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Research article

Island carrying capacity for three development types: ecological resource, agricultural production, and urban construction

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ABSTRACT

The evaluation of island carrying capacity is the premise for conducting the island spatial planning and can contributes to guiding island ecological conservation and socioeconomic developments. In this study, the island carrying capacities were evaluated for the three major development types, namely, ecological resource, agricultural production, and urban construction, based on the quantity and quality. The occupancy and vacancy rates of island carrying capacity were measured in different scenarios. Miaodao Archipelago and Dongtou Archipelago in China were selected as the study area to demonstrate the evaluation. The former is constituted all by spatially isolated rocky islands, while the latter is featured by the coexistence of the sandy and rocky islands and the connection with the mainland by bridges. The results indicated the high variances of occupancy and vacancy rates of island carrying capacity at multiple spatial scales. Across the two archipelagos, climate conditions, island composition, and spatial connections with the mainland controlled the spatial variance at this scale. For different types of islands, the sandy island presented distinctly higher occupancy and vacancy rates for agricultural production than the rocky islands. At the single island scale within the same archipelago, the developments of agricultural production and urban construction distinctly increased with the increase in the island area. The dependency of island constructions on the external world in Dongtou Archipelago was higher than that in Miaodao Archipelago. Meanwhile, the difference in traffic conditions between the two archipelagos did not distinctly influence the food dependency on the external world. Then, practical suggestions in terms of quantity control and quality promotion were proposed to improve the island carrying capacity.

1. Introduction

The carrying capacity as a concept originated from the studies from perspectives of population, demography, and sociology, and it has been continuously developed to a more integrated and comprehensive concept that involves multiple dimensions of resources, environment, ecology, society, and economy (Park and Burgess, 1921; Cohen, 1995; Prato, 2009; Moldan et al., 2012; Wei et al., 2014; Chen et al., 2020). The evaluation of carrying capacity can greatly help judge the state and efficiency of land utilization and provide a basis for land spatial planning (Lane, 2010; Santoso et al., 2014; Luo et al., 2020). In China, such evaluation is particularly important. Specifically, one plan called "territorial spatial plan" integrates multiple past plans and serves as the only plan to guide the land spatial configuration and optimization (Fang, 2017; Chen et al., 2019). In the process of territorial spatial planning, the "Double Evaluations" have been designated as the basis and premise to assist the planning (Yue and Wang, 2019; Ministry of Natural Resources of China, 2020; Zhou et al., 2020; Chi et al., 2022). As the primary part of the "Double Evaluations", the carrying capacity evaluation plays a fundamental role in the territorial spatial planning by ascertaining the quantity and quality of development types and identifying the main influencing factors. Ecological resource (DT1), agricultural production (DT2), and urban construction (DT3) are the three development types that cover the land space, represent different key functions, and directly serve as the basic unit to conduct the territorial spatial planning (Liu et al., 2017; Ministry of Natural Resources of China, 2020). During the last several years, carrying capacities for the three development types have been studied in different areas in China (Ding et al., 2019; Wang et al., 2020). However, the current studies are still in a preliminary stage and have paid little attention to the island.

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The island is a geographic unity with special location, clear boundary, and limited area (Chi et al., 2018, 2020a). The special location renders the island exposed to multiple natural and anthropogenic contexts; the clear boundary denotes the distinct isolation and gives each island its own feature; and the limited area results in the high sensitivity to disturbances (Chi et al., 2017; Ma et al., 2020). The three development types are widely observed over the islands and compactly distributed within such an isolated and limited space with various disturbances and high sensitivity. Meanwhile, the three development types present considerable differences across different scales. The evaluation of island carrying capacity can contribute to the island ecological conservation and socioeconomic developments through revealing the overall conditions and spatial distributions of the three development types and identifying the main influencing factors. It also guides the territorial spatial planning in different areas because islands with different characteristics can serve as natural laboratories for generating universal results and knowledge.

DT1 is crucial to the Earth's biodiversity maintenance, ecological integrity, and sustainable human development (Clark et al., 2011; Fan et al., 2017; Faber-Langendoen et al., 2019). Since the beginning of the 2010s, China has proposed the blueprint of "the construction of ecological civilization" and considered it as one of the national development principles (Xiao and Zhao, 2017). The importance of DT1 has risen to an unprecedented height. DT1 is particularly valuable to the island ecosystem and support its core function of biodiversity conservation at different levels (Jønsson and Holt, 2015; Borges et al., 2018). At species level, rare biological resources are harbored through speciation and endemism in the context of isolated spaces (Helmus et al., 2014; Borges et al., 2018). At ecosystem level, various ecosystem types are formed on the islands because of the unique habitats, and lots of islands have become the essential stops in the bird migration route (Chen et al., 2005; Wolanski et al., 2009; Chi et al., 2018). The DT2 is the basic industry of national economy and determines the survival of human beings (Cradock-Henry et al., 2019; Wu et al., 2020a). The protection of cultivated lands is a basic state policy in China and agricultural issues have always been paid much attention by the Chinese government (Niu and Fang, 2019). Different islands play different roles in the DT2. Generally, farmlands are widely distributed over sandy islands because of the flat terrain and fertile soils, but are always poorly developed on rocky islands due to the undulating terrains (Chi et al., 2018, 2019b, 2020b). Particularly, some inhabited islands have no farmlands, and their principle food is totally dependent on the external world, which makes a request for the traffic ability. The DT3 comprises all forms of constructions of buildings, structures, and infrastructures for residence, traffic, public service, industrial and commercial developments, and other functions (Gao et al., 2019). It represents the development and progress of human society, and inevitably negatively influences the natural ecosystem in the process of constructions, but these negative influences can be reduced through reasonable spatial planning, ecological restoration, and environmental management (Liu, 2018; Mahmoud and Gan, 2018; Wu et al., 2018; Kertész et al., 2019; Zhang et al., 2021). The DT3 is the most common exploitation type on islands, and different forms of constructions can be observed on different types of islands in China, rendering islands residential areas of island inhabitants, platforms for protecting and utilizing the ocean, and hubs of maritime transportation (Xie et al., 2018; Chi et al., 2018, 2019b, 2020b; Ma et al., 2020).

Various factors at different scales drive the distinct spatial heterogeneities in the three development types. At regional scale, different climate conditions largely determine the vegetation and soil types, and the socioeconomic environments set the context of the types, scopes, and intensities of human activities (Chi et al., 2018, 2020b; Kurniawan et al., 2019). The most noteworthy feature is the isolation condition from the mainland. In China, most islands are located near the mainland. Some island regions that carry frequent human activities have been spatially connected with the mainland via bridges or tunnels, such as Chongming Island in Shanghai City, Zhoushan Archiplago in Zhejiang Province, and Xiamen Island in Fujian Province (Huang et al., 2008; Lin et al., 2016; Chi et al., 2020b; Wu et al., 2020b). By contrast, more island regions are spatially isolated and connected with the mainland mainly via ships (Li et al., 2015; Yang et al., 2016; Deng et al., 2017; Chi et al., 2018). The isolation conditions control the communication of the islands with the external world and substantially influence the island developments Chi et al. (2020b). At island level, different types of islands exhibit their own features in different aspects. Islands can be divided into inhabited and uninhabited islands according to the inhabitation conditions, and into rocky, sandy, and coral reef islands according to the material constitutions (Nam et al., 2010; Xie et al., 2018; Chi et al., 2019a, 2020b). Distinct differences in the natural and anthropogenic factors can be observed across different types of islands, and result in the spatial variances of the three development types (Zhao et al., 2004; Nam et al., 2010; Chi et al., 2018). Even within the same island type, specific island parameters such as island area (IA) and distance to the mainland (DTM) determine the identity of each island (Chi et al., 2018, 2019a). All the factors bring about the spatial heterogeneities of the three development types over islands. The spatial heterogeneities are represented by two aspects: quantity and quality. The former indicate the areas and scopes of different development types while the latter denotes their specific development conditions per area. It is urgent to evaluate the island carrying capacities for the three development types and identify the influencing factors at the different scales.

Furthermore, the structure of the development types indicates the dependency of island developments on the external world. Currently, nearly every corner is associated with the external world, even the islands that are featured by the isolation (Xie et al., 2018; Chi et al., 2019a). Different types of materials and energies are exchanged across the islands and the mainland. The materials and energies that are consumed by the islands do not match those provided by the islands. In Miaodao Archipelago (MDA) in northern China, the islands provide various kinds of seafood for the external world. For instance, Daqin Island is famous for its kelp (*Laminaria japonica*) with high quality, and exports a large amount of kelp (Chi et al., 2018). In Dongtou Archipelago (DTA) in southern China, besides the seafood, important port resources are also provided and promote the traffic ability of the region (Chi et al., 2020b). Meanwhile, extensive and large materials and energies are imported from the external world to the islands, and they support the survival and living of island inhabitants and different types of constructions (Searcy, 2017; Chi et al., 2020a). Overall, the imported materials and energies are crucial to the islands, thereby rendering the islands dependent on the external world. The conditions of DT2 and DT3 largely determine the food supply and demand, and denote the materials and energies that are exchanged between the islands and the mainland. These exchanges are realized on the basis of the traffic ability of the islands. This study can help judge the dependencies of island developments on the external world.

Therefore, MDA and DTA were selected as the study area. The former is composed of spatially isolated rocky islands, while the latter is characterized by the coexistence of the sandy and rocky islands and the connection with the mainland by bridges. The island carrying capacities for the three development types will be evaluated in terms of quantity and quality. The occupancy and vacancy rates of island carrying capacity will be measured in three scenarios. Then, the influencing factors of the island carrying capacity and the dependencies of island developments on the external world will be discussed. Finally, suggestions to improve the island carrying capacity will be proposed (Figure 1). The objective of the study is the spatial pattern of island carrying capacity for the three development types, and five scientific questions need to be solved: (1) How are the island carrying capacities for the three development types evaluated? (2) How are the occupancy and vacancy rates of the island carrying capacity measured? (3) What are the main influencing factors of the spatial heterogeneities of island carrying capacity at different scales? (4) How are the dependencies of island developments on the external world judged? (5) How are practical suggestions proposed to improve the island carrying capacity? The purpose of the study is (1) to establish a

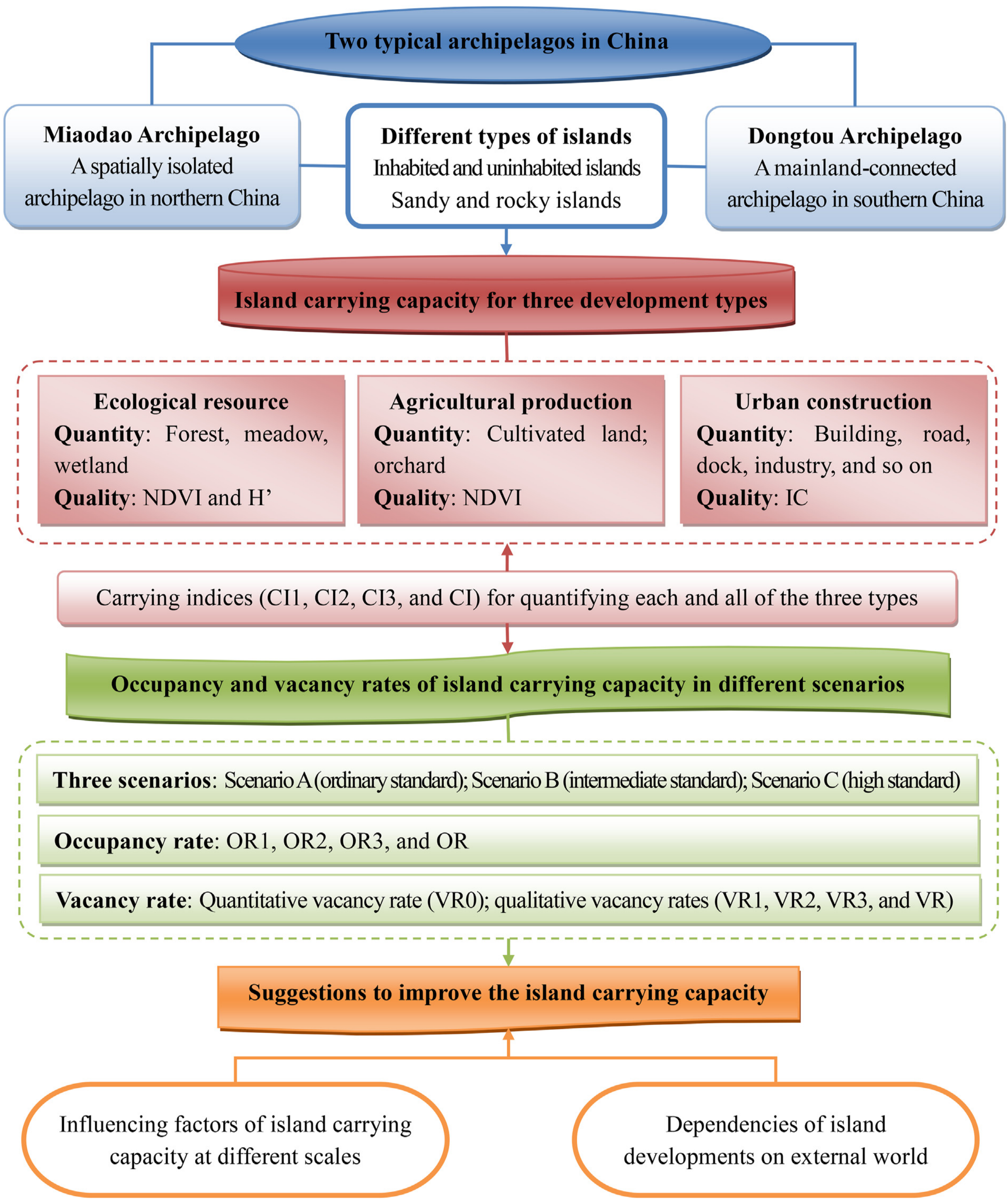

Figure 1. Framework for evaluating the island carrying capacity for ecological resource (DT1), agricultural production (DT2), and urban construction (DT3): NDVI: normalized difference vegetation index; H′: Shannon-Wiener index; IC: influence coefficient.

practical method to conduct the island carrying capacity evaluation and (2) to guide the territorial spatial planning in island regions.

2. Materials and methods

2.1. Study area and data source

2.1.1. Study area

MDA belongs to Shandong Province, and it is to the north of the Shandong Peninsula and at the junction of the Yellow and Bohai Seas; DTA belongs to Zhejiang Province, and it is at the estuary of Oujiang River and faces the East China Sea on the east (Figure 2). They are both important archipelagos that perform enormous ecological functions and carry various human activities. They provide unique habitats for biodiversity and function as the key nodes of bird migration route (Chi et al., 2019a, 2020a). Meanwhile, they are two of the 14 island counties in China and serve as the important platforms for human survival and development. MDA is the location of the Marine Ecological Civilization Comprehensive Experimental Area of Changdao while DTA is the location of Dongtou District of Wenzhou City. Land areas of MDA and DTA

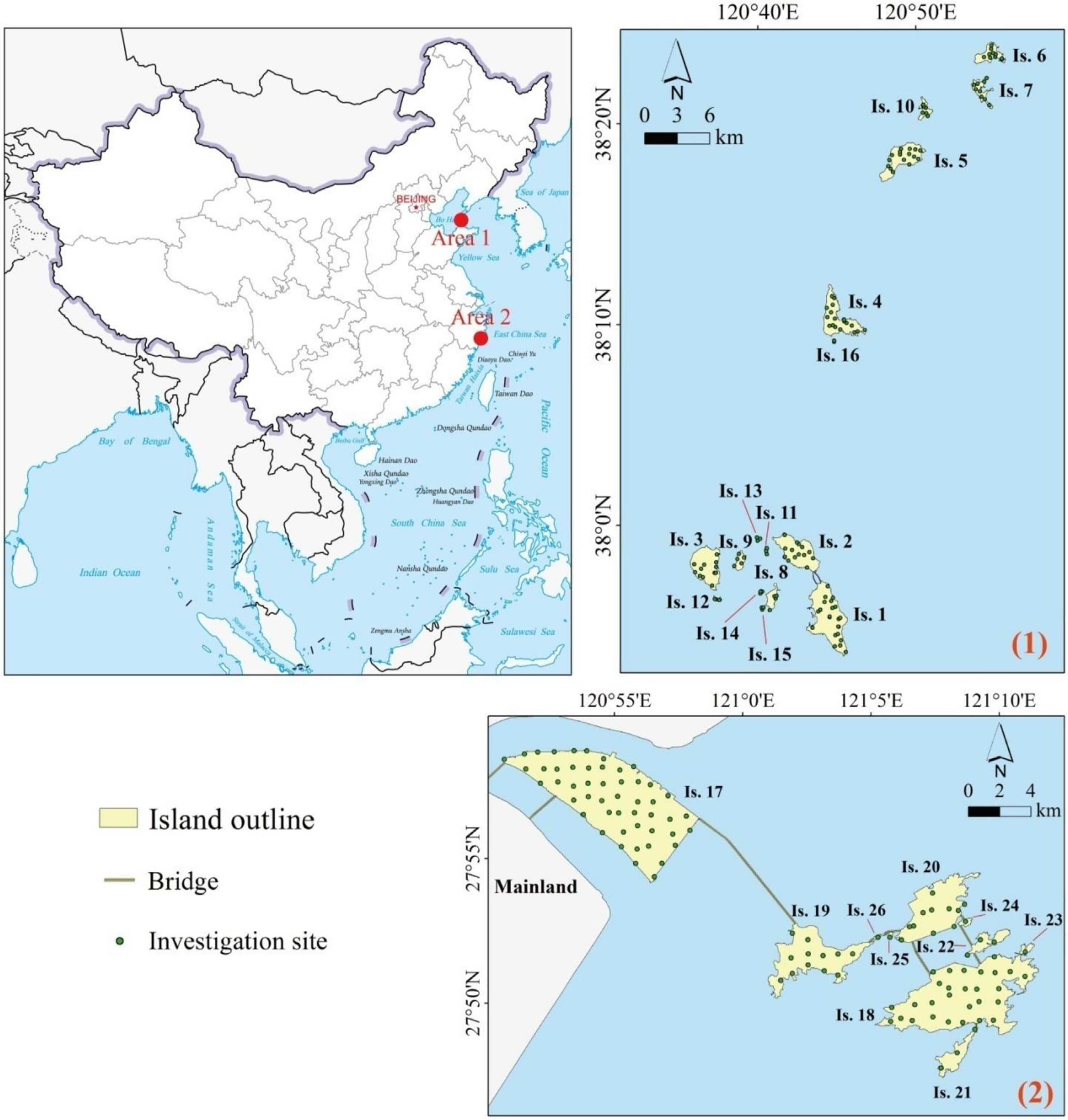

Figure 2. Location, island composition, and investigation sites of the study area: Area 1: Miaodao Archipelago (MDA) in northern China; Area 2: Dongtou Archipelago (DTA) in southern China. In MDA, Is. 1–Is. 16 are included using a descending order of areas: Is. 1: Nanchangshan Island; Is. 2: Beichangshan Island; Is. 3: Daheishan Island; Is. 4: Tuoji Island; Is. 5: Daqin Island; Is. 6: Beihuangcheng Island; Is. 7: Nanhuangcheng Island; Is. 8: Miaodao Island; Is. 9: Xiaoheishan Island; Is. 10: Xiaoqin Island; Is. 11: Tanglang Island; Is. 12: Nantuozi Island; Is. 13: Danglang Island; Is. 14: Yangtuozi Island; Is. 15: Niutuozi Island; Is. 16: Tuozi Island. In DTA, Is. 17–Is. 26 are included using a descending order of areas: Is. 17: Lingkun Island; Is. 18: Dongtou Island; Is. 19: Niyu Island; Is. 20: Zhuangyuan'ao Island; Is. 21: Banping Island; Is. 22: Dasanpan Island; Is. 23: Shengli'ao Island; Is. 24: Huagang Island; Is. 25: Shenmenshan Island; Is. 26: Qianmenshan Island. Of all the islands in MDA and DTA, Is. 17 is a sandy island while the others are all rocky islands according to the material constitution; Is. 11–Is. 16, Is. 25, and Is. 26 are uninhabited islands while the remaining islands are inhabited islands according to the inhabitation condition. The location map was sourced from Ministry of Natural Resources of China; the island composition maps were quoted from a previous relevant study by the authors (Chi et al., 2022).

are 59.26 km^2 and 153.30 km^2, respectively, and the total populations were 40.90 thousand and 154.50 thousand at the end of 2020, respectively (Economic Development Bureau of the Marine Ecological Civilization Comprehensive Experimental Area of Changdao, 2021; Bureau of Statistics of Dongtou District, 2021). Human activities with different types, scopes, and intensities coexist within the island, and exploit, damage, or conserve the island ecosystems in different aspects and to different degrees (Chi et al., 2018, 2020b).

Distinct differences in natural and anthropogenic contexts exist between the two archipelagos. (1) Island composition and area: MDA is constituted all by rocky islands and the total area of the islands is relatively small; by contrast, DTA is composed of sandy and rocky islands with a large total area. (2) Isolation: Islands in MDA are all spatially isolated; the seawater separates the islands from the mainland and the ship is the main form of transport that connects the islands and the mainland, thus the isolation is distinct; islands in DTA are connected with the mainland by bridges, which have been constructed since the beginning of the 21th century and greatly decrease the isolation. (3) Climate condition: MDA has a temperate, continental, and monsoon climate while DTA has a subtropical, oceanic, and monsoon climate. The distinct differences in climates create the different soil and vegetation types. (4) Human activities: Though all the human activities in the two archipelagos belong to the aforementioned three development types, the details present differences. The sub-types in DTA are much more various than those in MDA. Thus, the two archipelagos serve as the ideal laboratories for conducting this study and can provide universal results for the island carrying capacity in different contexts.

In this study, a total of 16 and 10 islands in MDA and DTA, respectively, were used as the studied islands. All the ten inhabited islands and their adjacent six large uninhabited islands in MDA were selected; areas of the selected 16 islands sum to 51.25 km^2. In DTA, ten islands that are successively connected by bridges and in a chain form were selected; areas of the selected ten islands sum to 102.10 km^2. The spatial distributions of the islands are shown in Figure 2 and the island basic information is presented in Table S1 in the Supplementary Materials.

2.1.2. Data sources

(1) Remote sensing

The SPOT 6 data, which has a high spatial resolution (1.5 m × 1.5 m for the panchromatic image), was used to generate the spatial data of different development types and sub-types. The Landsat 8 data has multiple spectra (30 m × 30 m), and served as the source for various spectrum-based ecological indices. The version two of Aster GDEM (30 m × 30 m) was used to generate terrain factors.

(2) Field investigation

Field investigations were implemented in two aspects. First, the preliminary spatial distributions of the development types were validated and modified. The uncertain types were specially investigated to verify their types; all-round validations were conducted over the islands as comprehensive as possible; and the development types and sub-types were then modified on the basis of filed validation. Second, a total of 245 sites were investigated for obtaining the field plant and soil data. Plant data were recorded in the field and soil data were measured in the laboratory after collecting soil samples in the field.

2.2. Three development types that occupy the island carrying capacity

The three development types were identified, and the carrying indices (CIs) were established based on quantity and quality. All the indicators were selected to quantify and spatially exhibit the quantity and quality of different development types. A size of 30 m × 30 m was used as the evaluation unit according to the spatial resolution of Landsat 8 data.

2.2.1. Ecological resource (DT1)

(1) Quantity

The quantity is measured using the areas of different sub-types within the DT1. MDA possesses two sub-types, that is, forest and meadow; DTA has three sub-types, including forest, meadow, and wetland. The forest are mostly plantation with *Pinus thunbergii* and *Casuarina equisetifolia* as the dominant species in MDA and DTA, respectively. The meadows are always adjacent to the forests. The wetlands are observed along the shoreline, particular on the sandy island (Is. 17).

(2) Quality

The quality of DT1 was quantified using two metrics, namely, Shannon-Wiener index (H′) and normalized difference vegetation index (NDVI). The former refers to the plant diversity while the latter refers to the vegetation growth condition. The two metrics cover the core function for biodiversity conservation at different levels. The H′ directly represents the species complexity and mainly denotes the biodiversity at species level, while the NDVI can represent the overall ecological state and mainly indicates the biodiversity at ecosystem level (Erdenetsetseg and Erdenetuya, 2006; Chi et al., 2020c). Their calculation methods can be referenced in the studies of Chi et al. (2019a, 2020a).

(3) Carrying index 1 (CI1)

The carrying index that represents DT1 (CI1) was measured in each evaluation unit based on the quantity and quality. First, areas of DT1 in each evaluation unit were obtained by merging the spatial data of DT1 and the evaluation units using *Union* tool in ArcGIS 10.0. Second, H′ and NDVI were standardized to the interval from 0 to 2 by using the 95th and 5th percentiles of all the index values in the two archipelagos as the upper and lower limits, respectively (Chi et al., 2019b). Third, the CI1 was calculated as follows:

$$CI1 = QT1 \times QL1, \tag{1}$$

$$QT1 = A1/TA, \tag{2}$$

$$QL1 = S\text{-}H' \times w + S\text{-}NDVI \times (1 - w), \tag{3}$$

where QT1 and QL1 are the values of quantity and quality for DT1, respectively; A1 and TA are the area of DT1 and the total area in an evaluation unit, respectively; S-H' and S-NDVI are the standardized values of H′ and NDVI in an evaluation unit, respectively; and *w* is the weighted value of S-H′ relative to S-NDVI and was given as 0.5.

2.2.2. Agricultural production (DT2)

(1) Quantity

Two sub-types, namely, cultivated land and orchard, exist in the study area. MDA only has cultivated lands while DTA possesses the two sub-types. Cultivated lands in MDA are all dry lands while those in DTA are mostly paddy fields. The orchard is only observed on the sandy island (Is. 17) with *Citrus reticulata* as the major type.

(2) Quality

The quality of DT2 was measured using NDVI. As mentioned earlier, the NDVI can accurately and rapidly represent the vegetation growth condition. Besides, it has been proven to be closely and positively with the DT2 (Hill and Donald, 2003; Li et al., 2019).

(3) Carrying index 2 (CI2)

The carrying index that represents DT2 (CI2) was measured through the procedures same to those of CI1. The CI2 was calculated using the method as follows:

$$CI2 = QT2 \times QL2, \tag{4}$$

$$QT2 = A2/TA, \tag{5}$$

$$QL2 = S\text{-}NDVI, \tag{6}$$

where QT2 and QL2 are the values of quantity and quality for DT2, respectively; A2 is the area of DT2 in an evaluation unit.

2.2.3. Urban construction (DT3)

(1) Quantity

MDA has four sub-types of DT3, including building, road, dock, and hardened ground. By contrast, DTA has more various sub-types. Besides the aforementioned four sub-types, ordinary water area, reservoir, pond, harbor basin, industrial land, and quarrying area also exist. The buildings can be divided into high-rise (>two stories) and low-rise buildings (≤two stories); the roads and docks are for the traffic purposes; the hardened grounds are artificial impervious lands without buildings and structures, including square, sunning ground, and to-be-built lands; ordinary water area, reservoir, pond, and harbor basin are four types of artificial water areas used for different purposes, including irrigation, drainage, landscape, water storage, aquaculture, and ship berthing; the industrial lands indicate different types of manufacturing enterprises; and the quarrying areas are the mountainous areas that have been used for stone materials and space resources, and observed only on the rocky islands, particularly on Is. 19 (Chi et al., 2018, 2020b).

(2) Quality

The quality of DT3 was measured by using quality coefficients (QCs). The QCs of different sub-types were determined according to the development intensity of sub-types and their contributions to the island human society. The sub-types that involve the traffic function include road, port, and harbor basin, and contribute to the external and internal communication for the islands; the industrial lands have a high development intensity and provide industrial products that are needed; and the high-rise buildings have a high capacity for accommodation (Hang et al., 2012; Xie et al., 2018; Chi et al., 2020b). These sub-types were assigned high QCs. The hardened grounds and ordinary water areas possess low development intensities and make relatively low contributions to the island human society (Chi et al., 2020b). Thus, their QCs were considered low. The remaining sub-types were assigned intermediate QCs. In this study, the high, intermediate, and low QCs were given as 2.0, 1.0, and 0.5, respectively.

(3) Carrying index 3 (CI3)

The carrying index that represents DT3 (CI3) was calculated using the following equations:

$$CI3 = \sum QT3_i \times QL3_i, \tag{7}$$

$$QT3_i = A3_i / TA, \tag{8}$$

$$QL3_i = QC_i, \tag{9}$$

where $QT3_i$ and $QL3_i$ are the values of quantity and quality for sub-type i of DT3, respectively; and $A3_i$ and QC_i are the area and QC of sub-type i of DT3 in an evaluation unit, respectively.

On the basis of CI1, CI2, and CI3, the carrying index that represents all the three development types (CI) was calculated using the following equation:

$$CI = CI1 + CI2 + CI3, \tag{10}$$

The spatial distributions of the three development types are shown in Fig. S1 in the Supplementary Materials. The spatial distributions of the carrying indices (CI1, CI2, CI3, and CI) are presented in Figure 3.

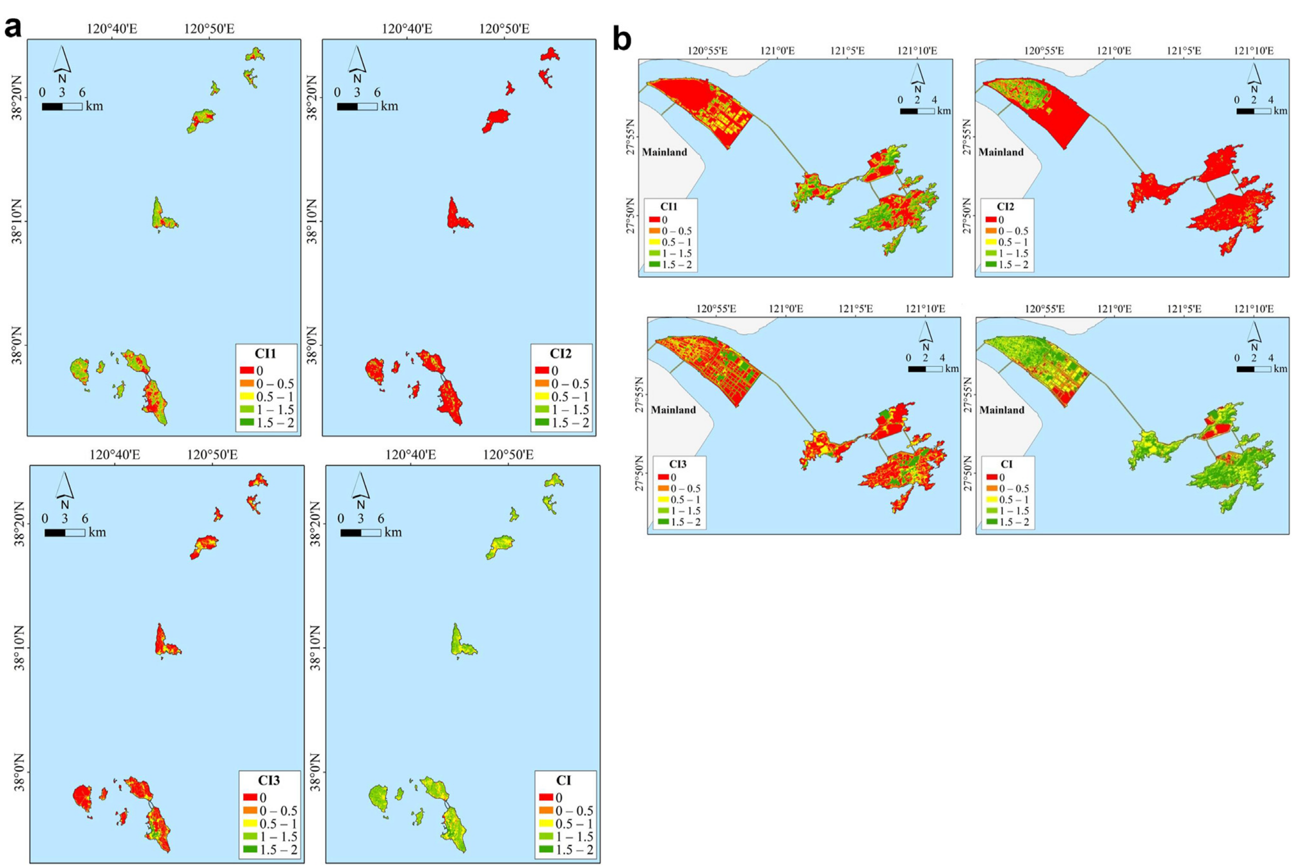

Figure 3. a Spatial distributions of carrying indices on Miaodao Archipelago (MDA). b Spatial distributions of carrying indices on Dongtou Archipelago (DTA). CI1: carrying index that represents ecological resource (DT1); CI2: carrying index that represents agricultural production (DT2); CI3: carrying index that represents urban construction (DT3); CI: carrying index that represents all the three development types.

2.3. Occupancy and vacancy rates of island carrying capacity

2.3.1. Three scenarios

Three scenarios were assumed to measure the occupancy and vacancy rates of island carrying capacity by using different standards.

(1) Scenario A: Ordinary standard

The ordinary standard was adopted in Scenario A. The quality values (QL1, QL2, and QL3) that are all given as 1.0 were used to recalculate the CIs by using the aforementioned equations, and these CIs indicated the ordinary standards for different development types. A circumstance for this standard is as follows: all the DT1 has ordinary conditions of H′ and NDVI (QL1 = 1), all the DT2 shows ordinary condition of NDVI (QL2 = 1), and the DT3 is constituted all by low-rise buildings (QL3 = 1).

(2) Scenario B: Intermediate standard

In Scenario B, the intermediate standard was adopted. Specifically, the quality values (QL1, QL2, and QL3) that are all given as 1.5 were used to recalculate the CIs, and these CIs denoted the intermediate standards for different development types. A circumstance for this standard is as follows: all the DT1 has good conditions of H′ and NDVI (QL1 = 1.5), all the DT2 shows good condition of NDVI (QL2 = 1.5), and the DT3 is constituted by the same proportions of low-rise and high-rise buildings (QL3 = 1.5).

(3) Scenario C: High standard

The high standard was used in Scenario C. The quality values (QL1, QL2, and QL3) that are all given as 2.0 were used to recalculate the CIs, and these CIs referred to the high standards for different development types. A circumstance for this standard is as follows: all the DT1 has the highest H′ and NDVI (QL1 = 2.0), all the DT2 shows the highest NDVI (QL2 = 2.0), and the DT3 is constituted all by high-rise buildings (QL3 = 2.0).

2.3.2. Occupancy rates

The occupancy rates of island carrying capacity were determined by comparing the CIs of development types with the standards in different scenarios in all the evaluation units. The method is as follows:

$$OR_A = \begin{pmatrix} 100\% & CI \geq 1.0 \\ CI \times 100\% & CI < 1.0 \end{pmatrix}, \tag{11}$$

$$OR_B = \begin{pmatrix} 100\% & CI \geq 1.5 \\ CI/1.5 \times 100\% & CI < 1.5 \end{pmatrix}, \tag{12}$$

$$OR_C = \begin{pmatrix} 100\% & CI \geq 2.0 \\ CI/2 \times 100\% & CI < 2.0 \end{pmatrix}, \tag{13}$$

where OR_A, OR_B, and OR_C are the occupancy rates in Scenarios A, B, and C, respectively. OR1, OR2, OR3, and OR are the occupancy rates that represents DT1, DT2, DT3, and all the three development types, respectively, and were measured using these equations based on CI1, CI2, CI3, and CI, respectively.

2.3.3. Vacancy rates

The vacancy rates of island carrying capacity were measured in two aspects: the quantitative and qualitative vacancy rates. The former is the vacancy rate in the unoccupied areas, and indicates the reserved space for the future new developments; the latter is the vacancy rate in the occupied areas and denotes the potentials for quality improvements of the current development types. The quantitative vacancy rate does not involve the different scenarios and was calculated as follows:

$$VR0 = A0/TA \times 100\%, \tag{14}$$

where VR0 is the quantitative vacancy rate; and A0 is the area of unoccupied lands. The qualitative vacancy rates involve different development types in different scenarios, and were calculated as follows:

$$VR1 = \begin{pmatrix} (S\text{-}CI1_x - CI1) \times 100\% & S\text{-}CI1_x \geq CI1 \\ 0 & S\text{-}CI1_x < CI1 \end{pmatrix}, \tag{15}$$

$$VR2 = \begin{pmatrix} (S\text{-}CI2_x - CI2) \times 100\% & S\text{-}CI2_x \geq CI2 \\ 0 & S\text{-}CI2_x < CI2 \end{pmatrix}, \tag{16}$$

$$VR3 = \begin{pmatrix} (S\text{-}CI3_x - CI3) \times 100\% & S\text{-}CI3_x \geq CI3 \\ 0 & S\text{-}CI3_x < CI3 \end{pmatrix}, \tag{17}$$

where VR1, VR2, and VR3 are the vacancy rates that represent DT1, DT2, and DT3, respectively; and $S\text{-}CI1_x$, $S\text{-}CI2_x$, and $S\text{-}CI3_x$ are the standards of CIs for DT1, DT2, and DT3 in Scenario x, respectively. Then, the vacancy rate that combines the aforementioned ones was calculated as follows:

$$VR = VR0 + \begin{pmatrix} (S\text{-}CI_x - CI) \times 100\% & S\text{-}CI_x \geq CI \\ 0 & S\text{-}CI_x < CI \end{pmatrix}. \tag{18}$$

where $S\text{-}CI_x$ is the standard of CI for all the three development types in Scenario x.

3. Results

3.1. Spatial distributions of occupancy and vacancy rates of the island carrying capacity

3.1.1. Occupancy rates

The spatial distributions of occupancy rates of the island carrying capacity are shown in Figure 4. The occupancy rates decreased from Scenario A to Scenario C for all the development types in the two archipelagos.

For OR1 in MDA, in Scenario A, the OR1 achieved 100% in the central part of DT1 while kept zero in areas of DT2 and DT3. The edge areas of DT1 showed OR1 in the interval of (0, 100%). In Scenarios B and C, most areas of DT1 had OR1 in the intervals of (50%, 100%) and (50%, 75%], respectively. The OR2 was zero in most areas of the islands, and only certain areas on parts of the islands (particularly Is. 1, Is. 2, and Is. 3) showed high OR2. The OR3 was generally high in residential areas. Most of the residential areas had OR3 in the intervals of (75%, 100%], (50%, 75%], and (25%, 50%] in Scenarios A, B, and C, respectively, and the OR3 in the docks and their adjacent areas on Is. 1 kept 100% in the three scenarios. As for the OR that represents all the three development types, it was 100% in most areas of the islands in Scenario A. In Scenarios B and C, areas with OR in the intervals of (50%, 100%) and (25%, 75%] covered the most areas, respectively.

In DTA in Scenario A, the OR1 achieved 100% in most areas of DT1 on the rocky islands, while part areas of DT1 on the sandy island (i.e., Is. 17) had OR1 in the interval of (50%, 75%]. In Scenario B, areas with OR1 = 100% still occupied a considerable proportion, and the other areas that had OR1 of 100% in Scenario A showed OR1 in the interval of (75%, 100%). In Scenario C, most areas of DT1 on the rocky islands had OR1 in the interval of (50%, 100%), and a small part showed OR1 of 100%. By contrast, the OR1 of DT1 on the sandy island (i.e., Is. 17) was generally in the interval of (25%, 50%]. The OR2 was high in the western part of the sandy island (i.e., Is. 17), while areas with high OR2 were in a sporadic distribution with very small areas on the rocky islands. The OR3 was high in the eastern part of the sandy island (Is. 17), the central part of Is. 18, the southern part of Is. 19, and the northern part of Is. 20, certain areas in which had OR3 of 100% in the three scenarios. As for the OR that represents all the three development types, areas with OR of 100% covered most areas of the islands in Scenario A, areas with OR in the interval of

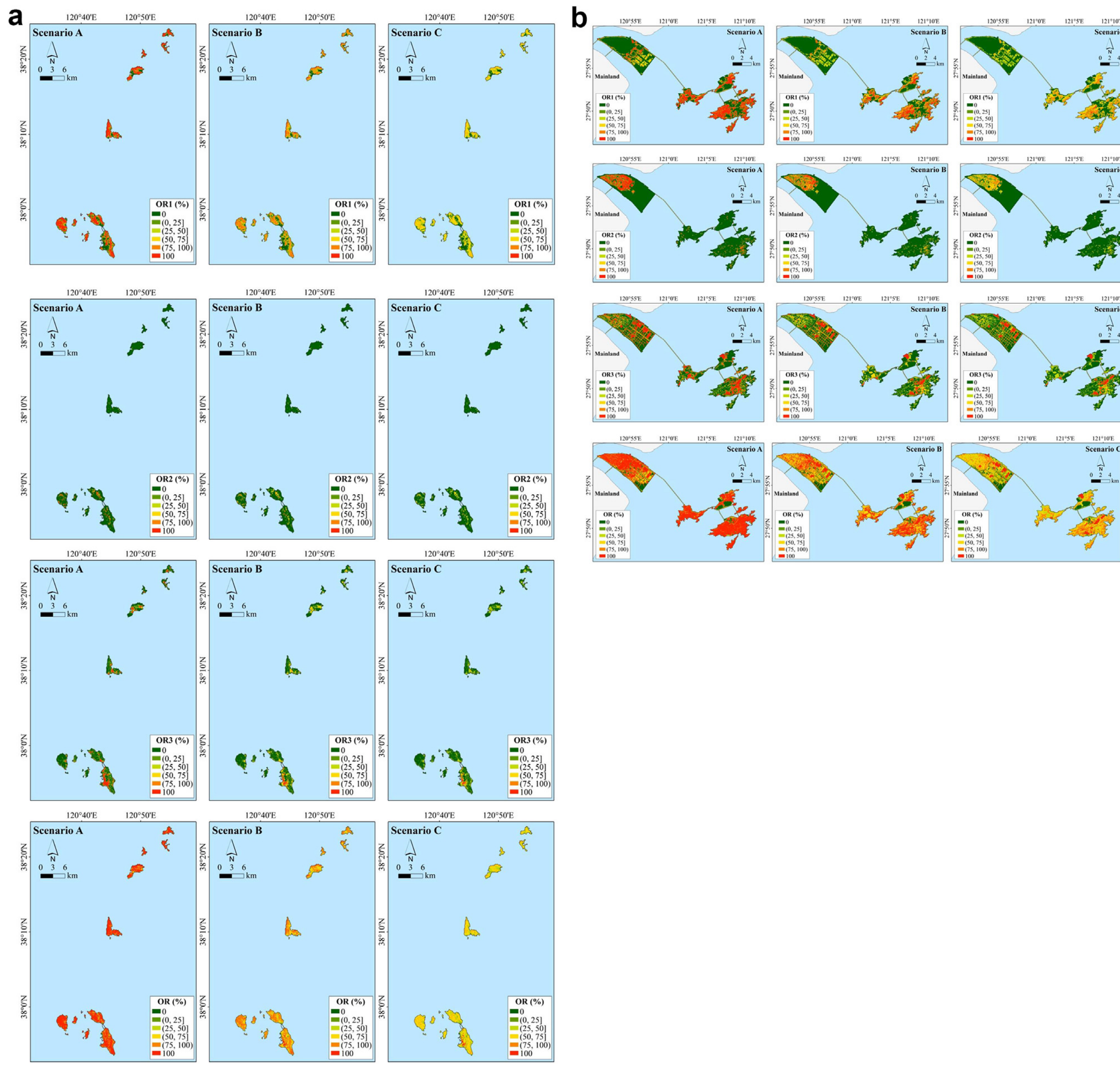

Figure 4. a Spatial distributions of occupancy rates of the island carrying capacity on Miaodao Archipelago (MDA). b Spatial distributions of occupancy rates of the island carrying capacity on Dongtou Archipelago (DTA). OR1: occupancy rate that represents ecological resource (DT1); OR2: occupancy rate that represents agricultural production (DT2); OR3: occupancy rate that represents urban construction (DT3); OR: occupancy rate that represents all the three development types.

(75%, 100%] were the most in Scenario B, and areas with OR in the interval of (50%, 75%] occupied the most.

3.1.2. Vacancy rates

The spatial distributions of vacancy rates of the island carrying capacity are presented in Figure 5. The VR0 is the quantitative vacancy rate and remains the same across different scenarios. The VR1–VR3 are the qualitative vacancy rates; they change across different scenarios and correspond to the aforementioned OR. The VR denotes the vacancy rate that combines the aforementioned ones and also varies across scenarios.

In MDA, the VR0 was spatially homogeneous with the value of zero over the islands, indicating that nearly all areas of these islands have been covered by the three development types. The VR1 was generally low in Scenario A and increased from Scenarios A to C. In Scenario C, areas with VR1 in the interval of (25%, 50%] covered the most of DT1. The VR2 kept zero in most areas across the three scenarios. In Scenarios B and C, areas with VR2 in the interval of (0, 50%] occupied certain but small areas. Similarly, the VR3 in Scenario A was zero in most areas, yet exhibited high values on certain areas, particularly on the inhabited islands, in Scenarios B and C. As for the VR, it was zero in most areas of the islands in Scenario A. In Scenarios B and C, areas with VR that belongs to (0, 50%] and (25%, 75%] covered the most, respectively.

In DTA, the VR0 was zero in most areas, yet achieved 100% in the southeastern part of Is. 17, the northern part of Is. 18, and the southern and northwestern parts of Is. 20, which were all the newly formed areas through sea reclamation. The VR1–VR3 all increased from Scenarios A to C, which was in accordance with those in MDA. Meanwhile, the increase of VR1 from Scenarios A to C in DTA was lower than that in MDA and the increase of VR2 from Scenarios A to C in DTA was higher than that in MDA (particularly in the western part of Is. 17). As for the VR, besides the unoccupied areas with VR of 100%, areas with VR of zero covered the most areas of the islands in Scenario A. Areas with VR in the intervals of [0, 25%] and (25%, 50%] were the most in Scenarios B and C, respectively.

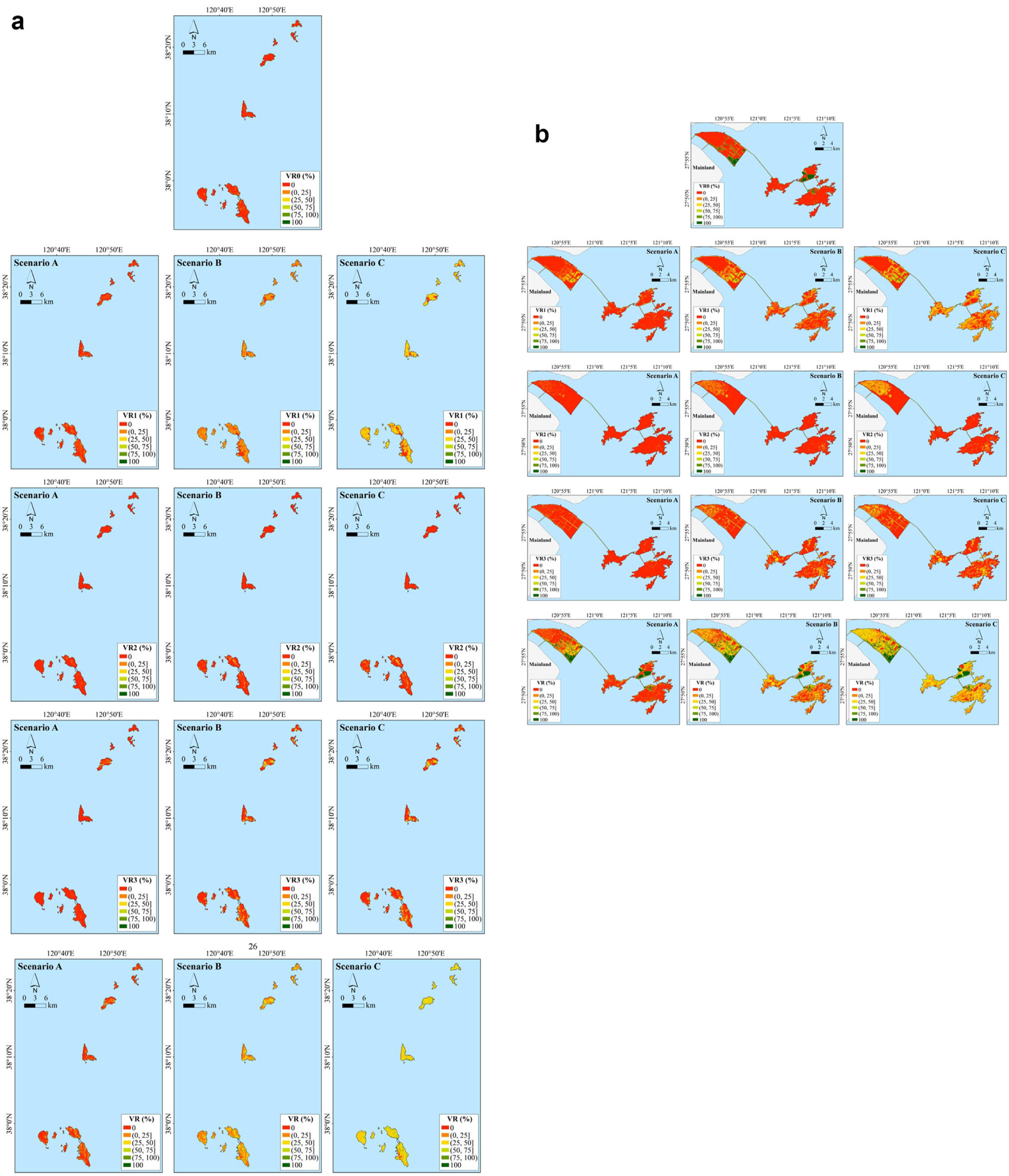

Figure 5. a Spatial distributions of vacancy rates of the island carrying capacity on Miaodao Archipelago (MDA). b Spatial distributions of vacancy rates of the island carrying capacity on Dongtou Archipelago (DTA). VR0 indicates the vacancy rate in the unoccupied areas, i.e., the quantitative vacancy rate, and VR1–VR3 indicate the vacancy rates in the occupied areas, i.e., the qualitative vacancy rates. VR1: vacancy rate that represents ecological resource (DT1); VR2: vacancy rate that represents agricultural production (DT2); VR3: the vacancy rate that represents urban construction (DT3); VR: vacancy rate that combines the aforementioned ones.

3.2. Occupancy and vacancy rates of the carrying capacity on different islands

3.2.1. Occupancy rates

The occupancy rates of carrying capacity on different islands are shown in Table 1.

In terms of MDA in Scenario A, OR1 was higher than 50% on all islands except Is.1 and Is. 16, which gained OR1 values of 48.65% and 42.32%, respectively. Is. 14, Is. 15, and Is. 8 achieved the highest three values of OR1. It indicated that high values of OR1 could be observed on both of the inhabited and uninhabited islands, so did the low values of OR1. The OR2 was higher than zero only on several inhabited islands, of

Table 1. Occupancy rates of carrying capacity on different islands in different scenarios.

Island		Scenario A				Scenario B				Scenario C			
		OR1	OR2	OR3	OR	OR1	OR2	OR3	OR	OR1	OR2	OR3	OR
Area 1	Is. 1	48.65	7.60	37.24	90.01	38.55	5.73	29.16	73.29	28.95	4.39	24.32	57.66
	Is. 2	61.25	12.58	17.74	88.53	49.86	9.26	12.12	71.18	37.44	7.03	9.15	53.62
	Is. 3	76.43	13.61	9.20	95.78	63.85	10.58	6.23	80.53	47.98	8.11	4.70	60.80
	Is. 4	73.65	1.81	20.99	93.75	60.11	1.33	14.53	75.91	45.25	1.00	11.10	57.35
	Is. 5	63.64	0.34	23.25	86.55	51.96	0.23	15.84	68.03	39.07	0.17	12.01	51.25
	Is. 6	64.67	0	18.17	81.40	53.61	0	12.40	66.00	40.24	0	9.37	49.61
	Is. 7	66.15	0	19.77	84.14	54.04	0	14.13	68.14	40.56	0	11.13	51.69
	Is. 8	78.54	5.19	12.12	93.55	62.65	3.57	8.28	74.46	46.99	2.69	6.32	56.00
	Is. 9	74.88	7.75	15.66	94.38	59.98	6.63	10.57	76.98	45.05	5.46	8.01	58.51
	Is. 10	75.96	0	11.99	86.97	63.22	0	8.17	71.39	47.45	0	6.24	53.69
	Is. 11	60.49	0	1.31	61.79	47.25	0	0.87	48.12	35.43	0	0.65	36.09
	Is. 12	76.37	0	1.66	78.01	56.01	0	1.10	57.11	42.01	0	0.83	42.84
	Is. 13	63.27	0	0.45	63.72	50.40	0	0.31	50.71	37.81	0	0.23	38.04
	Is. 14	90.20	0	5.73	95.70	70.74	0	3.82	74.56	53.05	0	2.87	55.92
	Is. 15	84.17	0	2.64	86.68	63.71	0	1.76	65.47	47.78	0	1.32	49.10
	Is. 16	42.32	0	22.34	62.70	29.86	0	20.31	49.79	22.39	0	18.35	40.74
Area 2	Is. 17	16.82	25.57	38.11	77.38	12.09	21.94	31.99	65.58	9.12	17.32	27.72	54.16
	Is. 18	57.46	7.00	34.50	91.90	50.15	5.44	28.29	82.48	40.86	4.18	24.36	69.40
	Is. 19	61.36	3.83	33.42	93.62	52.37	2.94	24.42	79.03	41.62	2.24	19.31	63.17
	Is. 20	41.68	1.12	21.82	62.35	34.71	0.89	17.89	53.08	27.62	0.68	15.60	43.90
	Is. 21	73.95	7.59	18.81	93.71	64.52	5.95	13.46	82.50	53.01	4.64	10.41	68.06
	Is. 22	59.70	2.82	34.44	90.85	49.25	2.09	24.03	74.72	38.63	1.57	18.40	58.59
	Is. 23	75.21	5.20	6.69	83.75	61.42	3.89	4.46	69.40	47.23	2.95	3.34	53.52
	Is. 24	77.90	0	16.88	92.65	69.44	0	12.75	82.01	56.54	0	10.37	66.91
	Is. 25	74.54	0	11.60	82.10	54.88	0	7.96	62.80	41.18	0	6.00	47.17
	Is. 26	38.57	0	34.58	70.32	26.35	0	27.02	53.33	19.76	0	22.20	41.96

Area 1:Miaodao Archipelago (MDA); Area 2: Dongtou Archipelago (DTA). Abbreviations for OR are the same as for Figure 4.

which Is. 2 and Is. 3 had the OR2 higher than 10%. On the remaining inhabited islands (Is. 6, Is. 7, and Is. 10) and all the uninhabited islands, the OR2 was zero. The highest OR3 was achieved by Is. 1, and Is. 5, Is. 16, and Is. 4 also had high OR3. Is. 16 was the only one uninhabited island that has high OR3 because it has been exploited as the port for connecting its adjacent inhabited island (Is. 4) with the other islands and the mainland. The remaining uninhabited islands showed low values of OR3. As for the OR, all the islands showed values higher than 60%, and six and twelve islands had OR values higher than 90% and 80%, respectively. Is. 3, Is. 14, and Is. 9 achieved the highest three OR values, whereas Is. 11, Is. 16, and Is. 13 showed the lowest three ones. In Scenarios B and C, the OR values of all the islands decreased compared with those in Scenario A, and variation characteristics across islands were similar in the three scenarios.

In DTA, the OR1 values on different islands were generally lower than those in MDA, and the sandy island (i.e., Is. 17) obtained the lowest one in all of the three scenarios. By contrast, Is. 17 achieved the highest values of OR2 and OR3 in different scenarios. The OR2 was generally low on all the rocky islands and the OR2 values of Is. 24, Is. 25, and Is. 26 were zero. The OR3 values on different islands within DTA was generally higher than those within MDA, and Is. 17, Is. 18, Is. 19, Is. 22, and Is. 26 showed distinctly higher OR3 values than the remaining islands within DTA.

The occupancy rates of carrying capacity on different types of islands across the two archipelagos are presented in Figure 6. For all islands across the two archipelagos, MDA showed higher OR1 but lower OR2 and OR3 than DTA. Within each of MDA and DTA, the inhabited islands had lower OR1 yet much higher OR2 and OR3 than the uninhabited islands. Within DTA, the sandy island exhibited lower OR1 but higher OR2 and OR3 than the rocky islands. Across different types of islands, the uninhabited islands in MDA achieved the highest OR1, while the sandy island in DTA obtained the highest OR2 and OR3. The OR for all islands was higher in Scenarios A and B but lower in Scenario C in MDA than in DTA. Besides, the OR was higher on the inhabited islands than on the uninhabited islands and on the rocky islands than on the sandy island within the two archipelagos in the three scenarios. Among different types of islands, the inhabited islands in MDA achieved the highest OR in Scenarios A and the rocky islands in DTA obtained the highest one in Scenarios B and C.

3.2.2. Vacancy rates

The vacancy rates of carrying capacity on different islands are shown in Table 2.

In MDA, the VR0 on most of the inhabited islands was lower than 10%, yet Is. 6, Is. 7, and Is. 10 showed VR0 values higher than 10%. The VR0 values varied greatly across different uninhabited islands and were zero and 36.97% on Is. 14 and Is. 16, respectively. The VR1 was distinctly higher on the uninhabited islands than on the inhabited island, whereas the VR2 and VR3 exhibited the opposite characteristics. Is. 12, Is. 2, and Is. 5 achieved the highest VR1, VR2, and VR3, respectively. From Scenarios A to C, the increase was more distinct in VR1 and VR3 than in VR2. As for the VR, it increased distinctly on each island from Scenarios A to C, and Is. 11, Is. 13, and Is. 16 obtained the highest three values.

In DTA, three islands had VR0 values higher than 10%, that is, Is. 17, Is. 20, and Is. 23, of which Is. 20 achieved the highest value of 33.46%, indicating the substantial spaces for future development. The values of VR1, VR2, and VR3 across islands exhibited similar characteristics to those in MDA. Is. 26 and Is. 17 had the highest values of VR1 and VR2 in all the three scenarios, respectively. Is. 17 obtained the highest VR3 in Scenario A, and Is. 22 achieved the highest VR3 in Scenarios B and C. For

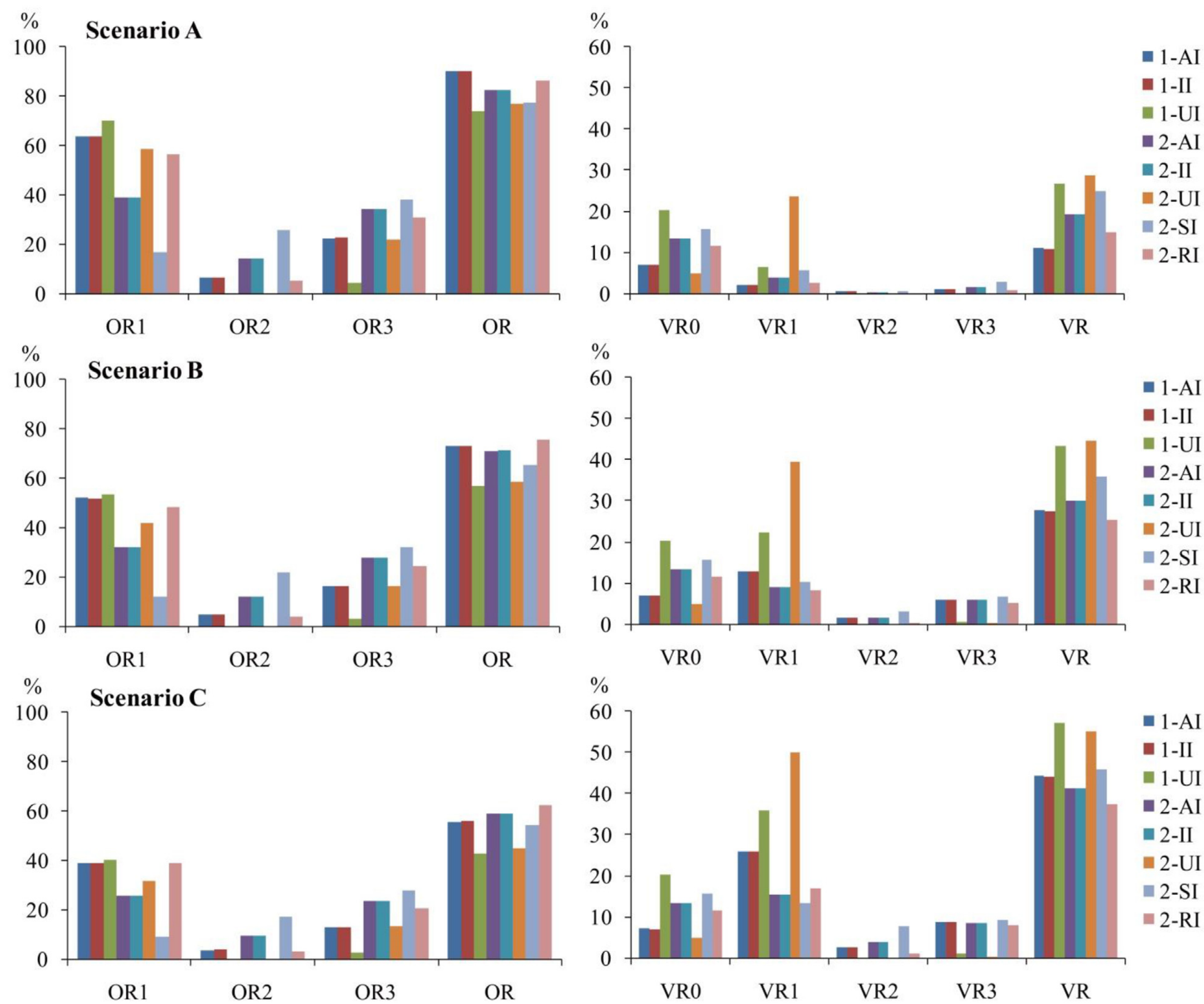

Figure 6. Occupancy and vacancy rates of the carrying capacity on different types of islands across the two archipelagos: Abbreviations for OR and VR are the same as for Figure 4 and Figure 5. The 1-*x* denotes Area 1, i.e., Miaodao Archipelago (MDA); the 2-*x* denotes Area 2, i.e., Dongtou Archipelago (DTA). AI: all islands; II: inhabited island; UI: uninhabited island; SI: sandy island; RI: rocky island.

the VR, Is. 18, Is. 19, Is. 21, and Is. 24 showed distinctly lower values than the remaining islands.

The vacancy rates of carrying capacity on different types of islands across the two archipelagos are presented in Figure 6. The VR0 did not involve the different scenarios. For all islands across the two archipelagos, the VRO was lower on MDA than on DTA. Within MDA, the inhabited islands had lower VR0 than the uninhabited islands, and the opposite situation was observed within DTA. Besides, the VR0 of the sandy island was higher than that of the rocky islands in DTA. The VR1 of all islands in MDA was lower in Scenario A and higher in Scenarios B and C than that in DTA. The uninhabited islands showed much higher VR1 than the inhabited islands in the two archipelagos, while the difference between the sandy and rocky islands was not distinct. The VR2 was generally low in both of the two archipelagos in the three scenarios, yet only the sandy island achieved a relatively high VR2 in Scenario C. The VR3 values of all islands across the two archipelagos were similar to each other, and the inhabited islands had much higher VR3 than the uninhabited islands. Within DTA, the sandy island exhibited slightly higher VR3 than the rocky islands. The VR distinctly increased from Scenarios A to C. All islands in MDA showed lower VR in Scenarios A and B and higher VR in Scenario C than all islands in DTA. Besides, the uninhabited islands had higher VR than the inhabited islands, and the sandy island obtained higher VR than the rocky islands.

4. Discussion

4.1. Influencing factors of the island carrying capacity at different scales

Distinct differences in regional natural conditions and human activities controlled the spatial variance across the two archipelagos. Overall, MDA showed higher OR1 yet lower OR2 and OR3 compared with DTA. As illustrated earlier, all the islands in MDA are spatially isolated with the mainland, which hinders the exchanges of materials and energies and increases the difficulty for human visits and inhabitation (Chi et al., 2017). By contrast, the islands in DTA are connected with the mainland and each other through a series of bridges, which considerably improved the external traffic conditions, decreased the isolation of the islands, and facilitated different types of human activities (Chi et al., 2020b). The population per km^2 in DTA (1007.83 ind.) was also higher than that in MDA (690.18 ind.). In consideration that DTA comprises a large amount of sea reclamation areas, which account for more than 35% of the total area and are partly unoccupied, the factual population density of DTA may be distinctly higher than that of MDA. It indicated that mainland-connected islands attracted more humans than spatially isolated islands. Correspondingly, the development of DT3 was more intensive in DTA than in MDA. In terms of the island composition, all islands in MDA are rocky islands, while sandy and rocky islands coexist in

Table 2. Vacancy rates of the carrying capacity on different islands in different scenarios.

Island		VR0	Scenario A				Scenario B				Scenario C			
			VR1	VR2	VR3	VR	VR1	VR2	VR3	VR	VR1	VR2	VR3	VR
Area 1	Is. 1	6.29	2.78	0.71	1.48	11.27	11.82	2.04	7.61	27.76	21.42	3.30	11.33	42.34
	Is. 2	7.54	2.91	1.32	0.74	12.51	13.25	3.96	4.79	29.54	25.67	6.07	7.10	46.38
	Is. 3	2.84	1.63	0.45	0.07	4.99	12.97	1.92	2.25	19.98	28.83	4.04	3.49	39.20
	Is. 4	5.83	1.13	0.04	0.13	7.13	13.28	0.22	5.33	24.66	28.13	0.48	8.21	42.65
	Is. 5	6.43	2.29	0.12	5.04	13.88	13.32	0.22	12.11	32.09	26.21	0.28	15.83	48.75
	Is. 6	18.12	1.26	0	0	19.39	11.11	0	5.06	34.30	24.48	0	7.79	50.39
	Is. 7	15.61	1.36	0	0	16.98	11.77	0	4.85	32.24	25.25	0	7.45	48.31
	Is. 8	3.57	2.89	0.69	0.14	7.29	17.76	1.62	3.02	25.97	33.42	2.38	4.64	44.00
	Is. 9	2.97	2.82	0.69	0	6.47	15.99	1.35	3.41	23.72	30.92	2.30	5.30	41.49
	Is. 10	12.79	1.24	0	0	14.04	12.68	0	3.33	28.81	28.45	0	5.07	46.31
	Is. 11	32.92	5.68	0	0	38.60	18.53	0	0.44	51.88	30.34	0	0.65	63.91
	Is. 12	12.19	10.25	0	0	22.44	30.14	0	0.55	42.89	44.14	0	0.83	57.16
	Is. 13	31.70	5.24	0	0	36.94	17.55	0	0.08	49.33	30.14	0	0.12	61.96
	Is. 14	0	4.33	0	0	4.33	23.56	0	1.88	25.44	41.24	0	2.84	44.08
	Is. 15	5.47	8.16	0	0	13.62	28.19	0	0.88	34.53	44.11	0	1.32	50.90
	Is. 16	36.97	3.54	0	0	40.51	14.83	0	0	51.80	22.29	0	0	59.26
Area 2	Is. 17	15.73	5.75	0.66	2.78	24.92	10.27	3.18	6.73	35.91	13.24	7.63	9.25	45.84
	Is. 18	6.82	1.41	0.06	1.05	9.35	6.04	0.53	5.21	18.60	14.49	1.43	7.85	30.60
	Is. 19	5.22	2.66	0.06	0.38	8.31	9.48	0.34	7.03	22.07	19.80	0.93	10.88	36.83
	Is. 20	33.46	4.80	0.02	0.48	38.76	10.79	0.07	3.26	47.57	17.69	0.22	4.73	56.10
	Is. 21	3.69	3.52	0.01	0.09	7.31	10.26	0.15	4.08	18.18	20.86	0.79	6.60	31.94
	Is. 22	5.73	4.38	0.01	1.03	11.15	11.01	0.17	9.61	26.51	20.87	0.55	14.26	41.41
	Is. 23	10.67	7.05	0.02	0.01	17.76	18.71	0.20	1.50	31.09	32.61	0.90	2.30	46.48
	Is. 24	3.09	5.03	0	0.05	8.18	12.45	0	2.95	18.49	25.26	0	4.74	33.09
	Is. 25	2.84	16.78	0	0.36	19.98	35.74	0	0.48	39.06	49.45	0	0.54	52.83
	Is. 26	7.31	32.26	0	0	39.57	44.14	0	0	51.45	50.73	0	0	58.04

Area 1:Miaodao Archipelago (MDA); Area 2: Dongtou Archipelago (DTA). Abbreviations for VR are the same as for Figure 5.

DTA. The difference in terrain condition across rocky and sandy islands rendered the sandy island more suitable for DT2 than the rocky islands (Huang et al., 2008; Chi et al., 2020b). The DT1, which was composed of natural community and artificial plantations in the study area, do not ask much for the traffic and terrain conditions and are susceptible to the occupation of DT2 and DT3. The higher OR2 and OR3 caused the lower OR1 in DTA in comparison with MDA. The results of VR across the two archipelagos also showed differences. Sea reclamation activities were widely conducted in DTA in recent decades, and parts of them are vacant and to be constructed. MDA also had sea reclamation activities, which are mainly on Is. 1 in a relatively small area. Thus, the VR0 was distinctly higher in DTA than in MDA. The VR1, VR2, and VR3 across the two archipelagos exhibited different situations in different scenarios. The VR1 of MDA was lower in Scenario A and higher in Scenarios B and C than that of DTA. The quality of DT1 in MDA was generally close to the ordinary standard, while certain areas in Is. 17 in DTA had bad quality of DT1 because they were covered by naturally formed wetland vegetation that is in an initial stage. However, the remaining islands in DTA generally exhibited higher quality of DT1 owing to the better climate conditions compared with MDA. Thus, the VR1 of MDA became higher than that of DTA when using the intermediate and high standards. The VR2 was generally low except the sandy island, particularly in Scenario C. It revealed that the rocky islands in these two archipelagos were not suitable for DT2 because of undulating terrains and small areas. However, this finding could not be applicable to all the rocky islands. Some rocky islands (e.g., Weizhou Island in China) were also occupied by large scale of agricultural activities (Zhu, 2009). Large areas, flat terrains, good climate conditions, fertile lands, and sufficient demands determine the island suitability for DT2, and how to accurately judge the suitability remains to be verified using more islands in further studies. The VR3 in the two archipelagos both distinctly increased from Scenarios A to C, indicating that the current quality of DT3 was not high and great potentials of future developments existed on the islands. As for the VR, it increased more distinctly in MDA than in DTA from Scenarios A to C, revealing that MDA has less and more potential of quality improvement than DTA when using low and high standards, respectively.

Different types of islands (i.e., inhabited and uninhabited islands; sandy and rocky islands) showed different carrying capacities. The uninhabited islands are characterized by small areas or distinct isolation and are not suitable for human inhabitation (Nam et al., 2010; Chi et al., 2019a). Thus, the developments of DT2 and DT3 were poorer than the inhabited islands, while the DT1 showed the contrasting characteristics. The uninhabited islands showed higher OR1 and VR1 than those of the inhabited islands. It indicated that the quantity of DT1 on the uninhabited islands was high, yet the quality was relatively poor and needed to be improved. The poor quality could be attributed to the harsh natural conditions and the high sensitivity to disturbances (Chi et al., 2017, 2019a). Distinctly higher occupancy and vacancy rates for DT2 were observed on the sandy island (i.e., Is. 17) than on the rocky islands in DTA, which has been illustrated earlier. The agricultural activities were mainly in the western part of the sandy island, while the eastern part was newly formed and served as areas for DT3 with high quality (Chi et al., 2020b). Thus, the two types, that is, DT2 and DT3, coexisted on the sandy island, and this island showed great potentials of quantity and quality for their future developments.

Across different islands, the relationships of carrying indices (CI1, CI2, CI3, and CI) with IA and DTM were analyzed using scatter diagrams (Fig. S2 in the Supplementary Materials). The IA and DTM are two basic parameters of an island and determine the maximum of the island carrying capacity and the isolation degree from the external world, respectively (Weigelt et al., 2016; Whittaker et al., 2017; Chi et al., 2018, 2020b). The connection of DTA with the mainland by bridges has considerably decreased the archipelago's isolation and made the DTM ineffective in representing the isolation. Thus, the relationships with DTM were only analyzed in MDA. Moreover, in consideration of the great difference in the carrying capacity between the sandy and rocky islands, the scatter diagrams for all and rocky islands were respectively generated in DTA. The coefficient of determination (R^2) of linear regression equation of the trend line was used to help judge the influences of IA and DTM. The IA had distinct relationships with CI2, CI3, and CI in MDA, with CI1, CI2, and CI3 in all islands of DTA, and with CI3 in rocky islands of DTA; among these indices in specific areas, only CI1 decreased and the remaining indices increased with the increase in the IA (Fig. S2 in the Supplementary Materials). No distinct relationships were observed between CI1 and IA in MDA and rocky islands of DTA. The distinct negative relationship between CI1 and IA in all islands of DTA could be attributed to the difference in CI1 between the rocky and sandy islands, i.e., the sandy island had a very large area and a very low CI1, thereby resulting in a high R^2. Thus, the IA was not a controlling factor of the DT1. The developments of DT2 and DT3 were influenced by the IA because a higher IA indicates a larger space and thus a higher possibility and potential for developing the two types. The relationship between IA and CI2 was distinct in MDA and all islands of DTA, yet not distinct in rocky islands of DTA. It indicated that the IA may generate influences on the DT2, yet to different degrees in different areas. By contrast, the distinct relationship between IA and CI3 could be observed in different areas, thereby revealing the important role of IA in influencing the DT3. Large islands generally contained higher intensities of human activities, which was in accordance with previous studies (Chi et al., 2018, 2020b). As for the DTM, no distinct relationships were observed with all the carrying indices, indicating that this parameter was ineffective in determining the island carrying capacity in this study area.

4.2. Dependencies of island developments on the external world

The carrying capacity of different development types could provide a basis for judging the dependencies of island developments on external world by using ratios among different carrying indices (Table 3). The "(CI2+CI3)/CI1" was used to judge the island construction intensity by comparing the sum of carrying indices of DT2 and DT3 with that of DT1, and the island construction intensity represents the consumptions of materials and energies and thus the dependency of island constructions on the external world. A higher ratio value indicates a higher dependency (Table 3). Overall, all islands in MDA shower much lower ratio value than DTA. From perspectives of the inhabited and uninhabited islands, DTA also exhibited higher ratio values than MDA. The ratio values of specific islands in MDA were generally lower than those in DTA. In MDA, only Is. 1 and Is. 16 showed ratio values higher than 0.5. Is. 1 is the location of the government of Changdao County and Is. 16 is exploited as a port. The remaining islands (Is. 2–Is. 15) all had ratio values lower than 0.5. In DTA, Is. 17 and Is. 26 showed ratio values higher than 1. Is. 17 is the sandy island and has been used for DT2 and DT3 in different parts within the island. Is. 26 is an uninhabited island and a considerable part of this island has been used to support the bridges that connect the islands in the archipelago. Is. 18–Is. 20 and Is. 22, which are important areas for human inhabitation, exhibited ratio values higher than 0.5. Therefore, the island construction intensity and the dependency of island constructions on the external world in DTA were higher than those in MDA. The bridges can provide much more transportation capacity than the ships because the ship transportations are always limited by the weather and frequency. The materials and energies consumed by island constructions are large, which made a high requirement for the traffic condition and rendered the mainland-connected islands high suitability for these constructions than the spatially isolated islands.

Table 3. Ratios among different carrying indices on different islands.

Area 1: Miaodao Archipelago (MDA)			Area 2: Dongtou Archipelago (DTA)		
Island	(CI2+CI3)/CI1	CI2/CI3	Island	(CI2+CI3)/CI1	CI2/CI3
Is. 1	0.99	0.18	Is. 17	4.94	0.62
Is. 2	0.43	0.77	Is. 18	0.70	0.17
Is. 3	0.27	1.73	Is. 19	0.52	0.12
Is. 4	0.27	0.09	Is. 20	0.59	0.04
Is. 5	0.31	0.01	Is. 21	0.28	0.45
Is. 6	0.23	0.00	Is. 22	0.52	0.09
Is. 7	0.27	0.00	Is. 23	0.13	0.88
Is. 8	0.19	0.43	Is. 24	0.18	0.00
Is. 9	0.30	0.68	Is. 25	0.15	0.00
Is. 10	0.13	0.00	Is. 26	1.12	0.00
Is. 11	0.02	0.00	AI	1.28	0.39
Is. 12	0.02	0.00	II	1.29	0.39
Is. 13	0.01	0.00	UI	0.42	0.00
Is. 14	0.05	0.00	RI	0.60	0.14
Is. 15	0.03	0.00	SI	4.94	0.62
Is. 16	0.82	0.00			
AI	0.43	0.29			
II	0.43	0.29			
UI	0.07	0.00			

AI: all islands; II: inhabited island; UI: uninhabited island; SI: sandy island; RI: rocky island. Abbreviations for CI1, CI2, and CI3 are the same as for Figure 3.

The ratio "CI2/CI3" was used to measure the food dependency of island inhabitants on the external world. Seafood abounds in the surrounding sea areas of islands. However, the other food types, such as staple food, vegetable, and meat, are always rare due to the limited area for developing all kinds of agricultural activities, particularly the rocky islands. Thus, the food needed by island inhabitants is always dependent on the external world. In the consideration that no agricultural activities were observed on many islands in this study (i.e., CI2 = 0), the ratio "CI2/CI3" was adopted, and a lower ratio indicates a higher food dependency on the external world (Table 3). All and inhabited islands of DTA exhibited higher ratio values than those of MDA, which was mainly caused by the existence of the sandy island (Is. 17) in DTA. Though the ratio value of Is. 17 was not high because the CI2 and CI3 were both high on this island, the areas of DT2 were greatly higher than those on the other islands. Conversely, the ratio value of the rocky islands in DTA was lower than that in MDA because some large islands (Is. 2 and Is. 3) in MDA showed relatively high ratio values. The development of DT2 on the sandy island could compensate for the low CI2 on the rocky islands in DTA. The ratio values of several islands were zero because no agricultural activities exited on these islands. This circumstance could be observed in both of MDA and DTA. It indicated that certain food types needed by these islands were totally dependent on the external world via ships or bridges, and both of ships and bridges could meet the demands for the food transportation from the mainland to the islands. That is to say, the difference in the traffic conditions between the two archipelagos did not distinctly influence the food dependency of the archipelago on the external world. However, the traffic conditions will be put to the test with the increase in the island population and food dependency.

4.3. Suggestions to improve the island carrying capacity

It is a perennial scientific question that if there is an upper limit of island carrying capacity for simultaneously supporting the human activities and maintaining the ecosystem (Guan et al., 2016; Yang et al., 2017; Chi et al., 2017). Due to enormous ecological functions and distinct sensitivity to disturbances, an upper limit of carrying capacity was always set to control the island human activities, which mainly refer to DT2 and DT3 in this study. For instance, a threshold of 40% was ever used as the upper limit of island carrying capacity. If the exploitation areas (e.g., buildings, roads, docks, farmland, and so on) on an island occupied more than 40% of the island total area, then the island carrying capacity was over occupied, and the island ecosystem was considered threatened (Yang et al., 2017). However, human activities on many islands actually exceed the threshold and still develop in balance, such as Chongming Island and Xiamen Island, which are most occupied by DT2 and DT3, respectively (Lin et al., 2016; Chi et al., 2020d). Whether a constant upper limit of island carrying capacity is needed should be reconsidered. In this study, Is.1, Is. 17, and Is. 18 also exceeded the aforementioned threshold using the sum of OR2 and OR3 in Scenario A, yet it is inappropriate to consider these islands over occupied, because certain vacancies still exited on the islands for future developments. Therefore, the upper limit of island carrying capacity cannot be generalized due to the great differences in the development modes of different islands. We proposed the following three suggestions: First, the upper limit of island carrying capacity should not be constant and different upper limits should be assigned to different islands through comprehensively evaluating the development types; second, besides the total control through the assignment of upper limit, the spatial configuration of different development types should be reasonably conducted through island spatial planning; third, the quality promotion of development types should be focused on to improve the island carrying capacity.

Specific suggestions were also proposed for the two archipelagos from perspectives of quantity and quality of the development types. (1) Quantity: The quantity optimization of different development types is an important solution to improve the island carrying capacity. The current priorities of different development types are different, that is, DT2 and DT3 generally have higher priorities than DT1. In both of the two archipelagos, areas that are suitable for DT2 and DT3 have been exploited for these two development types, and the remaining areas that are not suitable for the aforementioned two types were for DT1. Moreover, sea reclamation activities were conducted to supplement the lands mainly for DT3, particularly in DTA. However, the priority of construction activities inevitably occupied the DT1 and thus damaged the island ecosystem (Kurniawan et al., 2016; Chi et al., 2020b; Ma et al., 2020). Thus, the total amount and spatial configuration of the quantities of different development types should be scientifically assigned on different islands. On the inhabited islands that carry intensive human activities in the two archipelagos, such as Is. 1, Is. 16, and Is. 17, the priorities of development types should be determined based on the development suitability. In the reclamation areas within the islands, the DT3 should be given priority to adequately utilize the space resources of reclamation areas (Chi et al., 2020b). On the uninhabited islands, as well as other inhabited islands that show important ecological functions and high sensitivity, DT1 should be the preferred one, while the other two types should be strictly limited and only be permitted when the necessity and suitability are both high. It can be found that the suitability of different development types serves as a basis for the assignment of total amount and spatial configuration (Chi et al., 2022). (2) Quality: The quality promotion should be another major solution to improve the island carrying capacity. To some extent, the quality promotion has more feasibility than the quantity optimization because the former do not involve the conversions among different development types. For the DT1, the quality was generally higher in DTA than in MDA, which was mainly driven by the difference in climate conditions. Besides, forest pests (i.e., *Bursaphelenchus xylophilus*) occurred and deteriorated the plantation health in MDA in recent years (Chi et al., 2016). The forests constitute the main body of DT1 and are mostly plantations, and optimum species selection, community structure optimization, and pest and fire control should be conducted to improve the quality. The uninhabited islands possessed much higher potentials of quality promotion than the inhabited islands in both of the two archipelagos, and should be paid more attention. The wetland vegetation on the sandy island in DTA generally exhibited low quality. Moderate manual interventions can be conducted, including planting of particular wetland species and prevention of alien species invasion (e.g., *Spartina alterniflora*). The DT2 covered a small part on the rocky islands, but was the main development type in the western part of the sandy island and showed considerable potential for future development. Reasonable tillage management practice in all the processes should be conducted (Wright and Hons, 2005; Chi et al., 2020d). As for the DT3, the sub-types with intermediate qualities occupied the most, thus the VR3 were close to zero in Scenario A and distinctly increased from Scenarios A to C. The sub-types with high qualities are encouraged. The docks and roads indicate the external and internal traffic conditions of the islands, determine the dependencies of island inhabitants on external world, and serve as the basis for the island development. They should be regularly maintained and continuously enhanced. The high-rise buildings can provide much more carrying capacities than low-rise buildings while consume more materials and energies in the processes of constructions (Chi et al., 2020b). They should be encouraged on certain islands that have good traffic conditions and large demand for accommodation (e.g., Is. 1, Is, 17, and Is. 18). Different kinds of industries are also encouraged and they should be conducted by integrating the feature and advantages of the islands, such as island tourism and sea product processing (Moon and Han, 2018; Kurniawan et al., 2019). Meanwhile, negative influences from the industries should be cautioned and minimized through effective measures.

5. Conclusions

The island carrying capacities for the three development types were evaluated based on the quantity and quality of each type. CIs were established to quantify and exhibit the spatial distributions of island carrying capacity, thereby solving the first scientific question of the study. Three scenarios, that is, Scenario A, Scenario B, and Scenario C, were assumed to measure the occupancy and vacancy rates of island carrying capacity, and the metrics we adopted accurately reveal the occupancy and vacancy rates in different scenarios, thereby corresponding to the second scientific question. The main influencing factors of spatial heterogeneities of island carrying capacity across the two archipelagos, across different types of islands within the same archipelago, and across different islands within the same archipelago and island type were identified, and the results answered the third scientific question. Then, the dependency of island constructions and food dependency of island inhabitants on the external world were judged based on the ratios of different development types, thereby corresponding to the fourth scientific question. Suggestions about the upper limit of island carrying capacity were proposed and the specific suggestions for the three development types were made from perspectives of quantity and quality, thereby solving the fifth scientific question in the study.

The results in MDA and DTA revealed that the occupancy and vacancy rates of island carrying capacity presented clear spatial heterogeneities at different scales. Across the two archipelagos, MDA showed higher occupancy rate for DT1 yet lower occupancy rates for DT2 and DT3 compared with DTA. Climate conditions, island composition, and spatial connections with the mainland controlled the spatial variance at this scale. The quantitative vacancy rate was distinctly higher in DTA than in MDA because of the large scale of unused sea reclamation areas. The qualitative vacancy rates for the three development types exhibited different situations in different scenarios. Within each of the two archipelagos, developments of DT2 and DT3 on the inhabited islands were much better than that on the uninhabited islands, while DT1 showed the contrasting characteristics. The sandy island showed distinctly higher occupancy and vacancy rates for DT2 than the rocky islands. Across different islands, IA played an important role in influencing the DT2 and DT3, and the latter one received more influences. Their developments increased with the increase in the IA. The dependency of island constructions on the external world in DTA was higher than that in MDA. The bridges in DTA can provide much more transportation capacity than the ships in MDA. Meanwhile, the difference in traffic conditions between the two archipelagos did not distinctly influence the food dependency of the archipelago on the external world. Practical suggestions were proposed to improve the island carrying capacity. In terms of the quantity, total amount and spatial configuration of different development types should be scientifically assigned on different islands. The quality promotion should be another major solution and a more feasible way to improve the island carrying capacity.

Declarations

Author contribution statement

Yuan Chi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Dahai Liu: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Minxia Zhang: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

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