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ORIGINAL ARTICLE

Coastal Melaleuca wetlands under future climate and sea-level rise scenarios in the Mekong Delta, Vietnam: vulnerability and conservation

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Abstract
Melaleuca wetland ecosystems play crucial roles in ecology and human livelihood, yet the ecosystems are vulnerable to climate change and relative sea-level rise (SLR) impacts. Documents and research on climate change and SLR impacts on coastal Melaleuca wetlands in the Mekong Delta, Vietnam, are currently limited. Therefore, the present study aimed to identify changes in habitat suitability for a coastal Melaleuca wetland species in response to different future climate change and SLR scenarios, in the West Sea of the Mekong Delta, with the aid of an ensemble species distribution model (SDM) and the Sea Level Affecting Marshes Model (SLAMM). Melaleuca species occurrence records, bioclimatic and eco-physiological variables were utilized to predict potential distribution of the species in response to current and future climate scenarios (i.e. RCP4.5 and 8.5) for the year 2070. Wetland maps for 2020, a digital elevation model (DEM) and localized site-specific parameters (i.e. historic trend of SLR, erosion, subsidence and overwash) were utilized as input data for SLAMM to simulate spatial distribution of Melaleuca/forested wetlands under the two SLR scenarios. The final habitat suitability for the Melaleuca wetland species was identified based on these two resultant datasets, climatic suitability and spatial distribution of the wetlands. Simulated results suggested mean losses in suitable habitat of 29.8% and 58.7% for stable and subsidence scenarios, respectively, for the year 2070 in comparison to the baseline scenario. SLR combined with considerable subsidence rate was suggested as one of the main drivers responsible for the habitat suitability loss. The findings obtained from the current work are useful sources for planning conservation areas for the Melaleuca wetlands, to protect and preserve the ecosystems and their important services under future climate and SLR scenarios.

Keywords Melaleuca wetlands · Sea-level rise · Climate change · SLAMM · Mekong Delta · Vietnam

Introduction

Melaleuca wetlands occur mostly in coastal regions in tropical or sub-tropical regions and mainly distributed in Australia, and in South-East Asia, the Southern United States and the Caribbean (Tran et al. 2013). Melaleuca wetlands occur in several geomorphic settings, which connect to coastal waters to various degrees (Adame et al. 2020). Some Melaleuca wetlands located in low-lying coastal are categorized as tidal freshwater forested wetlands since they mostly grow in freshwater environments (Krauss et al. 2018); however, these wetlands can be periodically flooded by tides, leading to moderate salinity of their soils (Mensforth & Walker 1996; Boland et al. 2006).

Melaleuca wetlands provide various significant services to ecosystems and humankind. These ecosystem services include provisioning of habitats for wide variety of flora and

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fauna; protection of peat, soil and water resources; prevention of soil acidification and enhancement of water quality (Cuong & Dart 2011; Tran et al. 2013; Adame et al. 2019a) and climate change mitigation by its capacity in storage of large carbon stock (Bernal & Mitsch 2012; Mitsch et al. 2013; Tran et al. 2015; Lovelock & Duarte 2019; Adame et al. 2020). Melaleuca wetlands also support local livelihood with their forest products, such as vegetable, wood fuel, timber, tea-tree oil, honey, fish and medicine (VNEPA 2005; Tran et al. 2013; Dinh 2016). The wetlands are additionally valuable for ecotourism development, educational, cultural and heritage purposes (VNEPA 2005; Tran et al. 2013).

Despite these important ecosystems services, Melaleuca wetlands in the Mekong Delta, Vietnam, are under considerable risk due to climate change and sea-level rise (SLR) in addition to threats caused by local anthropogenic activities. These activities, such as the development of rice production, aquaculture practices and clearance of the Melaleuca forests for fuels and wood products, are significant causes of the Melaleuca wetland loss (Dang et al. 2021c). Importantly, climate change brings extreme seasonal variation in temperature and prolonged drought, which threaten Melaleuca wetlands due to forest fire issues (Thanh et al. 2020; Dang et al. 2021b; Van et al. 2021). These changes in climate combined with prolonged floods due to extreme rainfall from climate change also affect survival and growth of Melaleuca forests (Tran et al. 2013; Tran 2016). Moreover, SLR accelerates inundation and saltwater intrusion problems in coastal and lowland regions, and so creates further severe threats to Melaleuca wetlands (Tran et al. 2013; Thanh et al. 2020). Therefore, determining habitat suitability for the wetlands and planning conservation areas based on future climate and SLR conditions is a critical prerequisite for species conservation and the Melaleuca wetlands in the region.

Recently, there has been an increase in the use of species distribution models (SDMs) for studies on ecology and planning conservation areas (Peterson et al. 2011; Guisan et al. 2013). SDM approaches can identify high suitability habitats for species (Hammond et al. 2016; Gottwald et al. 2017) and so support the prioritization of these areas for conservation (Kremen et al. 2008). Previous studies have demonstrated that SDMs are effective tools for projecting habitat suitability for native species, including wetland plant species under future climate scenarios (Akumu et al. 2009; Kariyawasam et al. 2019; Shabani et al. 2020; Chhogyel et al. 2021; Dang et al. 2021a).

Sea Level Affecting Marshes Model (SLAMM) was developed to simulate shoreline changes and coastal wetland conversion to evaluate the susceptibility of wetland habitats to long-term SLR (Craft et al. 2009; Mcleod et al. 2010) and thus support decision-making for wetland conservation across a wide range of scales (i.e. local to regional scales) (Prado et al. 2019). SLAMM uses high-resolution spatial data to simulate wetland changes in response to SLR at landscape scales and so is capable of predicting wetland dynamics in response to SLR with higher accuracy in comparison to other methods (Craft et al. 2009; Clough et al. 2010; Wu et al. 2015). The model has been successfully applied in the USA (Mcleod et al. 2010) and some other regions around the world (Akumu et al. 2011; Li et al. 2015; Wu et al. 2015; Payo et al. 2016; Fernandez-Nunez et al. 2019; Prado et al. 2019; Raw et al. 2020; Wikramanayake et al. 2020; Dang et al. 2022). Amongst these previous studies, Dang et al. (2022) demonstrated that SLAMM is capable of simulating changes of mangrove wetlands in response to SLR in the Mekong Delta by using elevation data with high-vertical accuracy and precise localized parameters.

Although Melaleuca wetlands play critical ecological roles and support local communities, and are threatened by climate changes and SLR, studies on the likely effects of climate change and SLR on these important wetlands are scarce. Dang et al. (2021a) used a SDM approach (i.e. ensemble modelling) to develop maps of climatic suitability for Melaleuca wetland species under current and future climate scenarios representative concentration pathways 4.5 and 8.5 (RCP4.5 and RCP8.5) for 2070. However, Dang et al. (2021a) focused on Melaleuca species in both inland and coastal zones, and the impacts of SLR on the wetland species were simply assessed by identifying the SLR-induced inundation, but did not consider other critical processes involved in wetland changes in response to SLR, such as surface elevation changes due to subsidence, erosion, accretion and overwash. The present study aims to address the knowledge gap and provide information to support conservation and management of these important wetlands in the context of a changing climate and rising sea levels by combining SDMs and SLAMM approaches. The present study aims to (1) simulate spatial distribution of Melaleuca/forested wetlands in response to two SLR scenarios, RCP4.5 and RCP8.5, for the year 2070 using SLAMM approaches; (2) analyze changes in habitat suitability of Melaleuca wetland species under the two climate and SLR scenarios compared to present and (3) identify priority conservation areas for Melaleuca wetland species under the two climate and SLR scenarios based on the combined outputs from the two previous aims.

Materials and methods

Study area

Our study focused on Melaleuca wetlands in U Minh region, which are coastal areas in the West Sea of the Mekong Delta, Vietnam. The area is located within 20 km of the coastline, including parts of Ca Mau and Kien Giang provinces (Fig. 1). The study area has a humid tropical monsoon climate with an annual average rainfall of 2200–2400 mm (Van Cuong et al. 2019). The region experiences two different seasons: the rainy season from May to November and the dry season from December to April.

U Minh Melaleuca wetlands, one of the most critical wetland regions in the Mekong Delta, are mostly on peatlands and mainly dominated by *Melaleuca cajuputi* (*M. cajuputi*) species (Buckton et al. 1999; Nakabayashi et al. 2001; Dinh 2016). *Melaleuca cajuputi* is the dominant tree species found in swamp forests in the Mekong Delta in which *M. cajuputi* ssp. *cumingiana* is the dominant sub-species and indigenous to the region (Craven & Barlow 1997). The *M. cajuputi* forms natural, semi-natural and plantation Melaleuca forests in the U Minh wetlands (Buckton et al. 1999; Dinh 2016). Melaleuca wetlands do contain a few other tree species (i.e. *Ilex cymosa*, *Alstonia spathulata*, *Trema orientalis* and *Combretum acuminatum*) found in very small numbers and seasonally inundated grasslands form a ground layer of the wetlands (Buckton et al. 1999). *Melaleuca cajuputi* can, therefore, be considered the dominant, keystone species for this wetland type so the species distribution modelling focused on habitat suitability for this species under various climate and SLR scenarios.

Regarding structure of the Melaleuca forest wetlands, for U Minh Ha National Park, area of natural and plantation Melaleuca forests account for 1844.5 ha and 5668.9 ha, respectively (Khanh & Subasinghe 2017). Meanwhile, the figures for U Minh Thuong are 4705.2 ha and 1779.3 ha for natural/semi-natural and plantation Melaleuca forests, respectively (TTXVN [Vietnam News Agency] 2021). Melaleuca plantations in U Minh Ha wetlands range in age from 1 to 5 years (Van et al. 2018). The study area has a dense network of canals, which were installed to support not only agriculture and aquaculture practices, but also provide access to fire-fighting services for the forest areas due to fire danger of the forests (Dinh 2016).

The wetlands deliver a wide range of ecosystem services (i.e. storing fresh waters and controlling floods, enhancing soil and water quality and providing habitats for flora and fauna), which substantially support the balance of the deltaic environment (Nakabayashi et al. 2001; Tran et al. 2013). The wetlands also include critical natural reserves, such as U Minh Ha National Park, listed in the biosphere reserves of the world by UNESCO, and U Minh Thuong National Park, a Ramsar site (Khanh & Subasinghe 2017; Loc et al. 2018). The wetlands are extremely vulnerable to SLR effects because they are located in mostly flat and low-lying areas of the Mekong Delta (Nguyen & Woodroffe 2016) (Fig. 1). The wetlands are surrounded by extensive aquaculture and agriculture lands, so the present study only focussed on simulating changes to the Melaleuca wetlands, not other types of land cover.

Methodology

The approach utilized involved three key steps, which are presented in detail in the following sections:

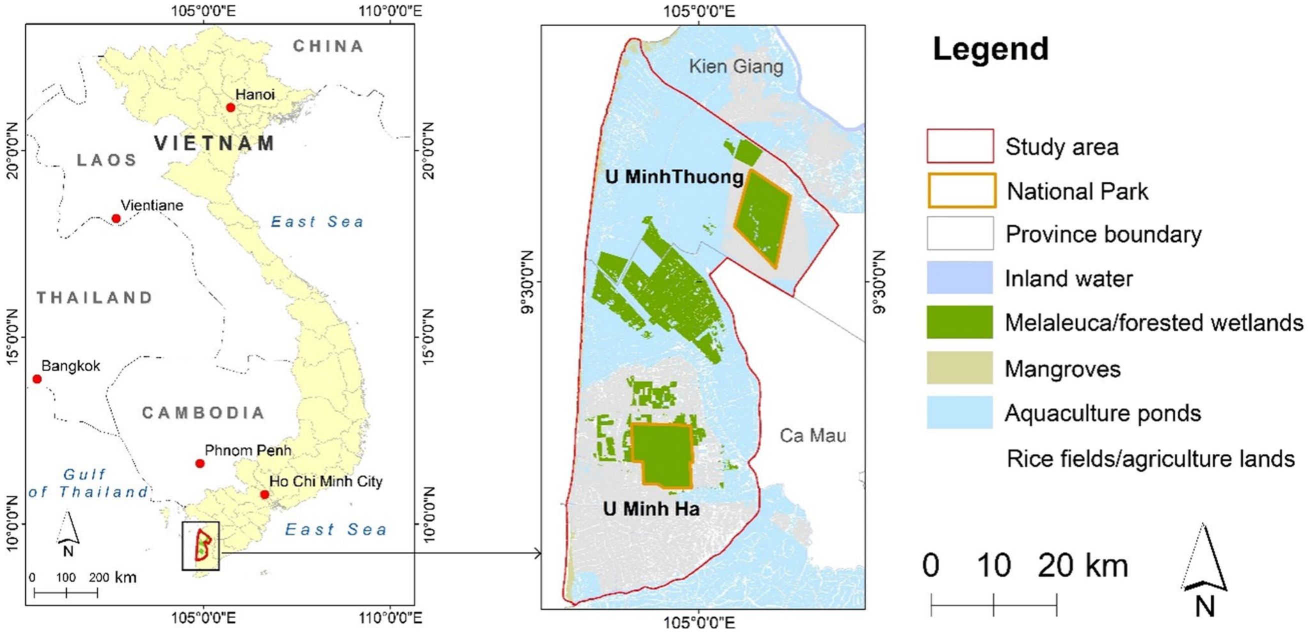

Fig. 1 Study area location with main wetland categories in the study area

(1). SDM approach (i.e. ensemble modelling) for predicting climatic suitability for *M. cajuputi*, the dominant species in Melaleuca wetlands, across the study area under current and various future climate change scenarios;
(2). SLAMM approach for simulating spatial distribution of Melaleuca/forested wetlands under different future SLR scenarios;
(3). Spatial analysis for identifying potential changes and conservation areas for Melaleuca wetlands under different future climate and SLR scenarios.

Species distribution model for projection of climate suitability of Melaleuca wetland species

SDM approach (i.e. ensemble modelling) was applied to predict climatic suitability of the key species in Mekong Delta Melaleuca wetlands, *Melaleuca cajuputi* (*M. cajuputi*) dominated by *M. cajuputi* ssp. *cumingiana*. Ensemble models were calibrated for *M. cajuputi* utilizing geo-referenced species occurrence records, eco-physiological and bioclimatic variables, which were performed at spatial resolution of 30 arc-seconds. A total of 573 occurrence data points for *M. cajuputi* was obtained from a variety of sources, including field surveys, online databases (i.e. Global Biodiversity Information Facility and Google Earth Pro), published/unpublished literature (i.e. previous studies, forest maps land-cover maps and other relevant data from government organizations) and expert consultations. Sampling bias in the occurrence data was minimized by applying spatial filtering techniques. After this task, 90 records for the species were used for further modelling exercise (Figure S1 in Supplementary document). Data on eco-physiological variables (i.e. elevation, soil types and soil acidity) were obtained from published and unpublished work (i.e. maps of soil types, soil acidity from FAO: www.fao.org/geonetwork and the Ministry of Agriculture and Rural Development (MARD), Vietnam respectively). Bioclimatic variables were acquired from the Worldclim database (available online: http://www.worldclim.org/) for current and future climatic conditions. Collinear variables were identified and excluded using the 'VIF' function in the USDM package (version 1.1–18) in R software, resulting in a set of seven non-collinear bioclimatic variables being selected for further analysis (Table S1). The mean of the three general circulation models (GCM), namely MRI CGCM3 (Meteorological Research Institute Coupled GCM Version 3), GFDL-CM3 (Geophysical Fluid Dynamics Laboratory Version 3) and CNRM CM5 (Centre National de Recherches Météorologiques Climate Model 5) was utilized for future climate scenarios, including RCPs 4.5 and 8.5 by the year 2070. The ensemble models used 75% and 25% of species occurrence data for model training and testing, respectively. The performance of ensemble models for *M. cajuputi* was assessed utilizing threshold-dependent true skill statistic (TSS) and threshold-independent receiver operating characteristics (ROC/AUC) measures. Both measures showed model performance was acceptable therefore validating the models for further use. In particular, the ensemble model predicted climatic suitability of *M. cajuputi* with overall accuracy scores of 0.992 and 0.916 according to ROC/AUC and TSS, respectively. The model generated sensitivity scores of 0.9556 and 0.9678, respectively. Thus, the model correctly projects the presence of *M. cajuputi* at a rate of 95.56% and its absence at a rate of 96.78%. The final projected climatic suitability maps for *M. cajuputi* categorized areas into four groups: high suitability (value > 0.6), moderate suitability (0.4–0.6), low suitability (0.2–0.4) and unsuitable (< 0.2). Climatic suitability maps of *M. cajuputi* species under current and future climate, i.e. RCP4.5 and RCP8.5 by the year 2070 are shown in Figure S2 (Supplementary document) (see Dang et al. (2021a) for full details of the modelling approach and results on predicting climatic suitability of *M. cajuputi*).

Sea Level Affecting Marshes Model (SLAMM) approach for projection of Melaleuca/forested wetland distribution under future SLR scenarios

The present study used SLAMM (version 6.2, available online: http://warrenpinnacle.com) for the simulation of climatic suitability for *M. cajuputi* under the future SLR scenarios, i.e. RCP4.5 and RCP8.5 by the year 2070. Essential inputs for the model performance included wetland maps in SLAMM categories, high-vertical resolution digital elevation model (DEM) and slope data. Specific site parameters, i.e. historic SLR rate, surface elevation change (subsidence or stable) scenarios, rates of vertical erosion/accretion and various SLR scenarios, were also important inputs. Conversions between wetland categories were considered using a complex and flexible decision tree in SLAMM by incorporating geometric and qualitative relationships (Clough et al. 2010). In SLAMM, each wetland category is allowed to convert to another type of wetland only once for each time step. The present study applied a time step of 5 years to simulate changes of wetlands in the study area. The simulated results on the potential spatial distribution of Melaleuca/forested wetlands under different future SLR scenarios by the year 2070 were afterward converted into raster data format and analyzed in ArcGIS.

Digital elevation model (DEM) and slope calculation

The current study used high-resolution DEM data with spatial resolution of 5 m and vertical resolution of less than 1 m, which was collected from the Ministry of Natural Resources and Environment (MONRE), Vietnam. The data was produced in 2008 using survey points and the topographical maps with the elevation points and contour lines, which were obtained from geodetic survey and photogrammetric data (Trần et al. 2016; Minderhoud et al. 2019). The DEM is considered as the best elevation data currently available for the region, and it was used for the projection of future SLR in Vietnam (Trần et al. 2016) and in other studies on SLR impacts in the Mekong Delta (Dang et al. 2020, 2021a, 2022).

Generally, the Melaleuca wetlands are located in higher elevation than other types of wetlands. Our analysis returned a mean elevation of 0.9 m (range of 0.5–4.3 m) for Melaleuca/forested wetlands, while the figures for mangroves, aquaculture ponds and agriculture lands were 0.6 m (range of – 0.4–4.2 m), 0.4 m (range of – 0.5–3.1 m) and 0.4 m (range of 0.1–3.4 m) respectively. Figure S3 in Supplementary document presents side-by-side maps of ground elevation and land-use/wetland distribution in the study area.

For further analysis in SLAMM, the DEM was clipped based on the study area boundary and was converted to 15 m of spatial resolution due to the limitation of computer capacity. Slope data in degrees was generated using spatial analysis tool in ArcGIS 10.4.1 (Figure S4). The DEM and slope data were afterward converted to ASCII Text format employing the data conversion tool in ArcGIS 10.4.1 for further modelling exercise in SLAMM.

Wetland map

The wetland map in the present study was acquired from Landsat 8 OLI images in 2020 from Dang et al. (2021c) and used as initial map for the prediction of climatic suitability under future SLR scenarios. The wetland map at 15-m spatial resolution was clipped with the DEM to have the identical extent and cell size. Afterward, the map was reclassified into corresponding SLAMM categories based on knowledge and ecological definitions identified in the SLAMM 6.2 technical document (Clough et al. 2012). This task was undertaken utilizing Reclassify function (spatial analysis tool) in ArcGIS 10.4.1. Three main wetland categories were analyzed in SLAMM: Melaleuca wetlands, mangroves and open inland water. It is noted that aquaculture ponds were considered as open inland water and agriculture lands surrounding the Melaleuca wetlands in the study area and were not considered in the analysis. The changes of these types of land-use are mostly driven by anthropogenic activities and are likely to limit the migration of the natural wetlands in reality, so these lands were excluded from the model to minimize unrealistic changes of the wetlands.

The wetland map was reclassified into corresponding SLAMM categories based on ecological definitions in the SLAMM 6.2 technical document (Clough et al. 2012), literature and experience. Melaleuca/forested wetlands were assigned as Nontidal Swamp (Code 3) in SLAMM. According to Clough et al. (2012), nontidal swamp includes Palustrine wetlands, and *Melaleuca* spp. wetlands in the tropical regions were considered as Palustrine forested wetlands (Adame et al. 2019b; Omar et al. 2020). Akumu et al. (2011) also classified Melaleuca wetlands as nontidal swamp in SLAMM in their study. In addition, the SLAMM codes for mangroves and open inland water were 9 (mangroves) and 15 (open inland water), respectively (Table S2). Subsequently, the wetland map in SLAMM categories was transformed to ASCII Text format for further modelling practice in SLAMM.

Relative sea-level rise scenarios and surface elevation change

Relative SLR, including considerations of the balance of Eustatic SLR, subsidence and accretion, was applied in the present study. The two different SLR scenarios by 2070 were adopted to assess the impacts of SLR on the Melaleuca wetlands. These SLR scenarios included RCP4.5 and RCP8.5 with SLR of 34 cm and 42 cm respectively by the year 2070 (or SLR of 55 cm and 75 cm respectively by the year 2100) (Trần et al. 2016).

In regard to surface elevation change, Minderhoud et al. (2018) suggested that subsidence rates for marshlands and wetland forests in the Mekong Delta were 6–7 mm/year for the period of 1988–2009. Hence, the present study used the mean net subsidence of – 6.5 mm/year, hereafter referred to as the subsidence scenario, in the study area for simulations of SLAMM, and assumed that the rate remained unchanged until 2070. We also used net surface elevation change of 0 mm/year, hereafter referred to as the stable scenario, to assess the sensitivity of the simulated results in response to uncertainties on surface elevation change.

Specific site parameters

Lovelock et al. (2015) estimated that SLR was 5.74 mm/year and 5 mm/year for the periods 1979/2001 and 2100/2014, respectively for the Mekong Delta. Hence, the present study used the average rate of 5.37 mm/year as the historic trend of SLR in the study area. The Great Diurnal Tide Range of 0.2 m in the West Sea of the Mekong Delta was adopted according to observation data from Hak et al. (2016). Swamp erosion rate and marsh erosion rate were set to 1.0 horz.m/year and 2.0 horz.m/year, respectively according to Clough et al. (2012), whereas tidal flat erosion rate of 1.66 horz.m/year was used for the study area based on (Liu et al. 2015). A 25-year period of overwash according to model definition was utilized since the value is in agreement with storm frequency in the Mekong Delta (Danh 2015). The average accretion rate of 4 mm/year for saltmarshes/mangroves in the region was used based on Krauss et al. (2014) and Saintilan et al. (2020). Due to shortage of site-specific data on swamp accretion, which was represented for the accretion of Melaleuca wetlands, the general global value of swamp accretion of 0.3 mm/year was used (Brenner et al. 2016).

Spatial analysis for identifying of potential changes of Melaleuca wetlands and conservation areas

The final distributions of habitat suitability for Melaleuca wetlands under current and various future climate and SLR scenarios were identified by the combination of climatic suitability distributions for *M. cajuputi* obtained from the SDM and the spatial distribution of Melaleuca/forested wetlands obtained from SLAMM. Climatic suitability maps of *M. cajuputi* for current and future scenarios, RCP4.5 and 8.5 for 2070 were categorized into 4 suitability classes (i.e. high, moderate, low suitability and unsuitable). Final habitat suitability areas were defined as the overlap areas of climatic suitability classes (i.e. high, moderate and low suitability) and Melaleuca/forested wetlands. In particular, for the current climate, the climatic suitability for *M. cajuputi* map was overlaid on the Melaleuca/forested wetland map in the current climate (2020). The areas of each of the three climatic suitability classes inside the wetlands were quantified. The same approach was undertaken for future scenarios as well. Therefore, the changes in habitat suitability areas of Melaleuca wetlands under future climate and SLR scenarios in relation to the current scenario were evaluated. The high-priority areas for conservation of the Melaleuca wetlands under future climate and SLR scenarios were considered as high climate suitability areas, which overlapped with the Melaleuca/forested wetlands in the same scenarios. These tasks were undertaken with the aid of analysis tools in ArcGIS version 10.4.1.

Results

Projections of Melaleuca/forested wetlands under future SLR scenarios

Simulated spatial distribution maps and predicted coverage area of Melaleuca/forested wetlands under various relative SLR scenarios by the year 2070, obtained from the SLAMM, are presented in Figs. 2 and 3. In general, our findings reveal that SLR is projected to considerably affect the potential distribution of the Melaleuca/forested wetlands. There were consistent reductions in the area of the wetlands under the two scenarios of SLR, with the reduction being greater under

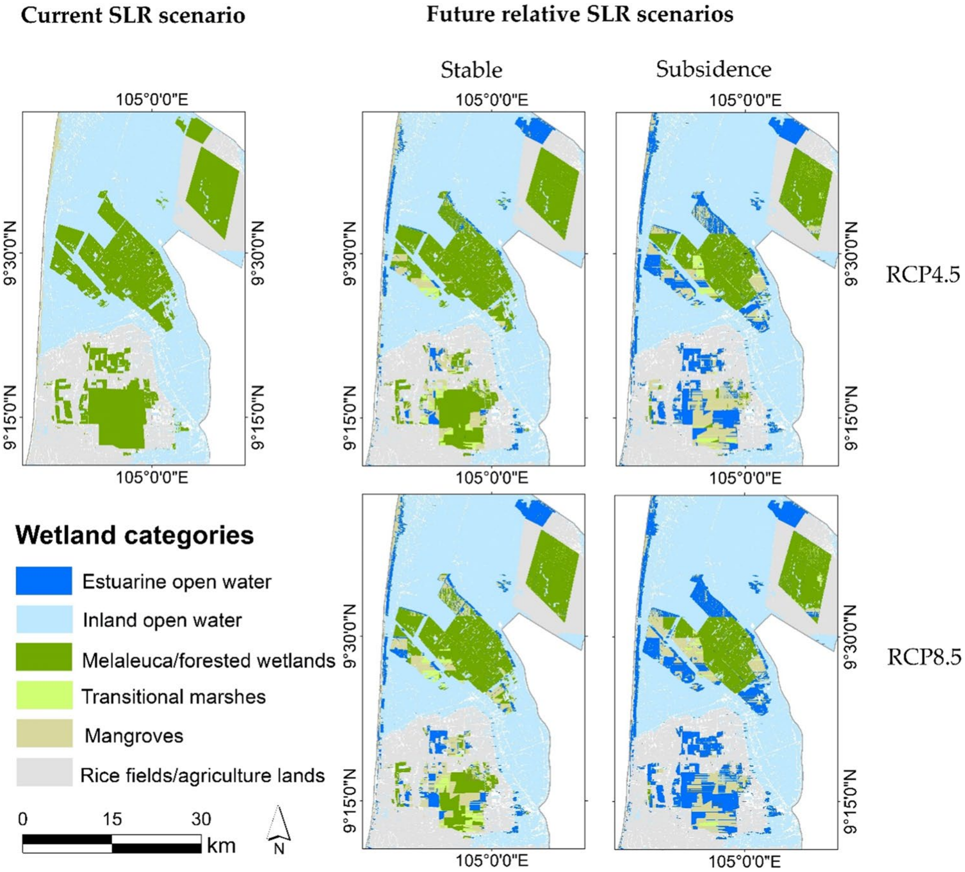

Fig. 2 Wetland maps in the study area under current time (2020) and different future relative SLR scenarios by the year 2070 obtained from the SLAMM

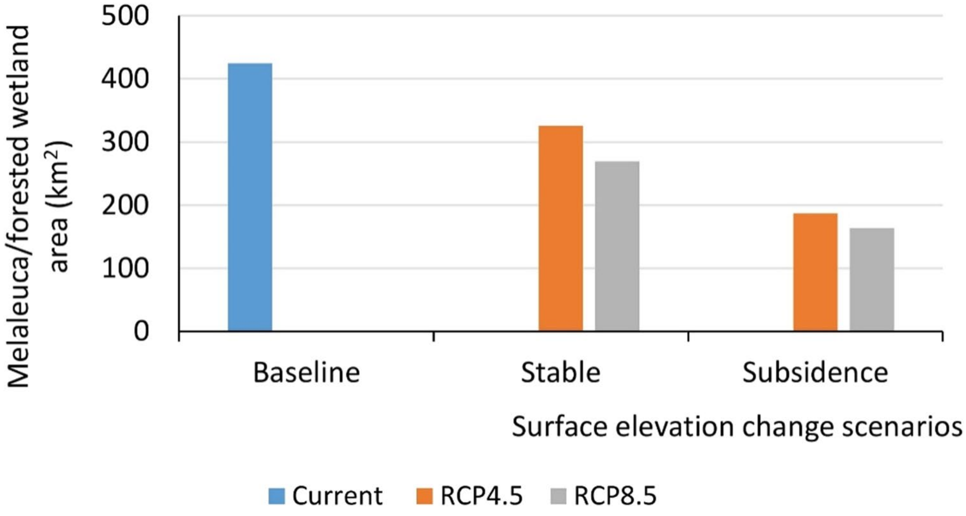

Fig. 3 Melaleuca/forested wetland area under current and different relative SLR scenarios by the year 2070

the RCP8.5, and the subsidence scenario, in comparison to the baseline scenario. In particular, under current scenarios, Melaleuca/forested wetland area occupied 424.2 km^2. For the stable scenario of surface elevation change, Melaleuca/forested wetland area was predicted to vary from 375.7 to 269.5 km^2 for the RCP4.5 and RCP8.5 scenarios, respectively. While for the subsidence scenario, the area decreased to 186.9–163.7 km^2 for the corresponding SLR scenarios. The wetlands in U Minh Thuong National Park remained relatively stable under SLR impacts; in contrast, the wetlands in U Minh Ha National Park were noticeably affected by SLR. A substantial area of the wetlands in the U Minh Ha Park was transferred into either transitional marshes and mangroves under the stable scenario of surface elevation change or estuarine open water under the subsidence scenario (Fig. 2).

Transitional marshes in the Mekong Delta include brackish grasslands, which are affected by brackish water and are inundated on a daily basis due to tides (Buckton et al. 1999). There were no transitional marshes in wetland classification for the year 2020 since these marshes occur with small areas in the study area and so consisted of mixed pixels and were not classified using Landsat imagery by Dang et al. (2021c). However, this wetland category increased under future SLR scenarios according to the SLAMM output due to the fact that SLR lower elevation of more lands in the study area for inundation.

Habitat suitability of Melaleuca wetlands under current and future climate and SLR scenarios

Habitat suitability for *M. cajuputi* was categorized into 4 classes including high, moderate, low suitability and unsuitable. Habitat suitability maps for the species under current and each climate and SLR scenarios are presented in Figs. 4 and 5. According to the baseline climate and sea-level scenarios, the simulated results shows that 424.2 km^2 is suitable for *M. cajuputi*, with 381.3 km^2 of this area being classed as high suitability and 42.8 km^2 being classed as moderate suitability. For the stable scenario, the area of high suitability for *M. cajuputi* decreased to 287.5 km^2 and 230.5 km^2 under the RCP4.5 and RCP8.5 scenarios, respectively, for the year 2070, whereas the area of unsuitable habitat increased to 98.5 km^2 and 154.7 km^2 for the corresponding climate and SLR scenarios. Under subsidence scenarios, the area of high suitability dropped to 172.3 km^2 and 174.9 km^2, and the area of unsuitable habitat increased up to 237.3 km^2 and 260.4 km^2 for the corresponding climate and SLR scenarios.

Changes of habitat suitability of Melaleuca wetland species under future climate and SLR scenarios

Changes in habitat suitability for *M. cajuputi* obtained from the combination approach of SDM and SLAMM are shown in Fig. 4 and Table 1. Generally, our findings show that there is consistent loss of *M. cajuputi* habitat under future climate and SLR scenarios compared to baseline scenario (2020). Unsurprisingly, the subsidence scenarios resulted in more serious loss compared to stable scenarios. Critically, most of the loss is projected to take place in the U Minh Ha biosphere reserves. By the year 2070, a significant proportion of Melaleuca habitat is projected to convert into transition marshes, mangroves and estuarine open water due to saltwater intrusion from SLR. In particular, for the stable scenario, losses of suitable habitat for *M. cajuputi* were 98.5 km^2 (23.2%) and 154.7 km^2 (36.5%) under RCP4.5 and RCP8.5, respectively by the year 2070. The figures for the subsidence scenario were 237.3 km^2 (559.9%) and 260.4 km^2 (61.4%) for the corresponding climate and SLR scenarios.

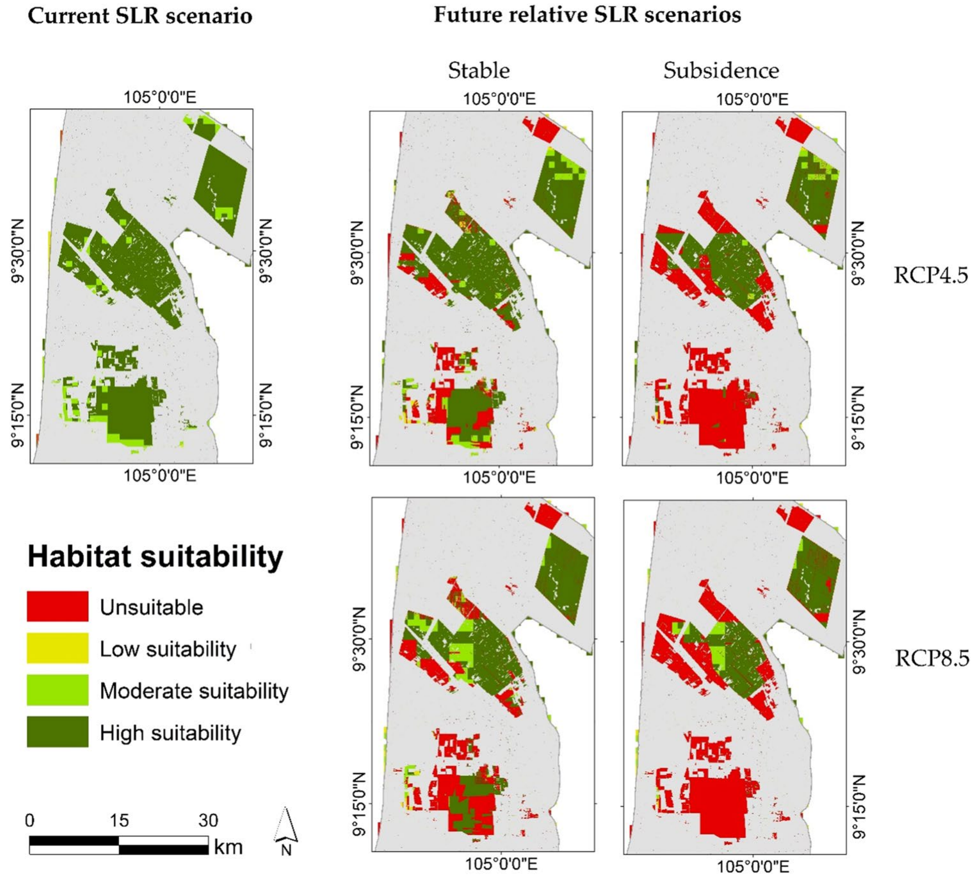

Fig. 4 Habitat suitability maps for *M. cajuputi* under current and future climate and SLR scenarios, i.e. RCP4.5 and RCP8.5 by the year 2070 obtained from the combination approach of SDM and SLAMM

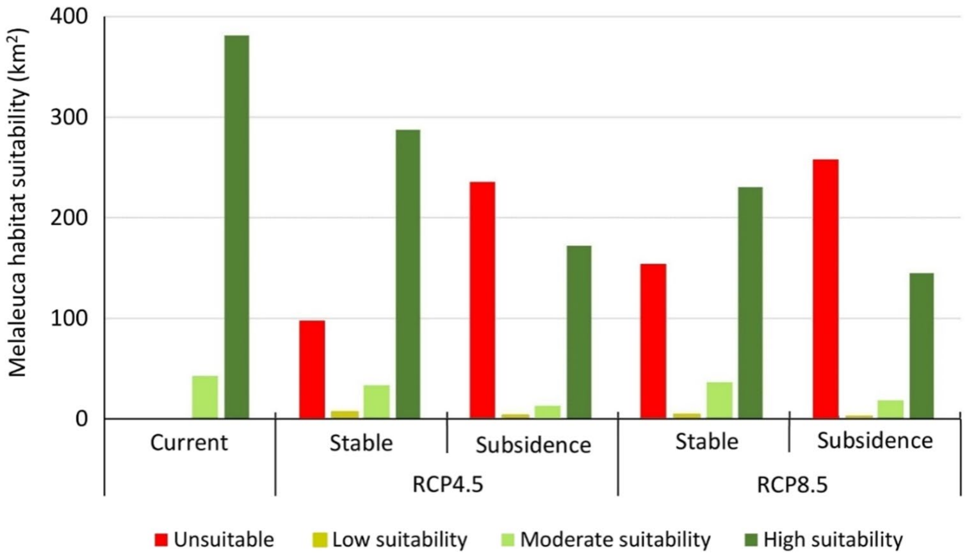

Fig. 5 Habitat suitability for *M. cajuputi* under current and future climate and SLR scenarios, i.e. RCP45 and RCP8.5 by the year 2070

Conservation areas of Melaleuca wetlands under future climate change and SLR scenarios

Spatial distribution and projected areas of conservation areas for Melaleuca wetlands under baseline and future climate and SLR scenarios are illustrated in Fig. 4 and Table 2. Priority conservation areas were identified as high suitability zones in Fig. 4. There was consistent reduction in conservation areas under the four future climate and SLR scenarios. In particular, under current climate and SLR scenarios, suitable habitats for conservation occupied 381.3 km^2 (90% of the Melaleuca/forested wetlands). For the stable scenario,

Table 1 Loss of habitat suitability for Melaleuca wetland species under different climate and SLR scenarios, i.e. RCP4.5 and RCP8.5, by the year 2070 in comparison to baseline scenario of 2020

SLR and climate scenarios	Loss (-) of habitat suitability areas (%)	
	Stable	Subsidence
RCP4.5	−23.22	−55.93
RCP8.5	−36.47	−61.4

Table 2 Conservation areas of Melaleuca wetland species under current scenario of 2020 and different climate and SLR scenarios, i.e. RCP4.5 and RCP8.5, by the year 2070

SLR and climate scenarios	Conservation areas (km^2)	
	Stable	Subsidence
Current	381.26	-
RCP4.5	287.46	172.33
RCP8.5	230.48	144.95

the figure dropped to 287.5 km^2 (67.8%) and 30.5 km^2 (54.33%) for the RCP4.5 and RCP8.5, respectively by the year 2070, whereas, for the subsidence scenarios, the figure significantly decreased to 172.3 km^2 (40.6%) and 144.9 km^2 (34.2%) for the corresponding climate and SLR scenarios. Importantly, our findings reveal that conservation areas of the Melaleuca wetlands experienced considerable loss under RCP8.5 and subsidence scenarios. Critically, substantial area of conservation reserve in the U Minh Ha National Park was lost because of SLR and subsidence processes, while some parts of the Ramsar site, U Minh Thuong National Park also became unsuitable for the Melaleuca wetlands (Fig. 4).

Discussion

Model accuracies and uncertainties

The present study predicted habitat suitability of Melaleuca wetland species based on both climatic suitability maps obtained from SDM (i.e. ensemble modelling) and projected Melaleuca/forested wetlands acquired from SLAMM. The accuracy of the two approaches influences reliability of the final projected results on habitat suitability for the wetland species. The validations of the two approaches found that they projected with acceptable accuracies.

In the case of the SDM, climatic suitability maps of Melaleuca wetland species under current and future climate, i.e. RCP4.5 and RCP8.5, by the year 2070 were shown to be of acceptable accuracy since the ensemble modelling approach showed good projective performance with high accuracy scores of 0.992 and 0.916 according to ROC/AUC and TSS, respectively. Additionally, the model correctly predicts the presence and absence of Melaleuca wetland species with a high accuracy of 95.56% and 96.78%, respectively. On further validation, the predicted climatic suitability for the wetland species under baseline climate scenario was in good agreement with the current distribution of Melaleuca/forested wetlands as identified through observation data (Dang et al. 2021c). Of the current Melaleuca/forested wetlands, 100% fall within areas modelled as suitable, with 90% and 10% of those areas simulated as being of high and moderate suitability, respectively. This agreement shows that most of simulated Melaleuca/forested wetland areas is categorized as high suitability classes and hence supports the reliability of model outcome. The predicted climatic suitability for Melaleuca wetland species is therefore considered sufficiently accurate as it corresponds to the currently observed Melaleuca/forested wetlands.

It is difficult to evaluate the accuracy of the SLAMM using observation data. This is because the wetlands have been impacted by the combined effects of local anthropogenic activities and global climate change, in addition to SLR. It is also noteworthy that there are other factors, which are likely to affect the wetland distribution, that were not included in SLAMM approach. These factors include alterations in hydrological regimes, erosion rates, sediment supply, storms due to climate changes, SLR and dam construction along the Mekong River under future scenarios. The absence of these factors is likely to underestimate the effects of future climate change on the Melaleuca wetlands. Moreover, future climate change will increase temperatures, atmospheric CO_2 concentrations and alter rainfall regimes, which are likely to change plant productivity and/or decomposition dynamics. These changes in turn could have implications for surface elevation sea-level responses, which were not considered in SDM and SLAMM approaches, due to data paucity and limitations of the current approaches. Furthermore, the present study only focuses on climate change and SLR effects on the Melaleuca wetlands without considering the influences of regional anthropogenic activities, such as agriculture and aquaculture practices and clearance of the Melaleuca forests for wood products and fuels. The exclusion of these factors leads to the underestimation of the vulnerability of the wetlands under future scenarios. Hence, the evaluation of potential threats to the Melaleuca wetlands in the region would be more accurate with the consideration of these absent factors in future studies.

Nevertheless, SLAMM has been shown to be effective in simulating wetland changes in other studies of tropical coastal regions (Li et al. 2015; Payo et al. 2016; Wikramanayake et al. 2020; Dang et al. 2022). Wu et al. (2015) suggested that SLAMM could be an effective approach to simulate coastal wetland changes with the use of accurate data and meaningful evaluation of the simulation outcome. Critically, Dang et al. (2022) found that SLAMM simulated wetland changes (i.e. mangroves) in the Mekong Delta with reasonable accuracy by using elevation data with high-vertical resolution of better than 1 m and accurate site-specific parameters. The current study used similar high-vertical resolution data and accurate site-specific parameters, which were observed in the study area. This demonstrates the potential of the SLAMM approach for simulating changes to the extent and distribution of the wetlands in the study area with acceptable accuracy.

Although SLAMM approach currently has these inevitable limitations, the approach has been shown as an innovative method for projecting changes in wetland distribution in the region in response to SLR impacts, which has not been considered in previous studies. This model is also the currently available landscape model, which considers key processes involved in SLR impacts on wetland ecosystems, viz., ground elevation changes, accretion, inundation, erosion and overwash (Craft et al. 2009; Clough et al. 2012; Wu et al. 2015). Critically, the model demonstrates its potential in simulating wetland changes with better accuracy than other methods (i.e. the Random Constraint Match model (RCM) and the Growing Cluster Model (GrC) with the chance to specify localized parameters according to Wu et al. (2015). Although as highlighted previously, it was difficult to validate the outcomes from the SLAMM approach in the present study, the approach used to project Melaleuca wetlands responses to climate change and relative SLR in this study is meaningful, and so contributes to the improvement of future studies on SLR impacts on wetlands, in particular, Melaleuca/forested wetland ecosystems. The insight achieved on the long-term potential effects of SLR on the wetland ecosystems in the region is useful for the development of appropriate adaption and mitigation strategies for Melaleuca wetland conservation under SLR impacts. However, the limitation on meaningful evaluation of the model outcome therefore calls for further studies, which needs to be done to better evaluate the performance of the model.

The impacts of climate change and SLR on Melaleuca wetlands

Assessing the potential effects of climate change on biodiversity is a key step in planning priority conservation areas since climate change is likely to influence species distributions, as the most sensitive species alter their distributions under future climate (Beaumont et al. 2005; Lu et al. 2020). For coastal wetlands, SLR additionally affects wetland species distributions. The findings of the present study indicate substantial impacts of climate change and SLR on Melaleuca wetlands in the study area. Habitat suitability *of M. cajuputi* reduced consistently under the two climate and relative SLR scenarios (i.e. RCP4.5, RCP8.5 and stable and subsidence) by the year 2070 in comparison to the baseline climate (Figs. 4, 5 and Table 1). In the worst case (i.e. RCP8.5 and subsidence scenario of surface elevation change), the model projected a reduction of up to 61.4% in suitable habitat area in comparison to the current climate and sea-level scenarios, whereas the figure for RCP8.5 and stable scenarios was 36.5%. This finding demonstrates the considerable threat of climate change and SLR on the Melaleuca wetlands in the region. Unsurprisingly, the decreases in habitat suitability for the Melaleuca wetland species were bigger under the RCP8.5, and subsidence scenarios than the RCP4.5 and stable scenarios (Figs. 4, 5 and Table 1). Previous studies also found that Melaleuca wetlands/species are under considerable threat from climate change and SLR (Williams 2007; Akumu et al. 2009, 2011; Watt et al. 2009; Traill et al. 2011; Dang et al. 2021a). Critically, Dang et al. (2021a) suggested an average of 30.0% loss of Melaleuca wetland species, including inland Melaleuca wetlands in the Mekong Delta, by the year 2070 due to climate change and SLR without consideration of land subsidence. This finding corresponds well to our findings with a mean loss of 29.8% under the stable scenario in relation to surface elevation change.

The *M. cajuputi* habitat suitability maps and the changes in the distribution of Melaleuca/forested wetland (Figs. 2 and 4) reveal that relative SLR significantly affects the potential distribution of this important wetland type in the study area. SLR not only causes areas of permanent inundation, but also accelerates saltwater intrusion into peatland Melaleuca/forested wetland areas, thus resulting in forested wetland loss (Tran et al. 2013; Thanh et al. 2020). The findings from the current work reveal that, by the year 2070, especially under subsidence scenarios, substantial areas of high and moderate habitat suitability for Melaleuca/forested wetland species (i.e. almost U Minh Ha National Park, partly U Minh Thuong National Park and other areas) become unsuitable. Due to SLR, these wetland areas get converted to mangroves, transition marshes and estuarine open water (Figs. 2 and 4). It is worth noting that Dang et al. (2021a) evaluated climate change impact on the Melaleuca wetland species in the Mekong Delta including Melaleuca wetlands in inland zones, and only considered SLR-induced inundation effects without subsidence and saltwater intrusion influence. Therefore, their results demonstrate less impacts of SLR on the wetland ecosystems than the present study's findings.

Conservation of Melaleuca wetlands under climate change and SLR

The pattern of conservation areas could be ultimately determined by both species distributions and human activities, i.e. land-use status (Mathevet et al. 2018). In the present study, the projected distributions of high suitability habitat and melaleuca wetlands under future climate and SLR scenarios and land-use/wetland changes were considered to identify high-priority conservation areas. Our findings highlighted the significant effects of climate change and relative SLR on current conservation areas of the Melaleuca wetlands in the study area. In particular, for the worst case (i.e. RCP8.5 and subsidence scenarios), high habitat suitability areas/predicted conservation area of the wetland was projected to decrease by 62.0%. Substantial current conservation areas were lost under RCP8.5 and subsidence scenarios. In particular, important conservation reserves within the U Minh Ha National Park completely disappeared due to SLR and subsidence processes, while some parts of the Ramsar site, U Minh Thuong National Park also became unsuitable for the Melaleuca wetlands (Fig. 4).

The severe effects of climate changes and relative SLR on current conservation areas urgently calls for high-priority conservation and preservation of existing Melaleuca wetlands in the region. Projected priority conservation areas from the present study can provide important support for managers in planning appropriate conservation strategies for long-term adaptation to climate change and SLR. Numerous specific recommendations can be formed based on our findings. First, existing nature reserves, which were predicted to remain available under climate change and SLR, especially the worst case (i.e. such as the Ramsar site, U Minh Thuong National Park) should continue to be protected and preserved with enhanced policies and strategies. Second, wetland areas that are not currently nature conservation areas, but are projected to remain as high suitability areas in the future, should be conserved and protected. Third, adaptation plans, such as changes in land-use strategies that may provide the wetland species an avenue to migrate and/or extend their coverage, are also essential to preserve the Melaleuca wetland ecosystems in the region. Finally, our findings reveal that subsidence processes could cause substantial loss of Melaleuca wetlands in the future. Therefore, for long-term conservation, it is critical to develop measures to reduce land subsidence in the region to mitigate the effects of inundation.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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