Assessing Environmental Factors for Seagrass Transplantation Site Suitability in Thailand

Nuttiga Hempattarasuwan[1], Yaowaluk Monthum[2], Methee Kaewnern[1], Tipamat Upanoi[3], Attawut Khantavong[4], Pattama Tongkok[5], Alongot Intarachart[4], Kulapramote Prathumchai[6], Thon Thamrongnawasawat[2] and Chatcharee Kaewsuralikhit[7*]

ABSTRACT

This study aims to identify the environmental factors influencing seagrass distribution, with the aim of evaluating the suitability of an area for seagrass growth. Upon determining factor values, we assessed the accuracy of the methods used to ensure the reliability of those values for proposed seagrass restoration sites. R programming and structured interviews were used to identify relevant factors, while a Geographic Information System (GIS) was utilized to pinpoint six suitable seagrass transplantation sites in the Gulf of Thailand and another six in the Andaman Sea. The selection of factors to evaluate the suitability of sites for seagrass transplantation included the presence of natural barriers that mitigate storm surges and diminish wave energy, their proximity to seagrass beds, shore elevation above the lowest low water mark, extent of seagrass coverage, sediment grain size, and organic matter content. The Simple Additive Weighting (SAW) method proved effective in identifying potentially suitable seagrass habitats. The overall accuracy of the suitability maps for seagrass transplantation ranged from 60.0% to 93.3%. Notably, high-suitable and very high-suitable sites for seagrass transplantation were identified in Phangan Island's Nai Wok Bay (81%), Thalen Bay - zone 3 (75%), Na Tham Bay at Samui Island (62%), and Tan Island - east side (55%), respectively. Our findings underscore that identifying areas and the specific types of habitats suitable for seagrass restoration can significantly inform decision-making and facilitate the implementation of actions aimed at restoring seagrass ecosystems.

Keywords: Andaman Sea, Gulf of Thailand, Seagrass restoration, Simple Additive Weighting (SAW), Site selection

INTRODUCTION

Seagrasses are marine flowering plants in shallow and sheltered coastal waters (Short *et al*., 2001) that provide myriad ecosystem services. They are responsible for 20% of marine and estuarine carbon sequestration. Additionally, they sequester nutrients, stabilize sediment, support high biodiversity (McGlathery *et al*., 2012; Duarte *et al*., 2013; Praisankul and Nabangchang-Srisawalak, 2017; Kanmarangkool *et al*., 2022), attenuate wave height and energy (Bradley and Houser, 2009), and control sediment to prevent re-suspension (Duarte *et al*., 2013). It is estimated that global spatial distribution of seagrass is 266,562 km^2 (McKenzie *et al*., 2020).

[1]Department of Fishery Management, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand
[2]Department of Marine Science, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand
[3]Marine and Coastal Resources Research and Development Institute, Department of Marine and Coastal Resources, Bangkok, Thailand
[4]Sriracha Fishery Station, Faculty of Fisheries, Kasetsart University, Chonburi, Thailand
[5]Kasetsart Agricultural and Agro-Industrial Product Improvement Institute, Kasetsart University, Bangkok, Thailand
[6]Department of Geography, Faculty of Social Sciences, Kasetsart University, Bangkok, Thailand
[7]Department of Fishery Biology, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand
[*]Corresponding author. E-mail address: chatcharee.s@ku.th
Received 13 December 2023 / Accepted 11 March 2024

Before 1940, seagrass declined at an estimated rate of 0.9% per year. That rate has accelerated to 7% per year since 1990 (Waycott *et al*., 2009). Seagrass meadows are lost to natural causes such as wasting diseases (Hughes *et al*., 2018) and high energy storms (Gera *et al*., 2014). However, destruction is more commonly caused directly and indirectly by anthropogenic impacts, such as land reclamation, land use patterns adjacent to seagrass meadow (Cullen-Unsworth and Unsworth, 2016; Quiros *et al*., 2017), boat moorings (Paulo *et al*., 2019) and poor water quality (Cullen-Unsworth and Unsworth, 2016).

Salinity, temperature, depth, substrate, waves, and currents limit seagrass distribution (Short *et al*., 2001), while water depth, bed morphology, and wave exposure impact seagrass survivability (Lanuru *et al*., 2018). High wave energy can erode planted areas, mobilize sediments and bury seagrasses, especially young seagrass meadows (Paulo *et al*., 2019). Limited availability of natural phenomena that impact photosynthetic activity such as light, nutrients, and epiphytes can also adversely impact the existence or proliferation of seagrasses (Short *et al*., 2001).

Efforts have been made to address seagrass loss and protect marine environments worldwide such as improving water quality, implementing boating and fishing restrictions, and adopting effective aquaculture practices. Habitat conservation and protection through legal instruments, environmental policies, management practices, planning techniques (Coles and Fortes, 2001; Short *et al*., 2001), and transplantation activities (Calumpong and Fonseca, 2001; Cullen-Unsworth and Unsworth, 2016), have also been implemented in efforts to restore habitats as well as to mitigate seagrass loss or damage. Researchers in the United States, Indonesia, and Thailand are among the groups that have investigated the efficacy of seagrass habitat restoration (Short *et al*., 2002; Lanuru *et al*., 2018; Stankovic *et al*., 2019).

A model for the selection of eelgrass transplantation sites was developed on the northeast coast of the Unites States, and two years after transplanting, the survival rate was as high as 62% (Short *et al*., 2002). A model for the selection of tropical seagrass transplantation sites was also developed and tested on the west coast of South Sulawesi in Indonesia. In that study, only two of six seagrass transplantation testing sites had a high rate of survival as demonstrated by Transplant Suitability Index scores (Lanuru *et al*., 2018). In addition, seagrass transplanted in Thailand's Sriracha Bay without a site evaluation had a survival rate of only 26.15% (Vichkovitten *et al*., 2016). The viability of seagrass rehabilitation and the ultimate success of those efforts are significantly impacted by careful planting and site selection, the latter of which is the major factor affecting the difficulty of seagrass rehabilitation (Short *et al*., 2002; Matheson *et al*., 2016).

As a result, evaluating and selecting suitable sites is crucial to the success of seagrass transplantation (Lanuru *et al*., 2018). Restoration efforts need to have strategically directed guidance to maximize the benefits and avoid misplaced action (Cullen-Unsworth and Unsworth, 2016). In the past fifteen years, there have been seagrass restoration efforts in Thailand, but most did not involve monitoring or result assessment. Primarily, restoration activities were Corporate Social Responsibility (CSR) efforts involving coastal communities that were promoted in social media without monitoring the effectiveness of the efforts. From 2018 to 2021, the Department of Marine and Coastal Resources transplanted seagrass in nine coastal areas in Thailand. Only one area reported a survival rate in the 70–95% range without increasing seagrass numbers and density (Marine and Coastal Resources Research and Development Institute, 2022). Thus, the objectives of this study are to: 1) identify the environmental factors that affect seagrass distribution in order to assess suitability of an area for seagrass growth, and 2) assess the accuracy of suitable methods to ensure the reliability of the factors for the proposed seagrass restoration sites. This research takes a novel approach in its analysis of a unique set of factors to assess suitability of an area, which can inform site selection for seagrass restoration efforts in the Gulf of Thailand and the Andaman Sea.

MATERIALS AND METHODS

Sampling sites

Data were obtained during periods of low tide from May 2022 to February 2023. The data from 218 sampling points at six sampling sites in the Gulf of Thailand (Figure 1 and 2) and from 335 sampling points at six sampling sites in the Andaman Sea (Figure 1 and 3) were collected to determine values and assess accuracy.

Data from a 2020 Department of Marine and Coastal Resources survey, showing seagrass mapping and boundaries, was used as a primary source of information for site selection, and the following criteria were applied in the site selection process: 1) had the same water depth as nearby natural seagrass beds, 2) had a history of existing seagrasses, 3) had a large enough area to accommodate the desired transplant objective, 4) was a less-disturbed habitat, and 5) experienced seagrass decline in the previous decade.

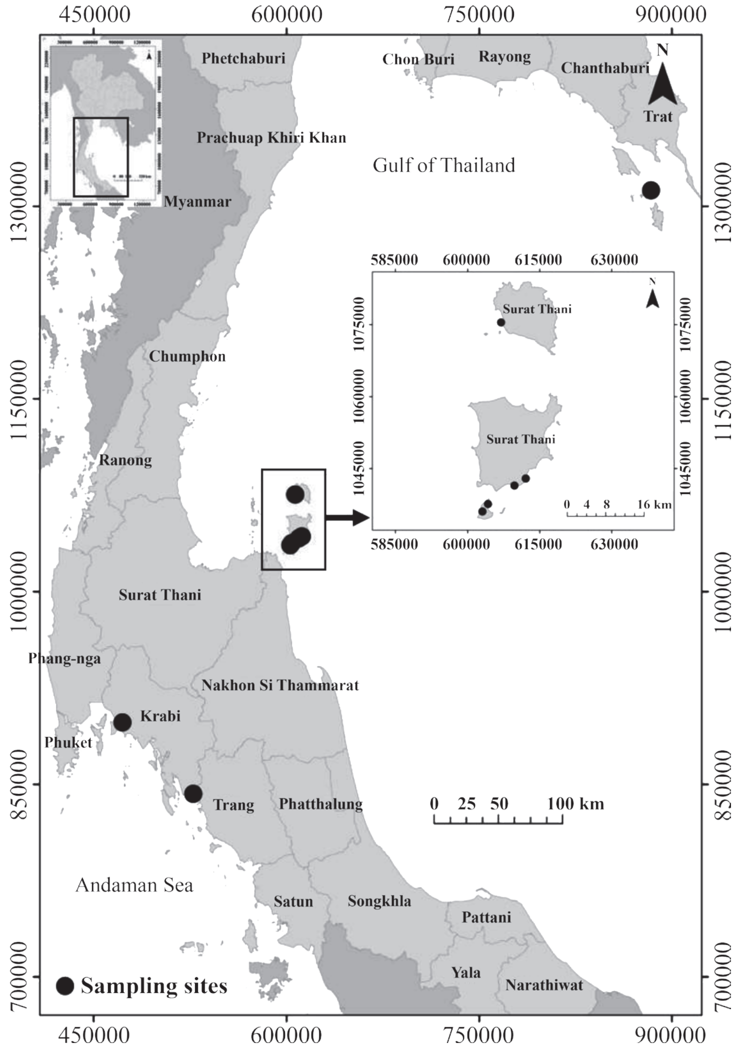

Figure 1. Maps of coastal provinces in Thailand and sampling sites.

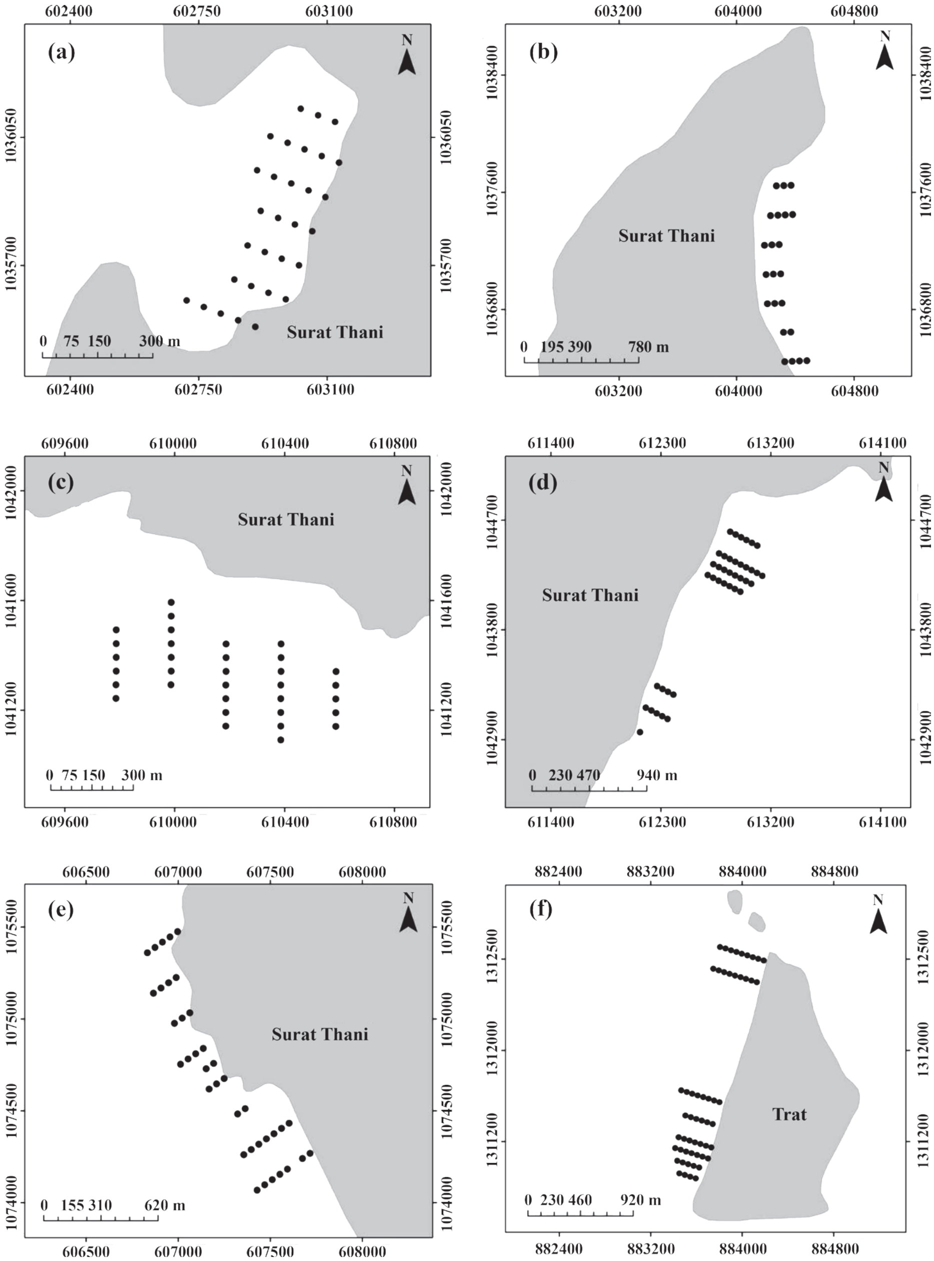

Figure 2. Maps showing the six sampling sites in the Gulf of Thailand: (a) Tan Island - west side (30 sampling points), (b) Tan Island - east side (22 sampling points), (c) Na Tham Bay (33 sampling points), (d) Hua Thanon Bay (40 sampling points), (e) Nai Wok Bay (37 sampling points), and (f) Kradat Island (56 sampling points).

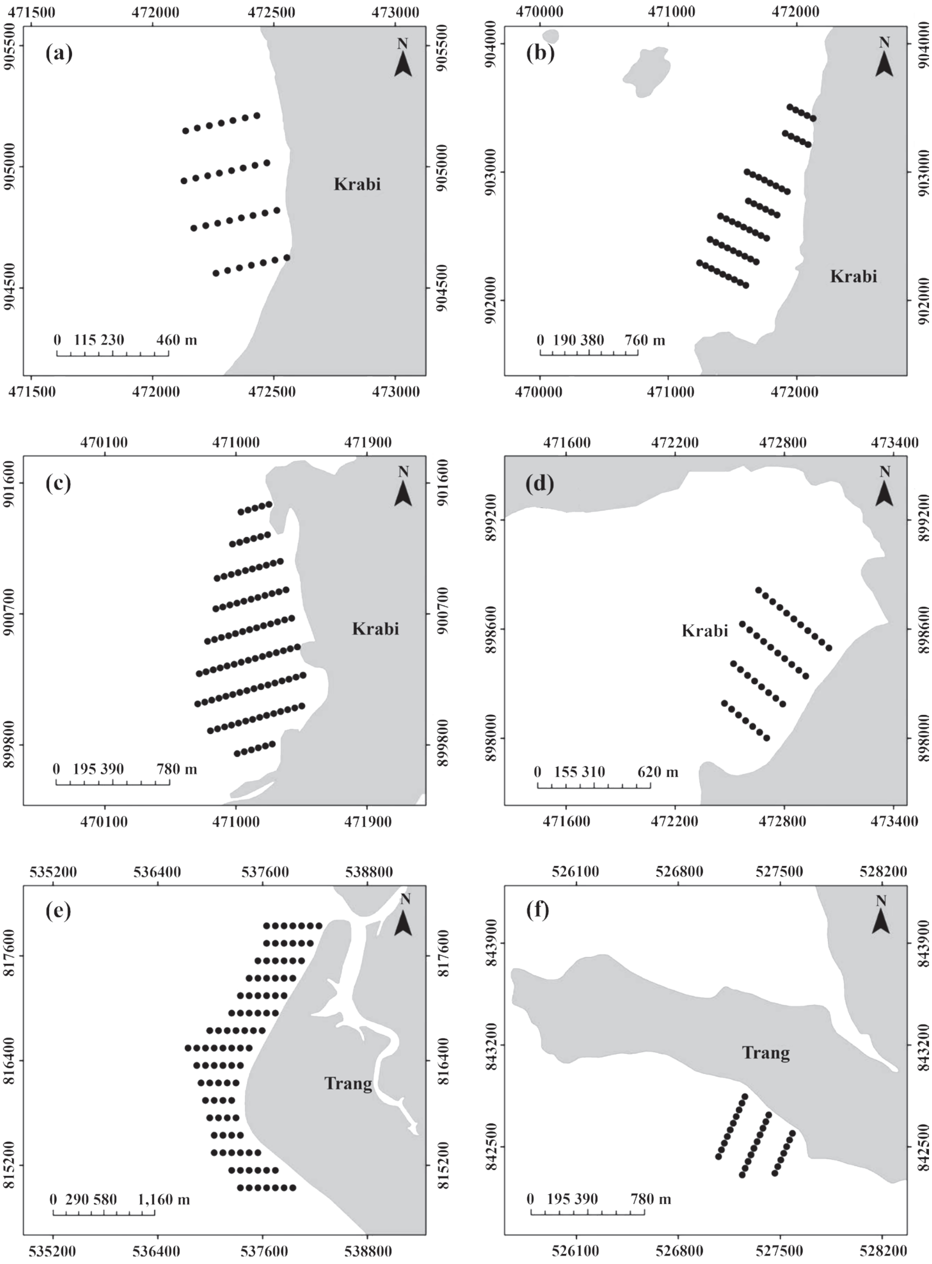

Figure 3. Maps showing the six sampling sites in the Andaman Sea: (a) Thalen Bay - zone 1 (30 sampling points), (b) Thalen Bay - zone 2 (51 sampling points), (c) Thalen Bay - zone 3 (97 sampling points), (d) Thalen Bay - zone 4 (36 sampling points), (e) Laem Yong Lum (94 sampling points), and (f) Laem Sai Bay (27 sampling points).

The research method

Figure 4 shows the following research steps: identify the criteria, determine the weight of combined criteria, generate suitability maps, locate potential seagrass transplantation sites, assess accuracy and analyze the maps and results.

Data collection

Based on existing literature (Short *et al*., 2002; Duarte *et al*., 2013; Lanuru *et al*., 2018), a comprehensive understanding of seagrass ecology, consultation with a panel of university experts and extensive field work, we selected these five parameters: 1) the existence of natural barriers that prevent storm surges and reduce wave energy and their distance from the seagrass beds, 2) shore height above the lowest low water, 3) seagrass coverage, 4) sediment grain size, and 5) organic matter content.

The distance between seagrass beds and natural shelters

Google Earth images and seagrass maps from the Department of Marine and Coastal Resources in 2020 were used as base maps for measuring distances between the seagrass beds and wind wave shelters. Measuring the distances from wind wave shelters to the seagrass beds at 22 representative sites in 16 provinces on both the Gulf of Thailand and the Andaman coast was conducted using a Geographic Information System (GIS) with Quantum GIS version 3.22.4. These distances were calculated in kilometers within the Transverse Mercator WGS -84 projection/UTM zone 47N. The collected data reflecting a representative average distance between seagrass beds and wind wave shelters in Thailand were used to identify the threshold criterion for further analysis of the four additional factors.

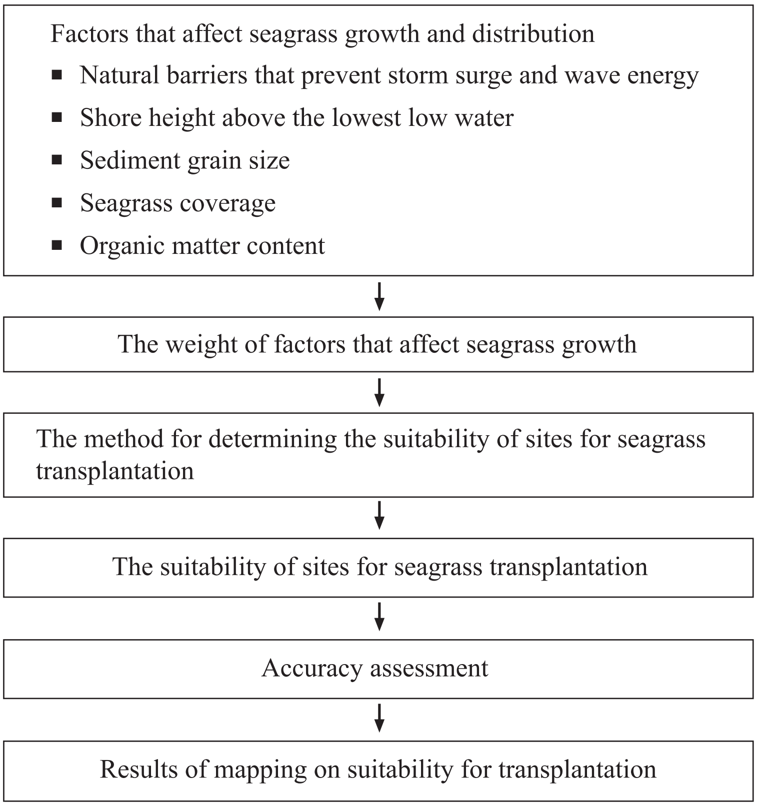

Figure 4. Research process.

A transect line survey

Transect lines from the coastline perpendicular to the end of the seagrass meadow were laid out at each study site. The distance of each transect line from the coastline was determined by taking into account to what point the water at low tide was at a depth of less than 0.8 m and conducive to walking and planting seagrass. The transect lines were 100 m or 200 m apart depending on characteristics of the survey sites such as size of study area, seagrass coverage, low tide water depth and seagrass mapping by the Department of Marine and Coastal Resources in 2020. Sampling points, 50 m apart, were plotted along each transect line.

The data from 153 sampling points at six sampling sites in the Gulf of Thailand and 272 sampling points at two sampling sites in the Andaman Sea were collected to determine factor values. At each location, the geographical coordinates of the sampling points were recorded via Global Positioning System (GPS), and shore height above the lowest low water, sediment grain size, organic matter content, and seagrass coverage were measured as follows:

(1) Shore height above the lowest low water

We obtained the shore height above the lowest low water (in centimeters) by using a theodolite and a surveyor's rod as employed by Leliaert and Coppejans (2003) and noted the height and time the data were collected. The height was used to calculate the shore height above the lowest low water level (H-LLW: Height above the lowest low water) from the water scale in 2022 and 2023 on the date, time, and location of data collection consistent with Monthum *et al*. (2023).

(2) Sediment sample collection - sediment grain size and organic matter content

We obtained three replicate sediment cores from a depth of 10 cm at each sampling point. After drying, the sediment samples were analyzed to determine grain size composition and total organic matter composition at the Marine Science Department's Laboratory at Faculty of Fisheries, Kasetsart University. An analysis of sediment grain size and total organic matter content can be performed by applying the Walkley-Black method (Walkley and Black, 1934).

(3) Seagrass ecological survey - seagrass coverage

We established 0.25 m^2 quadrats at each sampling point. Seagrass species and coverage percentage were measured in each quadrat.

Method for estimating suitable areas for seagrass planting

Analysis of the weighting influence that affect seagrass growth

Analyses of shore height above the lowest low water, sediment grain size, organic matter content, and seagrass coverage were carried out in the R program (R Core Team, 2020). The ggplot visualization package was used to establish a statistical histogram to identify an appropriate range of the factors that affect seagrass distribution and to determine the weight of the factors that affect seagrass growth. Thereafter, utilizing a GIS, the site ranking and score data were used to determine the best sites for seagrass transplantation.

Ten participants were interviewed by using a structured interview. The Delphi method applied to inquire of a group of seagrass experts from the Faculty of Fisheries at Kasetsart University. The goal was to establish the criteria of environmental conditions/factors affecting seagrass suitability and to allocate weight and rating values to each of those factors.

Simple Additive Weighting (SAW)

This research applied the Simple Additive Weighting (SAW) decision-making method. In using the SAW method, the weighted sum of every alternative's performance on each attribute is found. Each attribute is weighted. A total score for each alternative is obtained by multiplying each attribute's rating by its weight and adding all the resulting attribute scores. (Panjaitan, 2020; Vafaei *et al*., 2022).

Alternatives can be then ranked by total score with the highest score reflective of the best alternative while a comparison of scores can inform the quality and viability of other alternatives (Ibrahim and Surya, 2019; Panjaitan, 2020). As such, this method can support overlay operations in GIS (Malczewski, 1999).

The SAW method was applied in this study using the following equation.

$$S_i = \sum_{j=1}^{n} W_j R_{ij}$$

Where, S_i is the ranking for each alternative (or Suitability index for each pixel in map), W_j is the weighted value of each criteria (or Weighting influence); R_{ij} is the normalized performance rating value (or Rating score); i = 1,2,…, m and j = 1,2,3,…, n. A large S_i value indicates the best alternative.

Habitat suitability of sites for seagrass transplantation

(1) Preparation of data and generation of a suitability map of sites for seagrass transplantation

The suitability of a habitat and its substrate must be taken into account when considering it as a site for transplantation (Lanuru *et al*., 2018). In this study, mapping was conducted and data regarding four parameters, shore height above the lowest low water, seagrass coverage, sediment grain size, and organic matter content were encoded and saved in comma-separated value (csv) format and then converted to shapefiles. An Inverse Distance Weighted (IDW) interpolation in GIS software was used to model surfaces to form shapefiles assuming that closer values are more related than those farther apart (Maleika, 2020; ESRI, 2023). The outputs of interpolation of four parameters were then rasterized and reclassified accordingly. Reclassification was performed on each output layer by applying the relative weight due in the analysis of suitability for transplantation as follows: shore height above the lowest low water (50%), sediment grain size (20%), seagrass coverage (15%), and organic matter content (15%). Details are presented in Table 1. Consequently, spatial values obtained from mapping process were converted into vector-based GIS layers. The resulting habitat suitability map yielded five classes: very low-suitable, low-suitable, medium-suitable, high-suitable, and very high-suitable.

(2) Post-classification evaluation

We applied an error matrix to represent accuracy. An error matrix is effective in that the accuracies of each category are plainly described along with errors of inclusion (commission errors) and errors of exclusion (omission errors) which are present in a classification. It is the approach recommended by many researchers and "should be adopted as the standard reporting convention" (Congalton, 1991).

The accuracy of the results of the five classes of habitat suitability was assessed by applying an error matrix. The error matrix was calcuated using the field-measured dataset, which was split into training and testing datasets. To create maps reflecting transplantation suitability levels, data from 198 sampling points (70%) was allocated for training and data from the remaining 83 samples (30%) was used for testing. This data split is consistent with prior research (Downie *et al*., 2013; Kuhn and Johnson, 2013; Szantoi *et al*., 2015). Validated sites were determined in GIS using a random sampling technique (Baumstark *et al*., 2016).

The level of suitability of the sites for seagrass transplantation was determined by using a standard per-pixel percentage agreement to estimate overall accuracy between the two mapped levels of seagrass habitat suitability classes. Consistent with Congalton (1991), validation site data were intersected with map results and used to produce an error matrix table to calculate the overall producer's and user's accuracies, as defined in the following section.

RESULTS AND DISCUSSION

The distance between seagrass beds and natural shelters

Having natural landscape features such as barrier islands that protect against storm surge and wave energy was prioritized as the threshold, primary factor to be considered when choosing a location for seagrass transplantation (Table 1). From the 2020 Department of Marine and Coastal Resources survey, it was found that the average distance between seagrass beds and wind wave shelters at 22 representative sites in 16 provinces on the Gulf of Thailand and the Andaman coast was 15.04 km. This average distance was used to establish the threshold criterion in Table 1. Target areas should meet this criterion of having a wind wave shelter that is less than 15.04 km away. The distance between the seagrass beds at all eight sites and wind wave shelters was less than 15.04 km: Tan Island - west side (7.26 km), Tan Island - east side (12.63 km), Na Tham Bay (5.04 km), Hua Thanon Bay (1.11 km), (e) Nai Wok Bay (0.93 km), Kradat Island (1.36 km), Thalen Bay (12.83 km), and Laem Sai Bay (9.97 km). Therefore, an analysis of the additional four factors can be conducted for all subject sites.

The shore height above the lowest low water (H_LLW)

During high tide, stations with high H_LLW are in shallow water, while stations with low H_LLW are in deeper water. In the Gulf of Thailand study sites, seagrasses are distributed from 150 cm below H_LLW (-150 cm H_LLW) to 150 cm H_LLW, and they showed a non-normal distribution (p-value< 0.05). Seagrasses are predominantly distributed between 0 and 100 cm above H_LLW (Figure 5a), which is rated at only 2 levels and affects the weight index of H_LLW used in the weighted overlay analysis. To address this, we opted to analyze data ranging from 0 to 100 cm above H_LLW (Figure 5b) and found a normal distribution (p-value = 0.30). This allowed us to classify the data into the 5 rating values shown in Table 1. In the Andaman Sea, seagrasses are distributed from 0 to 220 cm H_LLW (Figure 4c) and showed a non-normal distribution. This distribution is classified into 4 rating values for the overlay analysis.

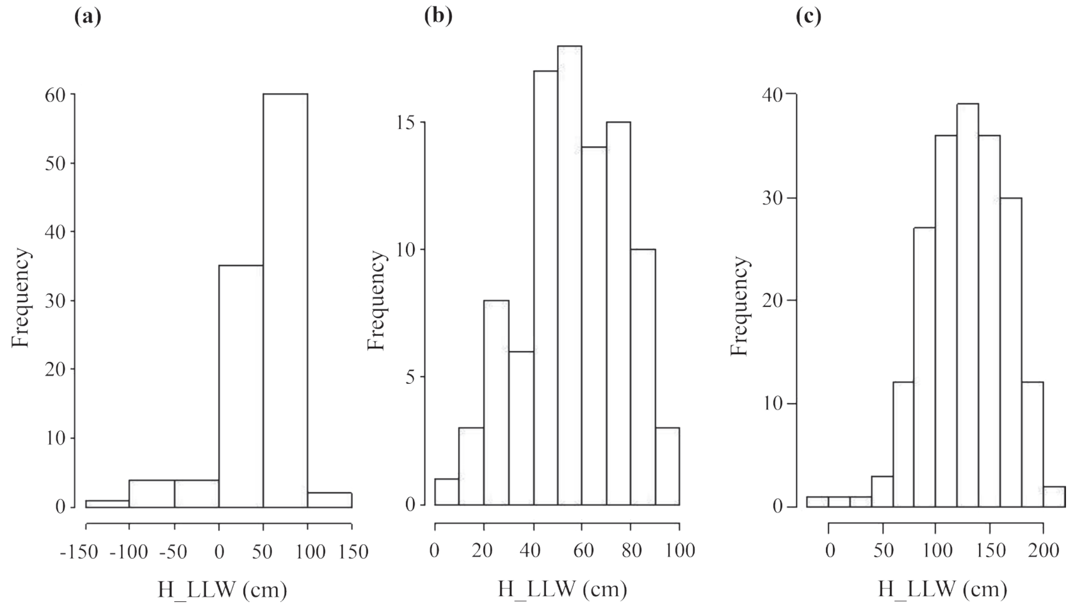

Figure 5. Histogram of seagrass existence frequency at different heights above lowest low water (H_LLW: cm) surveyed in the Gulf of Thailand ranging from: (a) -150 to 150 cm H_LLW, (b) 0 to 100 cm H_LLW, and (c) the Andaman Sea.

Heights above lowest low water (H_LLW) at the Gulf of Thailand sites were more concentrated in the 0–100 cm frequency range (Figure 5a) and the frequency values in that range were divided into 4 ranges (Figure 5b). However, the distribution of seagrass at the Gulf of Thailand sites had values lower than 0 cm and greater than 100 cm as well which justified adding a fifth range. Meanwhile, the Andaman Sea data had a normal distribution in the 60–200 cm range (Figure 5c). As a result, the division of the ranges of the Gulf of Thailand and Andaman Sea differed in both the H_LLW levels and the number of frequency ranges.

Sediment grain size (SC)

We analyzed the grain size dataset from the stations wherein H_LLW data were collected, focusing on the range from 0 to 100 cm above H_LLW. The results were reported in terms of silt-clay percentage. In the Gulf of Thailand sites, seagrasses were mostly found in areas with lower silt-clay percentages (1–5%), whereas in the Andaman Sea sites, they showed a broader distribution range (0–10%). Seagrasses in the Gulf of Thailand showed a preference for substrates with sandy bottoms, while those in the Andaman Sea preferred muddy sand bottoms with a wider range of silt-clay percentages, displaying a non-normal distribution (p-value<0.05) (Figure 6). The silt-clay percentage was categorized into 4 rating values for both the Gulf of Thailand and the Andaman Sea sites for the reclassification and overlay operation in GIS (Table 1).

Sediment organic matter (OM)

Sediment organic matter ranged from 0 to 1.2% (Figure 7a) of the samples collected at the Gulf of Thailand sites. A high frequency of seagrass was observed in sediment with 0.3–0.5% of organic matter with a non-normal distribution (p-value<0.05). Seagrasses in the Gulf of Thailand and the Andaman Sea sites showed no difference in their frequency related to percentage of sediment organic matter (Figure 7b). The sediment organic matter level was categorized into 4 rating values for the Gulf of Thailand sites and 5 for the Andaman Sea sites for the reclassification and overlay operation in GIS (Table 1).

Seagrasses coverage percentage

The presence of seagrasses is one of several key indicators of seagrass growth potential. The frequency of seagrass existence at different coverage levels, both in the Gulf of Thailand and the Andaman Sea sites, showed a non-normal distribution (p-value<0.05) (Figure 8). The varied coverage percentages were influenced by a natural distribution, which included both mono-specific and multispecies occurrences. The coverage percentage was classified into 4 rating values for both the Gulf of Thailand and the Andaman Sea for the reclassification and overlay operation in GIS (Table 1).

Factors and scoring

Table 1 below reflects the results of the analysis of the seagrass data, the five environmental factors that impact seagrass growth and the results from applying the weighted influence of those factors. If the target area met the threshold criterion of being located less than 15.04 km from a wind wave shelter (factor No. 1), then the other four factors were to be analyzed. The table additionally shows that the influence and weighted index classification of shore height above the lowest low water, sediment grain size, and organic matter content were not the same at the Gulf of Thailand sites as they were at the Andaman Sea sites.

Mapping and validation

Congalton (1991) explained that producer's accuracy is a measure of omission error or a measure of the probability of reference pixels being correctly classified. User's accuracy is a measure of commission error; it is derived by dividing the total number of correct pixels in each category by the number of pixels that were classified within that specific category.

The producer's and user's accuracy were obtained from the error matrix for five levels of transplantation suitability: very low-suitable, low-suitable, medium-suitable, high-suitable, and very high-suitable, as presented in Table 2. The classification of the suitability of the two Andaman Sea sites were highly accurate at 90% and 93.3%

Table 1. The influence measured as 'rating values' and weighted influence (%) of the factors used in the weighted overlay analysis of the sites in the Gulf of Thailand and the Andaman Sea.

No	Factor	Description	Weight influence (%)	Rating value
The Gulf of Thailand and Andaman Sea				
1	Existence of natural barrier that prevents storm surges and reduces wave energy	There is a wind wave shelter that could reduce the impact of strong waves within 15.04 km	If this criterion is met, proceed to analyze the other four factors	
		There is no wind wave shelter that could reduce the impact of strong waves within 15.04 km	No further analysis	
2	Seagrass coverage (% cover of seagrass)	0.00% (No seagrass)	15	1
		0.01–25% (low abundance)		2
		25.01–50% (medium abundance)		3
		50.01–75% (high abundance)		4
		75.01–100% (very high abundance)		5
The Gulf of Thailand				
3	Shore height above the lowest low water	< 20 cm and > 120 cm	50	1
		101–120 cm		2
		21–40 cm and 81–100 cm		3
		61–80 cm		4
		41–60 cm		5
4	Sediment grain size (% silt clay)	> 5%	20	1
		> 3–5%		2
		0–1%		3
		> 1–3%		4
5	Organic matter content (% organic matter)	0% and > 1.2%	15	1
		> 0.8–1.2%		2
		> 0.0–0.3% and > 0.5–0.8%		3
		> 0.3–0.5%		4
Andaman Sea				
3	Shore height above the lowest low water	> 220 cm	50	1
		< 61 cm and 181–220 cm		2
		61–100 cm and 141–180 cm		3
		101–140 cm		4
4	Sediment grain size (% silt clay)	> 15%	20	1
		> 10–15%		2
		0–2% and > 7–10%		3
		> 2–7%		4
5	Organic matter content (% organic matter)	0%	15	1
		> 0.0–0.2% and > 1.4%		2
		> 1.0–1.4%		3
		> 0.6 -1.0%		4
		> 0.2–0.6%		5

Table 2. Site suitability levels, producer's accuracy, user's accuracy, and overall accuracy of the locations.

Location	Level of habitat suitability	Producer's accuracy (%)	User's accuracy (%)	Overall accuracy (%)
Tan Island-west side (Gulf of Thailand)	a	-	-	84.0
	b	-	-	
	c	90.5	90.5	
	d	66.7	66.7	
	e	-	-	
Tan Island-east side (Gulf of Thailand)	a	-	-	70.0
	b	-	-	
	c	60.0	75.0	
	d	80.0	66.7	
	e	-	-	
Na Tham Bay (Gulf of Thailand)	a	-	-	80.0
	b	-	-	
	c	60.0	60.0	
	d	86.7	86.7	
	e	-	-	
Hua Thanon Bay (Gulf of Thailand)	a	84.6	100.0	77.8
	b	60.0	91.7	
	c	0.0	75.0	
	d	-	-	
	e	-	-	
Nai Wok Bay (Gulf of Thailand)	a	-	-	60.0
	b	-	-	
	c	50.0	75.0	
	d	87.5	50.0	
	e	33.3	100.0	
Kradat Island (Gulf of Thailand)	a	-	-	81.3
	b	50.0	100.0	
	c	66.7	80.0	
	d	100.0	80.0	
	e	-	-	
Thalen Bay-Zone 4 (Andaman Sea)	a	-	-	90.0
	b	-	-	
	c	95.2	90.9	
	d	77.8	87.5	
	e	-	-	
Laem Sai Bay (Andaman Sea)	a	-	-	93.3
	b	100.0	93.3	
	c	-	-	
	d	-	-	
	e	-	-	

Note: Level of habitat suitability: a = Very Low-suitable; b = Low-suitable; c = Medium-suitable; d = High-suitable; e = Very High-suitable

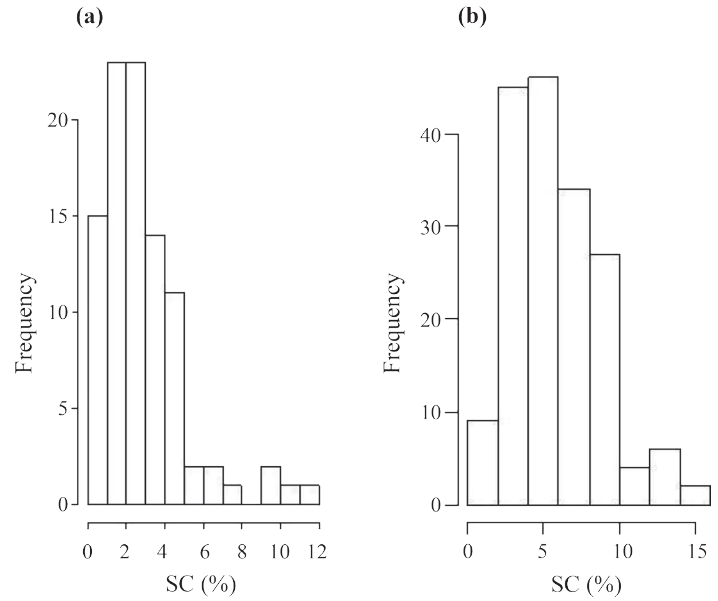

Figure 6. Histogram of seagrass existence frequency at different sediment organic matter levels (% organic matter) surveyed in: (a) the Gulf of Thailand, and (b) the Andaman Sea.

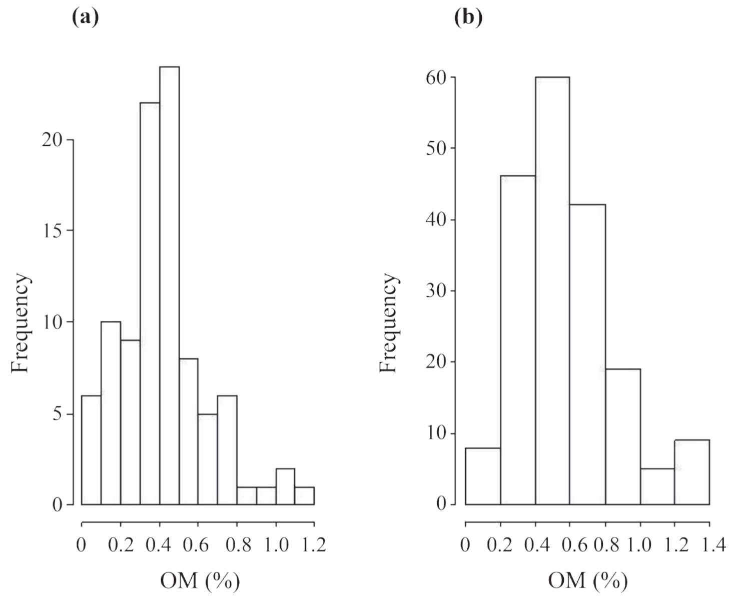

Figure 7. Histogram of seagrass existence frequency at different sediment organic matter levels (% organic matter, OM) surveyed in: (a) the Gulf of Thailand, and (b) the Andaman Sea.

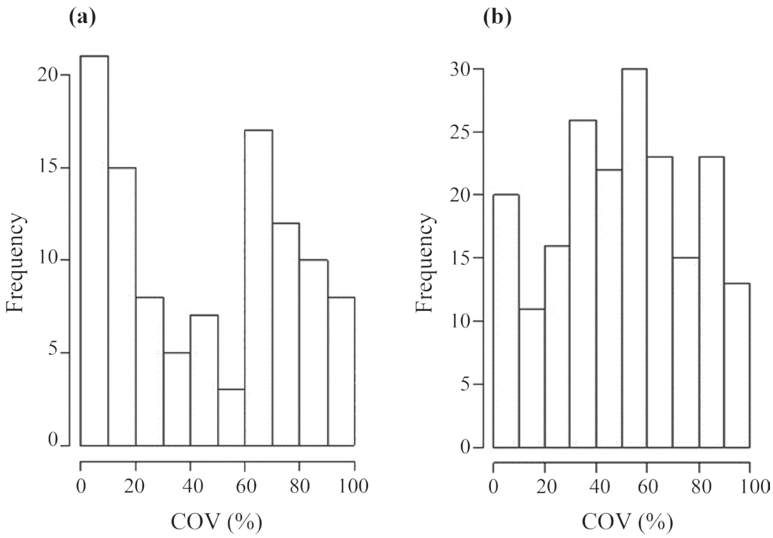

Figure 8. Histogram of seagrass existence frequency at different percentage coverage (COV) surveyed in: (a) the Gulf of Thailand, and (b) the Andaman Sea.

respectively, while the overall accuracy (OA) of the classification of the six Gulf of Thailand sites ranged between 60.0% and 84.0%. Laem Sai Bay produced the highest level of OA at 93.3% whereas Nai Wok Bay's OA of 60.0% was the lowest.

Looking more specifically at some noteworthy findings, the producer's accuracies were low for the very high-suitable and medium-suitable levels (33.3% and 50.0% respectively) at Nai Wok Bay. This indicates that more of those pixels were misclassified as high-suitable and very high-suitable. The user's accuracy of Nai Wok Bay's high-suitable classification was 50%. As a result, Nai Wok Bay yielded a 60% overall map accuracy. At Kradat Island, although the producer's accuracy for the low-suitable and medium-suitable classifications (50.0% and 66.7% respectively) were lower than for the high-suitable level, other values such as the user's accuracy and overall accuracy were relatively high.

The produced base maps of seagrass habitats and potential areas of further investigation are presented in Figures 9 and 10. An analysis of the areas and proportions of various habitats under different schemes, for example, that 81% of the Nai Wok Bay- Phangan Island site, 75% of Thalen Bay - zone 3, 62% of the Na Tham Bay-Samui Island site and 55% of the Tan Island-east side site were high-suitable or very high suitable for transplantation. Contrarily, 99% of the Laem Sai Bay in Trang Province site was low-suitable for transplantation, as shown in Table 3.

Applicability to decision-making

Informed site selection is critical to effective seagrass transplantation efforts (van Katwijk *et al*., 2009). In tropical and subtropical areas, several methods have been applied to attempt to identify suitable sites. In Indonesia, Lanuru *et al*. (2018) used a preliminary transplant suitability index calculation test model. The model was developed based on historical and current seagrass distribution, proximity to natural seagrass beds, wave exposure, water depth, and water quality. Their model revealed that only two of nine total sites were predicted to be most suitable for seagrass transplantation. In Malaysian coastal waters, an acoustic dataset from a multibeam echosounder and species occurrence data were used to model suitable seagrass habitats. This study found that the bathymetry data was the most influential predictor (Muhamad *et al*., 2021). In Thailand, Vichkovitten *et al*. (2016) found a 26.15% seagrass survival rate when simply focusing on coastal areas and only evaluating reduced current and wave action as factors. This study, however, evaluated a more comprehensive set of factors to obtain more pertinent and helpful data to map habitat suitability and inform effective transplantation efforts.

The existence of a natural barrier plays an important role as a threshold factor. Other factors such as shore height above the lowest low water, seagrass coverage, sediment grain size and organic matter contents are additional important and measurable environmental parameters. Further, this research generated suitable site maps to inform actual transplantation by specifying the last point on each transect line where the depth of water at low tide is 0.8 m. Data collection, criteria specification and classification methods used to generate classified layers for an overlay operation using GIS are repeatable and represent an alternative to existing methods.

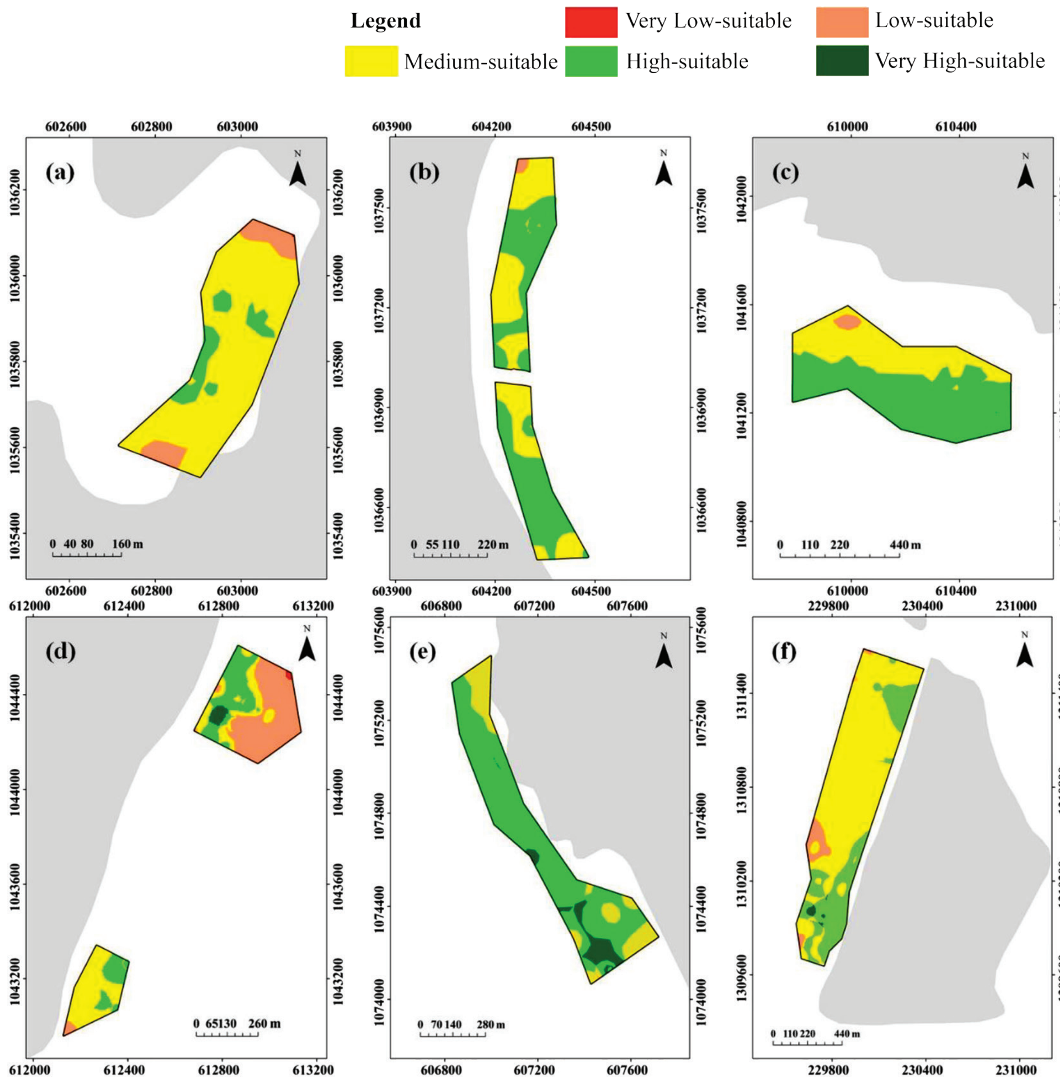

Figure 9. Maps of suitability for seagrass transplantation in the Gulf of Thailand: (a) Tan Island - west side, (b) Tan Island - east side, (c) Na Tham Bay, (d) Hua Thanon Bay, (e) Nai Wok Bay, and (f) Kradat Island.

Assessing the long-term success rate of transplantation will require lengthy and potentially costly monitoring of a restored site. Successful transplantation is significantly impacted by the period of transplantation and site selection (Vichkovitten *et al*., 2016). Though no model can account for every eventuality, we expect that our method can make seagrass transplantation more time and financially efficient. Our analysis of the factors impacting transplantation suitability informs, among other things, that the greater the suitability of a site, the greater number of seagrasses shoots it can sustain.

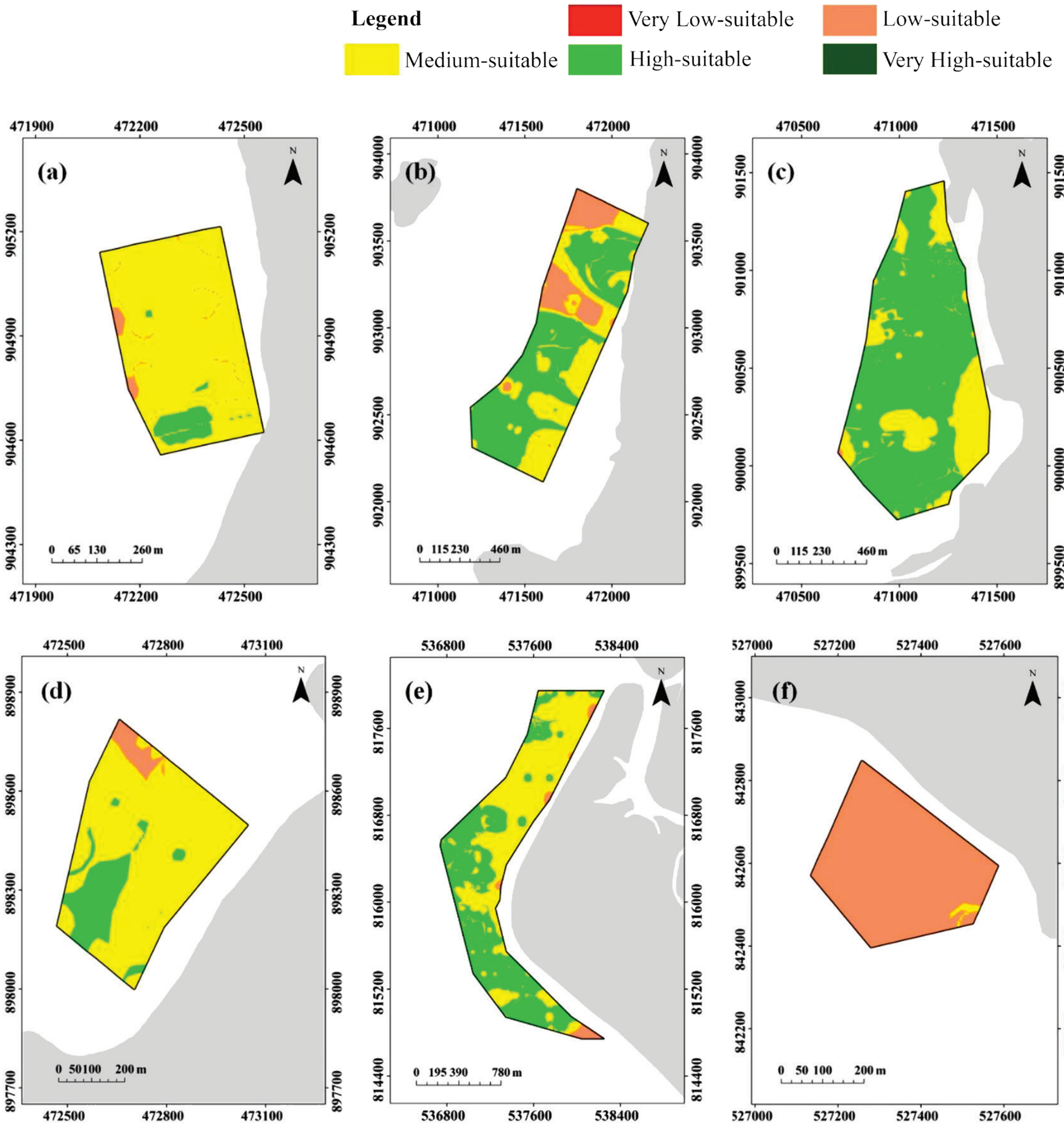

Figure 10. Maps of suitability for seagrass transplantation in the Andaman Sea: (a) Thalen Bay - zone 1, (b) Thalen Bay - zone 2, (c) Thalen Bay - zone 3, (d) Thalen Bay - zone 4, (e) Laem Yong Lum, and (f) Laem Sai Bay.

Table 3. Sites, area and transplantation suitability.

Location	Very Low-suitable m² (%)	Low-suitable m² (%)	Medium-suitable m² (%)	High-suitable m² (%)	Very High-suitable m² (%)	Total area m² (%)
Tan Island -west side	25.00 (0.02)	10,604.62 (9.89)	85,120.61 (79.41)	11,438.34 (10.67)	-	107,188.57 (100.00)
Tan Island -east side	-	1,330.71 (0.96)	61,336.25 (44.35)	75,642.83 (54.69)	-	138,309.79 (100.00)
Na Tham Bay	-	4,348.08 (1.81)	87,996.74 (36.58)	148,211.55 (61.61)	17.12 (0.01)	240,573.49 (100.00)
Hua Thanon Bay	674.05 (0.34)	76633.9 (38.97)	67239.79 (34.20)	48157.50 (24.49)	4,599.42 (2.34)	196,630.61 (100.00)
Nai Wok Bay	-	108.52 (0.04)	49,664.47 (19.08)	189,557.58 (72.83)	20,934.79 (8.04)	260,265.36 (100.00)
Kradat Island	-	29,998.29 (4.33)	483,849.52 (69.87)	174,607.50 (25.21)	4,078.32 (0.59)	692,533.62 (100.00)
Thalen Bay - zone 1	-	5,396.25 (2.57)	191,511.18 (91.07)	13,388.17 (6.37)	-	210,295.60 (100.00)
Thalen Bay - zone 2	-	113,193.58 (15.51)	253,837.91 (34.78)	362,745.71 (49.71)	-	729,777.20 (100.00)
Thalen Bay - zone 3	-	835.43 (0.10)	215,788.76 (25.30)	636,358.65 (74.60)	-	852,982.84 (100.00)
Thalen Bay - zone 4	-	11,727.30 (4.77)	196,440.82 (79.85)	37,851.38 (15.39)	-	246,019.50 (100.00)
Laem Yong Lum	-	44,675.23 (2.68)	875,792.27 (52.59)	744,864.51 (44.73)	-	1,665,332.01 (100.00)
Laem Sai Bay	-	117,616.93 (98.97)	1,222.70 (1.03)	-	-	118,839.63 (100.00)

CONCLUSION

Long term seagrass loss requires a focused effort on restoration and will require a consideration of the potential viability of future habitats. The existence of natural barriers that prevent storm surges and reduce wave energy and their distance from the seagrass beds, shore height above the lowest low water, seagrass coverage, sediment grain size, and organic matter content were the key factors that contributed to the success of seagrass transplantation. The SAW decision-making method can provide a baseline to identify potentially suitable seagrass habitats. The overall accuracy of the maps of suitability for seagrass transplantation ranges between 60.0% and 93.3%. Our findings identify areas and types of areas where seagrass can be restored/transplanted which can inform decisions about seagrass restoration area selection. Future emphasis should be placed on testing the actual success of restoration at sites identified by our method and predictions and a comparison of this restoration success to SAW method results.

ACKNOWLEDGEMENTS

This work was funded by the National Research Council of Thailand. We are grateful to the Department of National Parks, Wildlife and Plant Conservation for providing authorization to conduct this work and for research support. We would like to thank Assoc. Prof. Dr. Wara Taparhudee and Dr. Roongparit Jongjaraunsak for sharing their expertise on applying the theodolite and surveyors' rod technique. We also thank the anonymous reviewers for their constructive comments and assistance in improving the original and subsequent drafts of this manuscript.

LITERATURE CITED

Baumstark, R., R. Duffey and R. Pu. 2016. Mapping seagrass and colonized hard bottom in Springs Coast, Florida using WorldView-2 satellite imagery. **Estuarine, Coastal and Shelf Science** 181: 83–92. DOI: 10.1016/j.ecss.2016.08.019.

Bradley, K. and C. Houser. 2009. Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. **Journal of Geophysical Research** 114 (F01004): 1–13. DOI: 10.1029/2007JF000951.

Calumpong, H.P. and M.S. Fonseca. 2001. **Seagrass transplantation and other seagrass restoration methods.** In: Global Seagrass Research Methods (eds. F.T. Short and R.G. Coles), pp. 425–443. Elsevier Science, Amsterdam, Netherlands.

Coles, R. and M. Fortes. 2001. **Protecting seagrass–approaches and methods.** In: Global Seagrass Research Methods (eds. F.T. Short and R.G. Coles), pp. 445–463. Elsevier Science, Amsterdam, Netherlands.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. **Remote Sensing of Environment** 37(1): 35–46. DOI: 10.1016/0034-4257(91)90048-B.

Cullen-Unsworth, L.C. and R.K.F. Unsworth. 2016. Strategies to enhance the resilience of the world's seagrass meadows. **Journal of Applied Ecology** 53(4): 967–972. DOI: 10.1111/1365-2664.12637.

Downie, A.L., M. von Numers and C. Boström. 2013. Influence of model selection on the predicted distribution of the seagrass *Zostera marina*. **Estuarine, Coastal and Shelf Science** 121–122: 8–19. DOI: 10.1016/j.ecss.2012.12.020.

Duarte, C.M., H. Kennedy, N. Marbà and I. Hendriks. 2013. Assessing the capacity of seagrass meadows for carbon burial: Current limitations and future strategies. **Ocean and Coastal Management** 83: 32–38. DOI: 10.1016/j.ocecoaman.2011.09.001.

Environmental Systems Research Institute. 2023. How inverse distance weighted interpolation works. https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/how-inverse-distance-weighted-interpolation-works.htm. Cited 4 Sep 2023.

Gera, A., J.F. Pagès, R. Arthur, S. Farina, G. Roca, J. Romero and T. Alcoverro. 2014. The effect of a centenary storm on the long-lived seagrass *Posidonia oceanica*. **Limnology and Oceanography** 59(6): 1910–1918. DOI: 10.4319/lo.2014.59.6.1910.

Hughes, R.G., M. Potouroglou, Z. Ziauddin and J.C. Nicholls. 2018. Seagrass wasting disease: Nitrate enrichment and exposure to a herbicide (Diuron) increases susceptibility of Zostera marina to infection. **Marine Pollution Bulletin** 134: 94–98. DOI: 10.1016/j.marpolbul.2017.08.032.

Ibrahim, A. and R.A. Surya. 2019. The implementation of Simple Additive Weighting (SAW) method in decision support system for the best school selection in Jambi. **Journal of Physics: Conference Series** 1338(1): 012054. DOI: 10.1088/1742-6596/1338/1/012054.

Kanmarangkool, S., N. Whanpetch, T. Pokavanich and S. Meksumpun. 2022. Annual productivity of seagrass at Khung Kraben Lagoon, Chanthaburi Province, Thailand. **Journal of Fisheries and Environment** 46(3): 221–230.

Kuhn, M. and K. Johnson. 2013. **Applied predictive modeling.** Springer, New York, USA. 600 pp.

Lanuru, M., S. Mashoreng and K. Amri. 2018. Using site-selection model to identify suitable sites for seagrass transplantation in the west coast of South Sulawesi. **Journal of Physics: Conference Series** 979(1): 012007. DOI: 10.1088/1742-6596/979/1/012007.

Leliaert, F. and E. Coppejans. 2003. The marine species of Cladophora (Chlorophyta) from the South African East Coast. **Nova Hedwigia** 76: 45–82.

Malczewski, J. 1999. **GIS and Multicriteria Decision Analysis.** John Wiley and Sons, New York, USA. 392 pp.

Maleika, W. 2020. Inverse distance weighting method optimization in the process of digital terrain model creation based on data collected from a multibeam echosounder. **Applied Geomatics** 12(4): 397–407. DOI: 10.1007/s12518-020-00307-6.

Marine and Coastal Resources Research and Development Institute. 2022. **Integrated Seagrass Restoration Action Report Year 2022.** Department of Marine and Coastal Resources, Bangkok, Thailand. 93 pp.

Matheson, F.E., J. Reed, V.M. Dos Santos, G. Mackay and V.J. Cummings. 2016. Seagrass rehabilitation: successful transplants and evaluation of methods at different spatial scales. **New Zealand Journal of Marine and Freshwater Research** 51(1): 96–109. DOI: 10.1080/00288330.2016.1265993.

McGlathery, K.J., L.K. Reynolds, L.W. Cole, R.J. Orth, S.R. Marion and A. Schwarzschild. 2012. Recovery trajectories during state change from bare sediment to eelgrass dominance. **Marine Ecology Progress Series** 448: 209–221.

McKenzie, L.J., L.M. Nordlund, B.L. Jones, L.C. Cullen-Unsworth, C. Roelfsema and R.K.F. Unsworth. 2020. The global distribution of seagrass meadows. **Environmental Research Letters** 15(7): 074041. DOI: 10.1088/1748-9326/ab7d06.

Monthum, Y., A. Khantavong, N. Hempattarasuwan, C. Roengthong, P. Tongkok, J. Chusrisom and C. Kaewsuralikhit. 2023. The Effect of Shore Height on the Distribution of Upper Intertidal Seagrass in the Andaman Sea, Thailand. **Journal of Fisheries and Environment** 47(2): 73–84.

Muhamad, M.A.H., R. Che Hasan, N. Md Said and J.L.S. Ooi. 2021. Seagrass habitat suitability model for Redang Marine Park using multibeam echosounder data: Testing different spatial resolutions and analysis window sizes. **PLoS ONE** 16(9): e0257761. DOI: 10.1371/journal.pone.0257761.

Panjaitan, M.I. 2020. Simple Additive Weighting (SAW) method in determining beneficiaries of foundation benefits. **Jurnal Teknologi Komputer** 13(1): 19–25.

Paulo, D., A. Cunha, J. Boavida, E. Serrao, E. Gonçalves and M. Fonseca. 2019. Open coast seagrass restoration. Can we do it? Large scale seagrass transplants. **Frontiers in Marine Science** 6(52): 1–15. DOI: 10.3389/fmars.2019.00052.

Praisankul, S. and O. Nabangchang-Srisawalak. 2017. The economic value of seagrass ecosystem in Trang Province, Thailand. **Journal of Fisheries and Environment** 40(3): 138–155.

Quiros, T.E.A.L., D. Croll, B. Tershy, M.D. Fortes and P. Raimondi. 2017. Land use is a better predictor of tropical seagrass condition than marine protection. **Biological Conservation** 209: 454–463. DOI: 10.1016/j.biocon.2017.03.011.

R Core Team. 2020. **R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.** https://www.r-project.org/ Cited 2 May 2022.

Short, F.T., R.G. Coles and C. Pergent-Martini. 2001. **Global seagrass distribution.** In : Global Seagrass Research Methods (eds. F.T. Short and R.G. Coles), pp. 5–30. Elsevier Science, Amsterdam, Netherlands.

Short, F., R. Davis, B. Kopp, C.A. Short and D. Burdick. 2002. Site-selection model for optimal restoration of eelgrass Zostera marina in the Northeastern US. **Marine Ecology-progress Series** 227: 253–267. DOI: 10.3354/meps227253.

Stankovic, M., R. Kaewsrikhaw, E. Rattanachot and A. Prathep. 2019. Modeling of suitable habitat for small-scale seagrass restoration in tropical ecosystems. **Estuarine, Coastal and Shelf Science** 231: 106465. DOI: 10.1016/j.ecss.2019.106465.

Szantoi, Z., F.J. Escobedo, A. Abd-Elrahman, L. Pearlstine, B. Dewitt and S. Smith. 2015. Classifying spatially heterogeneous wetland communities using machine learning algorithms and spectral and textural features. **Environmental Monitoring and Assessment** 187(5): 262. DOI: 10.1007/s10661-015-4426-5.

Vafaei, N., R.A. Ribeiro and L.M. Camarinha-Matos. 2022. Assessing normalization techniques for Simple Additive Weighting method. **Procedia Computer Science** 199: 1229–1236. DOI: 10.1016/j.procs.2022.01.156.

van Katwijk, M.M., A.R. Bos, V.N. de Jonge, L.S.A.M. Hanssen, D.C.R. Hermus and D.J. de Jong. 2009. Guidelines for seagrass restoration: Importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. **Marine Pollution Bulletin** 58(2): 179–188. DOI: 10.1016/j.marpolbul.2008.09.028.

Vichkovitten, T., A. Intarachart, K. Khaodon and S. Rermdumri. 2016. Transplantation of tropical seagrass *Enhalus acoroides* (L.) in Thai coastal water: Implication for habitat restoratio. **GMSARN International Journal** 10: 113–120.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. **Soil Science** 37(1): 29–38. DOI: 10.1097/00010694-193401000-00003.

Waycott, M., C. Duarte, T.J.B. Carruthers, *et al*. 2009. **Accelerating loss of seagrasses across the globe threatens coastal ecosystems.** Proceedings of the National Academy of Sciences of the United States of America 2009: 12377–11238. DOI: 10.1073/pnas.0905620106.