire Maday Island, where the main infrastructure of the SEZ is located.

Preliminary analysis of vegetation and urban composition of Thilawa and Dawei are included in the study to reach a better general understanding of the environmental consequences of SEZs. Thilawa SEZ was developed in Kyauktan and Thanlyin Townships, 25 km south of Yangon City. Dawei SEZ is located in Dawei, the capital of the Tanintharyi Region on the Thai–Myanmar peninsula.

2.2. Data acquisition and processing

The study involved the calculation of direct and indirect changes in land cover and marine activities due to SEZ creation. Direct changes refer to the conversion of natural land cover types for human uses and an increase of human activity. Indirect changes refer to the conversion of natural land covers, such as forests and mangroves, into cropland to compensate for the conversion of croplands into

Fig. 2. Examples of field visits used to help guide the development of training polygons and validation. The photos are taken across Maday island (see Fig. 1). A: gas pipeline terminal, B: relocated residents, C: oil and gas pipelines, D: pipelines passing through croplands and new plantations.

Table 1
Details of satellite data and other information used in the project.

Satellite	Acquisition date	Digital number	Resolution	Sensor specification (wavelength)	Number of bands	Path/ row
Worldview-3	2019 Dec 5	10400100557AF500	0.5 m	Multispectral with four bands (blue: 450–510 nm, green: 510–580 nm, red: 630–690 nm, near-IR: 770–1040 nm)	4	131/048
Worldview-2	2011 Dec 13	103001000F0DEE00	0.6 m			132/051
Quickbird	2016 Jan 6	1010010004BDF300		Multispectral with four bands (blue: 450–520 nm, green: 520–600 nm, red: 630–690 nm, near-IR: 760–900 nm)		
Landsat 8 (OLI)	2017 Nov 22 2020 Jan 29	LC08_L2SP_132048_20190221_20200829_02_T1 LC08_L2SP_131050_20191215_20201023_02_T1	30 m	Band 1 Coastal 0.43–0.45 Band 2 Blue 0.45–0.51 Band 3 Green 0.53–0.59 Band 4 Red 0.64–0.67 Band 5 NIR 0.85–0.88 Band 6 SWIR 1 1.57–1.65 Band 7 SWIR 2 2.11–2.29 Band 8 Pan 0.50–0.68 Band 9 Cirrus 1.36–1.38 Band 10 TIRS 1 10.6–11.19 Band 11 TIRS 2 11.5–12.51	11	
Landsat 5 (TM)	2012 Jan 19	LT05_L1TP_132048_20110215_20200823_02_T1 LT05_L1TP_131050_20110123_20200823_02_T1	30 m	Band 1 Blue 0.45–0.52 Band 2 Green 0.52–0.60 Band 3 Red 0.63–0.69 Band 4 NIR 0.76–0.90 Band 5 SWIR 1.55–1.75 Band 6 Thermal 10.40–12.50 Band 7 SWIR 2 2.08–2.35	7	
Data			**Source**			
Geographical location			Humanitarian Data Exchange and Myanmar https://data.humdata.org/dataset/acled-data-for-myanmar			
Road network			https://data.humdata.org/dataset/damage-assessment-in-the-chein-khar-li-ku-lar-village-rakhine-state-myanmar			
Geographic boundaries of villages and townships			Information Management Unit's GIS resources. http://themimu.info/gis-resources			
Information Management Unit's GIS resources						

infrastructure development elsewhere; that is, indirect changes are the result of cropland displacement. Information obtained from the Directorate of Investment and Company Administration (The Government of Myanmar 2020) was used as reference data to manually identify the location and extent of existing SEZs in Myanmar and then digitized on Google Earth. Kyaukpyu SEZ was selected as an experimental site for land cover classification for several reasons, including the scale of the project, the severity and magnitude of its impacts, its proximity to human settlements, the reliance of pre-existing local livelihoods on ecosystem services, the possibility of field data collection, and the availability of satellite data.

Changes in land cover were quantified using the very high resolution imagery (VHRI) orthorectified satellite images from Worldview 3 (2019), Worldview 2 (2011), and Quarto (2005). Data were captured at close dates for three years in the same study area. For the main study area in Maday Island, pre-construction, during-construction, and post-construction periods were compared using images from three acquisition dates (t0 = January 7, 2006; t-1 = December 13, 2011; t-2 = December 5, 2019) with spatial resolutions of 0.5 and 0.6 m. These images were mainly used to track and classify land cover changes in Kyaukpyu SEZ by using the random forest (R.F.) classification method. Hyperspectral satellites and synthetic aperture radar were not available for our region and study period. However, VHRI data are deemed sufficient to distinguish between different land cover classes accurately and easily (Aung et al., 2020). All the images were pre-processed and mosaicked in ArcGIS Pro using apparent reflectance function. This function is used to adjust reflectance, or brightness satellite imagery to minimize variation between scenes from different dates and different sensors.

We included Landsat 5 and 8 satellite data for 2011 and 2019 based on the construction periods for Thilawa and Dawei to explore SEZ expansion and overall environmental changes. We collected and stacked the best available 28 Landsat scenes (cloud cover <10%, acquisition between December and February), covering four tiles (paths: 131–132, rows: 048–051), by using Landsat bands that record surface reflectance in the visible, near-, and mid-infrared spectra and that have a minimum resolution of 30 m. Radiometric calibration and atmospheric correction via fast line-of-sight atmospheric analysis of spectral hypercubes (FLAASH) were applied to the original Landsat images to obtain the ground surface reflectance (ρ). Table 1 summarizes the details of the satellite data.

For verification and the collection of training samples, we conducted field visits to Kyaukpyu SEZ on Maday Island in December 2019 (Fig. 4). These spatial data were then compared with previously digitized data in Google Earth. The land cover classification of the study area was determined based on the existing land cover maps of Rakhine State developed by the United Nations Operational Satellite Applications Program (UNOSTAT) in 2015 (MIMU 2010; OCHA 2015). The data provide land cover types classified from Landsat 8 acquired between January and February 2015 at 30 m pixel resolution. The classification data are categorized into five broad classes: forest, mangrove, cropland (paddy fields), barren soil, and vegetation. For the purpose of this study, we classified eleven specified categories: forest, barren, scrubland, development, cropland, water, and mangrove. Furthermore, countrywide forest and mangrove cover change data developed by Bhagwat et al. (2017) and De Alban and Jose Don (2020a) were useful for cross-checking forest land classification in the region. We derived three extensive training datasets from the expert interpretation of Google Earth imagery in the same study periods. We combined ground-truth data with randomly chosen samples and manually digitized 1300–1800 training polygons for each respective study period distributed throughout the study area to cover all satellite images. These training

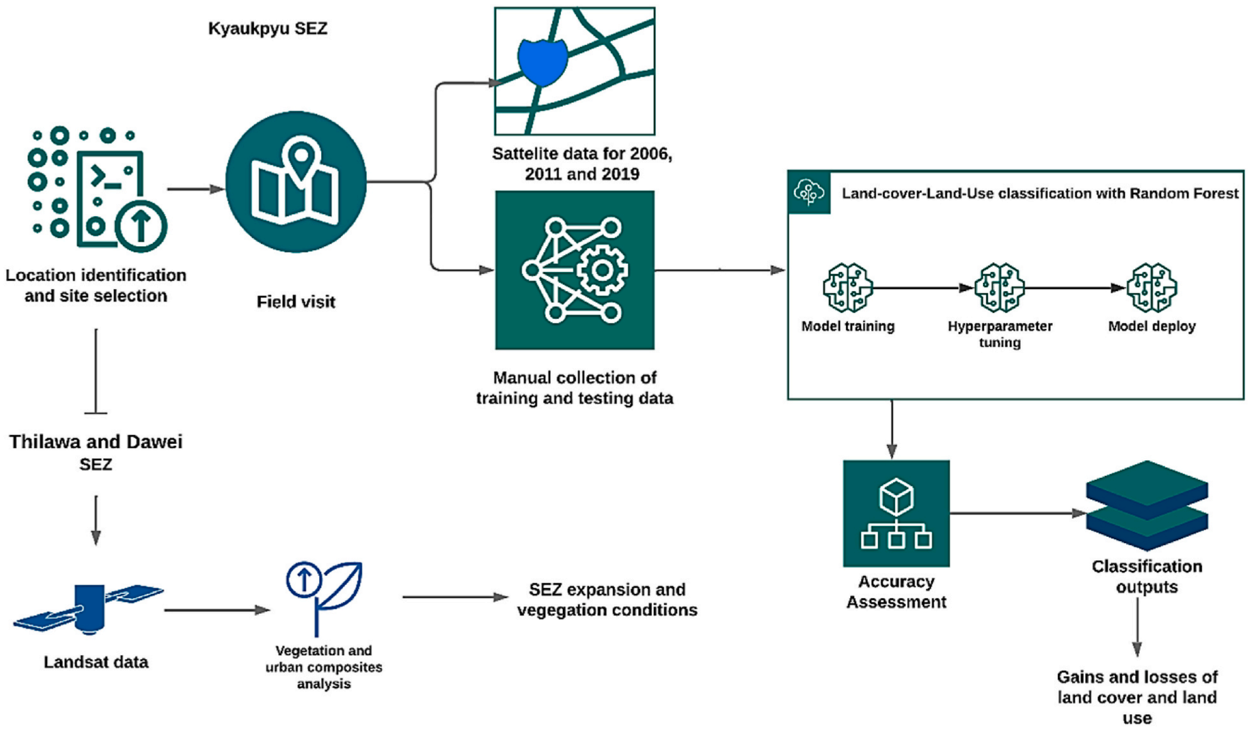


Fig. 3. Workflow for the VHRI image classification of Kyaukpyu SEZ, and image analysis of Thilawa and Dawei SEZ for comparative purposes.

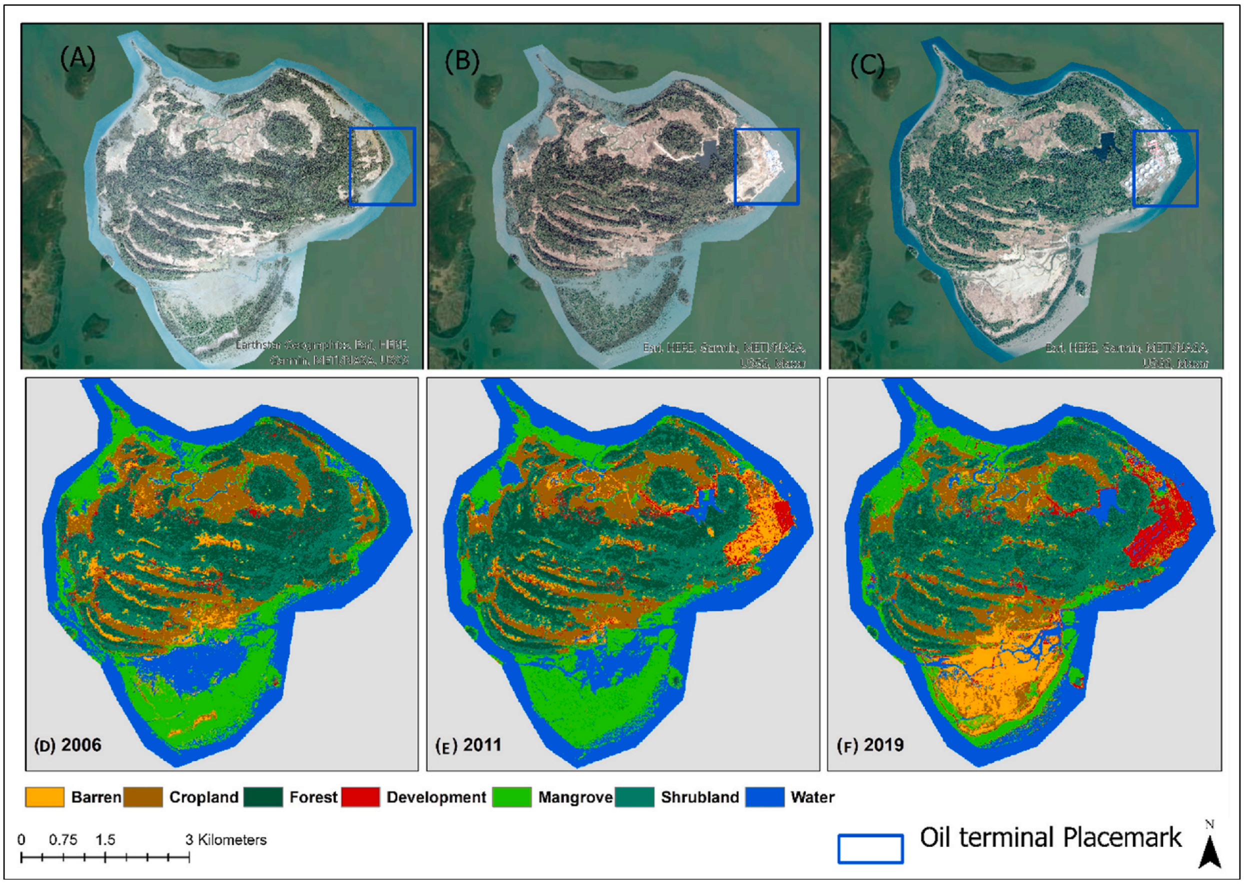


Fig. 4. Image A–B: True color composite maps of the study area showing Kyaukpyu SEZ. Image A is from December 13, 2013, showing the area before the construction of the SEZ. Image B is from January 6, 2016, showing there are during the construction period and image C is from December 5, 2019 showing the period after the construction. Source: https://imagehunter.apollomapping.com/search/b2395628ff904ce187695ee38b07737d (order number: APMQ9642). Image D–C: Classification maps of the SEZ: 2006 pre-construction, 2011 during construction, and 2019 post-construction land cover maps of Kyaukpyu SEZ classified into seven land cover classes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

samples and reference data were then used as input variables for the calibration of the R.F. model. In the first step of classification, we created a binary column in the training dataset to split polygons into the train (50%) and test (50%) by using the R-studio programming software.

3. Image classification

The land cover classification technique was applied and evaluated in the Google Earth Engine (GEE) platform by using the supervised classifier algorithm and VHRI imagery for each year. The general workflow of the study is shown in the flowchart in Fig. 3.

The VHRI satellite data were imported to GEE through Google Cloud Storage using the Python-programming interface. GEE extracted the training and testing data to update the training parameters and the number of testing data. The training dataset was used to train the supervised classifier algorithm, whereas the testing data set was used to assess the accuracy of the resulting classification map. The VHRI was used for tracking and classifying land cover changes in the SEZ. As the study area has low elevation, it was not necessary to add a digital elevation model and a slope. Given the limited band composition of VHRI data, calculating vegetation and soil indices was impossible. In light of their proven effectiveness and high generalization capabilities, the supervised classification model R.F. was chosen for the classification task. As a non-parametric machine learning algorithm, R.F. is particularly suitable for LULCC classification due to its effectiveness in producing high classification accuracy using high-resolution satellite data (Hassan et al., 2018; Horning 2010; Liaw and Wiener 2002; Rodriguez-Galiano et al., 2012). We compared the results of implementing R.F. and support vector machine (SVM) in the GEE platform. As the R.F. model achieved better classification accuracy than SVM for all the classes, R.F. was applied to obtain the land cover classification maps for each study period.

R.F. is an ensemble machine learning algorithm and a decision tree. Each tree is created using a subset of the training dataset through a bagging approach, and nodes are split using the best variable from randomly selected variables (Singha et al., 2019). In most cases, approximately 65% of in-bag samples are applied for training, and 35% of out-of-the-bag samples are used for internal cross-validation of the computer model performance. Before classification, we carried out R.F. hyperparameter tuning to select the best hyperparameter values. Each decision tree was independently established by training each tree in the forest (ntree) with the number of input predictor variables (mtry) selected randomly (Aung et al., 2020). In this study, hyperparameter tuning was conducted for the minimum leaf parameter. Given the limited number of bands in the satellite imagery, the best variables per split were two. We used 200 decision trees and tested a different minimum leaf population at each time. Lastly, we selected hyperparameter values, trained the classifier, and obtained classified raster images and accuracy assessment results.

The accuracy assessment was first internally computed in R.F. classification. However, based on the best practices recommended by Olofsson et al. (2014), we adopted a stratified random sampling design to conduct a precise accuracy assessment of the model. Accuracy assessment involves the estimation of the accuracy of maps, the quantification of each class area, and the evaluation of the classifications' uncertainty (Mellor et al., 2013; Sharma et al., 2017). The required sample size was obtained using the following formula:

$$n = \frac{\left(\sum W_i S_i\right)^2}{\left[S(\widehat{O})\right]^2 + \left(\frac{1}{N}\right)\sum W_i S_i^2} \approx \left(\frac{\sum W_i S_i}{S(\widehat{O})}\right)^2 \tag{1}$$

where n is the number of units, $S(\widehat{O})$ is the standard error of the estimated overall accuracy, Wi is the mapped proportion of the area of class i, and S_i is the standard deviation of i.

$$S_i = \sqrt{U_i(1 - U_i)} \tag{2}$$

A target standard error for the overall accuracy was defined as 0.01. A sample size of 50–100 was allocated to the smaller classes using the proportional approach, and the rest of the samples were proportionately allocated for each change strata. The estimated

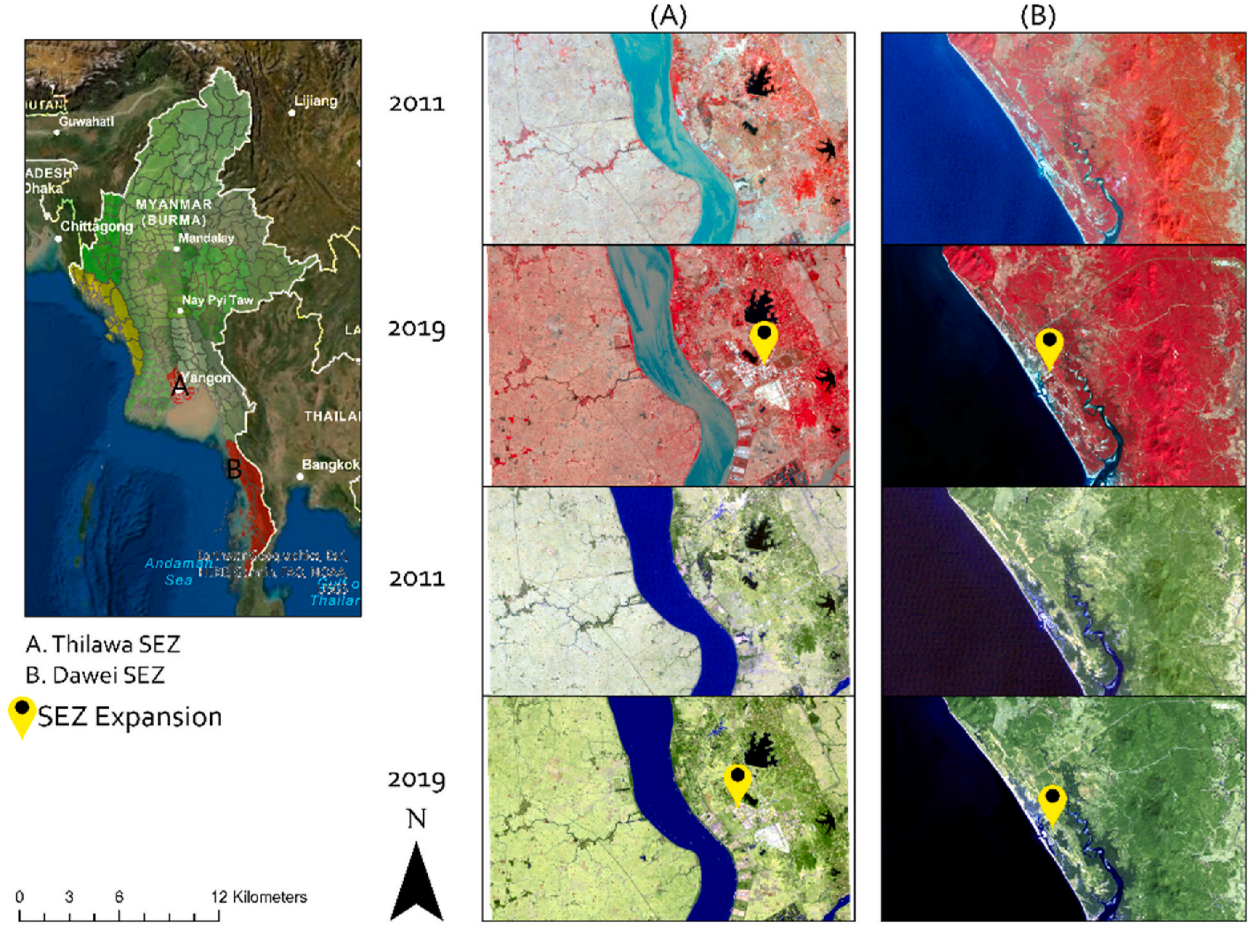


Fig. 5. False-color composite maps showing the Thilawa and Dawei SEZs. Images A and B show the expansion of Thilawa and Dawei SEZs, respectively. The yellow symbol indicates the expansion and shows the vegetation cover of Thilawa and Dawei SEZs from 2011 to 2019. The band combination of vegetation cover for 2011 is 4 (red), 3 (green), and 2 (blue), and for 2019 is NIR band 5 (red), 4 (green), and 3 (blue). The band combination of urban expansion for 2011 is 1 (red), 4 (green), and 7 (blue), and for 2019 is SWIR 2 band 7 (red) and SWIR 1 bands 6 (green) and 4 (blue). The images were derived from 2011 (Landsat 5TM) and 2019 (Landsat 8). Image courtesy of U.S. Geological Survey (USGS 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Area (in hectares) change in land-cover-land-use classes and overall net gain and losses in Kyaukpyu SEZ in 2006, 2011, and 2019.

Class Name	Acquisition Date						Net LULC Change					
	2006 (Ha)		2011 (Ha)		2019 (Ha)		2006–2011	2011–2019	2006–2019	2006–2011 (% change)	2011–2019	2006–2019
	Area	Percent	Area	Percent	Area	Percent						
Cropland	320	16%	307	12%	379	15%	−13	72	59	−4.22%	23.49%	18.28%
Scrubland	348	17%	780	32%	796	32%	432	16	448	124.14%	2.05%	128.74%
Development	66	3%	77	3%	121	5%	12	43	55	18.15%	55.60%	83.84%
Forest	349	17%	345	14%	302	12%	−4	−43	−47	−1.15%	−12.36%	−13.37%
Mangrove	338	17%	333	14%	216	9%	−5	−117	−122	−1.52%	−35.18%	−36.16%
Barren	97	5%	109	4%	186	7%	12	77	89	11.96%	70.76%	91.18%
Water	511	25%	513	21%	484	19%	2	−29	−27	0.36%	−5.60%	−5.26%

variances were then computed using the sample size allocation method.

4. Results

The results internally generated from the R.F. algorithm showed satisfactory accuracies of over 85% for 2006, 82% for 2011, and 84% for 2020. The results are summarized in Supplementary Table 4. The producer and user accuracies for Mangrove were the highest for all years. The marine traffic class obtained the second-highest accuracy. The infrastructure development and residential categories were also relatively accurate. However, the forest category had the lowest accuracy for all the years. The lower accuracy can be due to the challenge of differentiating between forested land and scrubland. Producer accuracy (omission error) refers to how often real features on the ground are correctly shown on the classified map or the probability that a specific land cover of an area on the ground is classified as such. User accuracy (commission error) refers to reliability or how often the class on the map is present on the ground. Therefore, scrubland also received relatively low results. Similarly, the producer and user accuracies for cropland and plantations were at the lower end of accuracy. These results can also be caused by the similarity between the two classes. Water, wetland, and barren land had moderate accuracy for all years. Additional accuracy assessment results in area proportions and sample count using the methodology of Olofsson et al. (2014) are presented in Supplementary Tables 1–3.

The land cover classification of Kyaukpyu SEZ using satellite data denotes substantial changes in the LULCC of Maday Island due to the construction of the SEZ and its associated operations such as fossil fuel storage and transportation and due to land displacement (Fig. 4). Fig. 5 displays the deep seaport and land reclamation projects in the original VHRI.

The numerical values are shown in Table 2. During the pre-construction period, the study area was dominated by forests, cropland, mangroves, and water bodies. Maday Island was a remote and virtually unspoiled island on the coast occupied by approximately 2400 residents, whose livelihoods solely depended on small-scale fisheries and agriculture. Forest covered 349 ha in 2006 (i.e., over 17% of the total surface area). Based on visual interpretation of the satellite images and on field observations, 17% (338 ha) of the island was covered or surrounded by mangrove forests, and 16% (320 ha) were croplands mostly dominated by paddy and winter crop fields. Almost 12% of the land was scrubland, and 6% was barren. This result may be due to the satellite's image acquisition during winter, which can be extremely dry and arid in Rakhine State. Some parts of these lands can be fallow lands during the dry season. As the island has a relatively low population density, only 2% of the total area was inhabited. Similarly, the development area was almost nil, with only 66 ha of the entire island. Given that the total area is small and sparse, these two classes were nearly undetectable in the maps. The island is surrounded by approximately 25% of water.

During the SEZ construction period in 2011, mangrove saw the most extensive loss, with the decline of more than 35% (117 ha) followed by forested land with 43 ha (12%) total decline. Consequently, the water area, including wetland ecosystems, shrank by up to 29 ha. However, the increase in scrubland was substantial, with more than 16 ha covering. The classification map (Fig. 4) indicates that a large forest area was converted to scrubland. This conversion may have first occurred due to the clearance or removal of stable, mature forests to make way for pipeline construction. This result can be identified as direct loss. Second, an extensive regrowth of non-forest vegetation occurred over time. This pattern of land change refers to cropland displacement and replacement overtime and can be identified as indirect loss. An accelerated increase in anthropogenic activities was noted, with more than 43 ha of land classified as infrastructure development. As shown in Fig. 4, the seaport area was the only visible infrastructure on the island. As the area of loss is larger than the total development area, the area of indirect loss is greater than that of direct loss. However, the land clearance pattern can be observed in the expansion of barren land which can be identified as direct loss.

During the post-construction or operation period of the SEZ, development, scrubland and barren land continued to increase substantially. An 83% increase in infrastructure development originated from completing the construction of oil terminals near the port area. Simultaneously, scrubland increased due to forest to non-forest conversions resulting from the continuous expansion of new projects. One of the most striking transformations was observed for a large area of water, mangrove, and forest due to land reclamation adjacent to the island. This caused major forest and mangrove losses (122 and 47 ha, respectively). This is a clear pattern of direct loss. Between 2006 and 2019, cropland area also expanded about 18% although it experienced initial decline, indicating indirect changes.

Overall, the infrastructure development land type experienced the most extensive transformations during the study period (2006–2019). The increase in barren and scrubland was also substantial. Significant loss of forests and mangroves was also noted. Mangroves declined more rapidly than other land cover classes, and a net loss of 122 ha was noted (a decline of 36.16%). This loss-and-gain pattern is likely to have been affected by the SEZ's operation, as the destructive form of land use associated with construction activities, oil terminals, and ports can significantly alter vegetation. Other anthropogenic activities such as cropland also intensified. The total change in the water area was minimal.

To gain insight into the expansion of SEZs in other locations in Myanmar, we visualized before- and after-images of the two largest SEZs in the country, Thilawa and Dawei. For this analysis, we used Landsat 5 and 8 data and identified the SEZ area's expansion. Fig. 5 presents false-color maps showing vegetation and urban conditions. The vegetation composite (near infrared composite) is useful for analyzing the extent of development activities within the vegetated areas. Specifically, red areas have better vegetation health, and the white color indicates the SEZ development regions. The urban band composite (short-wave infrared band combination) displays vegetation in green and SEZ expansion in blue. Bare soils or barren lands are shown in brown. These results are an example of the country's economic zone footprints over the decade.

5. Discussion

Although satellite imagery can be used to estimate environmental impacts based on visible SEZ features with likely environmental impacts, such as oil refineries, oil terminals, power plants, and factories, we estimated various impacts on land using machine-learning classification methods to ensure a more reliable assessment of environmental risk. The investigated land-cover types have undergone significant changes due to the development of SEZs. Their expansion mostly leads to a direct loss of forests and mangroves. From 2006 to 2012, a large mangroves and forest area were converted into scrublands, and this trend continued until 2019. Following high-intensity forest clearance due to infrastructure construction, the near-term post-construction environment can become dominated by non-forest vegetation, such as grasses and shrubs. This conversion pattern is typically associated with urban expansion in the forested area (van Vliet and Jasper, 2019). An extensive forest disturbance decreased forest ability to regenerate and caused a major change in dominant species, shifting from one forest type to another or a forest to non-forest vegetation. Scrublands are often more resilient to stress than forests and may establish themselves permanently. The forest's conversion pattern to scrubland is observed mostly in the surrounding areas of the deep seaport and the oil terminals. Hence, direct losses of forest due to SEZ expansion are mostly associated with the construction of transportation infrastructure and oil and gas pipelines. Also previous research has attributed extensive forest loss to oil and gas pipelines (Aung et al., 2020; Leach 2012).

Mangroves experienced rapid decline and several conversion patterns. A large mangrove ecosystem was transformed into water due to land reclamation and oil terminal construction. This finding can be attributed to the construction of the industrial zone and deep seaport within the SEZ. It might also be due to the expanded residential area triggered by activities related to the SEZ and the migration of workers employed to construct the seaport and oil and gas pipelines. As shown in Fig. 4 (B and C), the deep-water port and pipelines diagonally crossing the study area were the most prominent infrastructure constructions. Agbagwa and Ndukwu (2014) reported that oil and gas pipelines and related activities destroyed an extended area of mangroves during the construction and operation processes in Nigeria. Mangroves are fragile coastal ecosystems susceptible to threats from anthropogenic activities, such as land reclamation, dredging, sedimentation from runoffs, and oil pollution. The construction of new ports has damaged mangroves during construction and operating port-related activities, such as increased maritime traffic. A similar result was found in China, where growing coastal economic activities accelerated coastal ecosystem degradation from the 1950s onwards (He et al., 2014). The Pearl River Delta SEZ study reported that rapid development had brought severe environmental degradation in the region (Gao et al., 2019). Kyaukpyu SEZ is an oil and gas logistic hub for China with related heavy industries and transport. Increased shipping traffic often leads to massive marine pollution and threatens natural habitats around ports and near shipping routes.

Hundreds of hectares of mangrove were lost on the east coast of Sumatra due to oil spills (Yaakub et al., 2014). Mangroves are the vital interface between land and sea and provide coastal buffers when natural disasters such as tsunamis or storm surges occur (De Alban and Jose Don, 2020b). Myanmar has the eighth largest mangrove forest and is regarded as the current mangrove deforestation hotspot globally (Zöckler and Aung 2019). Within Myanmar, Rakhine, Tanintharyi (Dawei SEZ), and Yangon (Thilawa SEZ) are the main mangrove deforestation hotspots (Leimgruber et al., 2005). However, fragile marine ecosystems and mangrove forests are poorly represented among the priority areas for conservation in Myanmar (Connette et al., 2016). Marine traffic from SEZs is predicted to increase risks to already endangered and sensitive ecosystems. The mangrove forests of Rakhine are highly biodiverse and provide multiple ecosystem services upon which the majority of the local population depends (Leimgruber et al., 2005).

From 2006 to 2020, a large area of reclaimed land was converted to barren and cropland. As a result, cropland displacement is replaced by the new cropland areas. This pattern was previously observed in urban expansions in other parts of the world (van Vliet and Jasper, 2019). The residential area also expanded swiftly within the study period. However, a considerable land change in houses and croplands occurred. These changes can be due to the confiscation of lands and houses at the project planning stage, the expansion resulting from the villagers' resettlement, and the increase in migrant workers. As shown in Fig. 3, areas in proximity to the development of the oil terminal and ports changed from residential areas and croplands to infrastructure development and barren areas.

The areas far from the oil terminals converted from tree-covered into scrublands and residential areas. Disputes over land acquisition are common in connection with SEZ development, mainly when they involve a land transformation from farmland to industrial use or the expropriation of homes and properties. The authorities acquired and demarcated more than 741 ha of farmlands on Maday Island (International Commission of Jurists 2017). The acquisition process of residential land is opaque, and no record exists showing the total area of confiscated and relocated residential lands (Oxfam 2017). The same scenarios were observed in Cambodia, India, Kazakhstan, Laos, Pakistan, Russia, and Thailand, especially in connection with Chinese-financed SEZs (Bhaskar 2018; Brussevich 2020; Laungaramsri and Sengchanh 2019; Naeem et al., 2020; Sampat 2015; Turgel et al., 2019).

The local communities are often concerned about land confiscations; environmental, social, and health problems; and human rights abuses (Oxfam 2017). The communities received little to no information about the planning stage. Not surprisingly, a majority of the villagers who participated in a survey conducted in Dawei SEZ also responded that the issues of forced relocation and the appropriation of land are their main problems (Blank et al. 2019). The local community surrounding the Thilawa SEZ has been displaced and experienced a loss of livelihood (Junji 2014). Kyaukpyu and Dawei Port may be environmentally more sensitive than Thilawa SEZ due to their location in coastal regions and heavy industries, oil and gas logistics, and manufacturing activities.

By contrast, Thilawa SEZ focuses on light manufacturing, technology, and innovation (Oxfam 2017). Notably, Thilawa and Dawei are mostly operated by Japanese companies with historically higher standards of environmental and social safeguards than China, which is currently responsible for Kyaukpyu SEZ's development (Asano, 2015; Aung et al., 2021; Kudo 2016; Reilly 2013; Yang et al., 2009) The standard of environmental and social protection, and grievance mechanisms may be higher in Thilawa and Dawei SEZs. Due to the limited access to high-resolution data at large scale, the current study uses coarse resolution images to visualize Thilawa and Dawei SEZs using vegetation and urban indices. Although this technique allows us to understand the overall expansion of development zones, LULCC dynamics associated with SEZs cannot be assessed on this basis. Therefore, future research can investigate other SEZs and conduct a comparison to produce local or regional LULCC maps resulting from SEZ development. Few studies have previously assessed the direct and indirect land resulting from SEZ expansion at the local and global scale. The results of this study may serve as a methodological foundation to bridge this research gap. This study shows the maritime implications of SEZ and the need to prioritize research in this area. Although the model used in this study is useful for measuring the aggregate area of marine traffic, an object detection technique such as a neural network framework might make it possible to generate a more exact count of shipping traffic.

6. Conclusions

The number of SEZs is expected to continue growing in the coming decades, and recent projections indicate that this expansion may severely affect the environment, socio-economic conditions, and international security. This growth offers an opportunity to guide development trajectories to minimize these impacts. The results derived from the analysis in this study indicate that SEZ development comes at the cost of valuable land resources, such as agricultural, mangrove, and forest lands. The VHRI dataset enables such predicaments to be assessed with accuracy and comprehensiveness unachievable in data-poor regions such as Myanmar.

Access to port facilities in the Bay of Bengal is a priority for China, and the development of Kyaukpyu SEZ is of strategic geopolitical and economic importance. However, accountability is lacking regarding environmental and social protection and human rights violations. Lax social and environmental regulations may not be a viable long-term competitive advantage to attract investment in SEZs. Environmental and human rights protections in Myanmar's SEZ law need to be amended if it is to align with national and international environmental and human rights laws. The beneficial effects of SEZs and their positive spillovers depend on the institutional context, regulatory regime, and supporting policies. Improved environmental impact assessment and strategic environmental assessment will also be required if the SEZs in Myanmar are to develop in a sustainable way.

Given the limited availability of cross-country data to measure SEZ outcomes and characteristics, most of the research on SEZ environmental impact has relied on site-specific analysis. That approach provides reliable analyses of individual zones' influence on the ecosystem and livelihoods and provides useful insights into their implications for the regional economy and security. The site-specific nature of such analysis makes it difficult to generalize across economic, social, political, and legal contexts. However, the impacts on the ecosystem in one location can still be used as a lesson in any part of the world and the methodology can be replicated for the study of other SEZs to create a stronger basis for generalization.

Author statement

Thiri Shwesin Aung: Conceptualization, Methodology, Software, Data Curation, Formal analysis, Validation, Resources, Writing-Original draft, Visualization, Investigation.

Indra Overland: Validation, Resources, Writing, Reviewing, Proof-reading.

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Ethical statement for solid state ionics

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2022.100809.

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