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Research Paper

Dramatic mariculture expansion and associated driving factors in Southeastern China

Jing Wu[a], Tomás Marín Del Valle[a], Mary Ruckelshaus[b], Guojin He[c], Yongyong Fu[a], Jinsong Deng[a], Jianguo Liu[d], Wu Yang[a,*]

[a] *Center for Intelligent Ecology and Sustainability, College of Environmental and Resource Sciences, Zhejiang University, 866 Yuhangtang Rd., Hangzhou 310058, China*
[b] *Natural Capital Project, School of Environmental and Forest Sciences, University of Washington, 3715 West Stevens Way NE, Seattle, WA 98195, USA*
[c] *Aerospace Information Research Institute, Chinese Academy of Sciences, 9 South Dengzhuang Rd., Beijing 100094, China*
[d] *Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48823, USA*

HIGHLIGHTS

- We map the spatiotemporal dynamics of mariculture in Southeastern China.
- We find a 709% increase in total mariculture area between 2003 and 2016.
- Animal and seaweed mariculture went through different rates and timing of expansion.
- Sustainable mariculture requires systematical spatial planning and regulations.

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ABSTRACT

Mariculture has a profound potential to meet the escalating demand for food. However, so far the understandings of spatiotemporal dynamics of mariculture and indicators of underlying mechanisms are altogether missing in the existing literature. Using high-resolution satellite images, here we provide a first ever detailed analysis to map the spatiotemporal dynamics and explore associated driving factors of mariculture expansion in Southeastern China. We find a 709% increase in total mariculture area between 2003 and 2016, with 836% increase of seaweed mariculture and 264% growth of animal mariculture, respectively. In addition, animal and seaweed mariculture went through different rates and timing of expansion. Animal mariculture area increased steadily in the two periods, exhibiting an annual growth rate of 8.2% (0.71 km^2/year between 2003 and 2010) and 11.2% (1.54 km^2/year between 2010 and 2016), respectively, while seaweed mariculture area experienced a rapid onset followed by a steep decline in the rate of expansion with an annual growth rate of 95.2% (28.82 km^2/year between 2003 and 2010) and 1.5% (3.52 km^2/year between 2010 and 2016), respectively. We find both seaweed and animal mariculture expand from the coastline out towards the ocean, surround the islands from the inside to the outside, infill the inner harbor dispersedly, and tend to aggregate away from human disturbance. Sustaining the provision of ecosystem services from coastal and marine ecosystems will require comprehensive monitoring and assessment, systematic spatial planning of mariculture and other uses, regulations of mariculture behaviors via environmental awareness education, scientific training of farm design, and management of feed and energy use in China and beyond.

1. Introduction

According to the Sustainable Development Goals (SDGs), one of the biggest global challenges for human societies is how to sustainably meet the demands of 9.7 billion people in 2030 (UN DESA, 2019) for food and livelihoods, while facing the impacts of climate change and environmental degradation (Duarte et al., 2009; FAO, 2018). With the fastest growth among major food production sectors, aquaculture is increasingly considered as a promising solution to demographic development through the provision of food and nutrition, employment and

* Corresponding author.
E-mail address: wyang@zju.edu.cn (W. Yang).

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livelihoods, and earnings from trade of fish and fish products (Costello, Cao, Gelcich, Cisneros, Free, & Froehlich, 2019; Duarte et al., 2009; Godfray et al., 2010). Globally, the share of aquaculture in fish production increased from 27% in 2000 to 46% in 2018 (FAO, 2018, 2020).

Although inland freshwater aquaculture is more common, its development is limited by scarce land and insufficient freshwater supply (Holmer, 2010). In contrast, worldwide marine and coastal aquaculture has no such limitations and has been growing rapidly in the past two decades, with a total yield increase from 14.2 million tons in 2000 to 30.8 million tons in 2018 (Here official statistics only consider animal yield [i.e., the yield of finfish and invertebrates], which accounted for 38% of total global aquaculture yield in 2018) (FAO, 2020). China has produced more farmed aquatic food than the total of the rest of the world since 1991 and has become the world's largest exporter of fish and fish products since 2002 (FAO, 2018). In 2018, China alone produced 64.6 million tons of aquatic products, of which aquaculture accounted for 77% (MARA, National Fisheries Technology Extension Center, & China Society of Fisheries, 2019); and Chinese animal mariculture yield (18.0 million tons) and seaweed mariculture yield (18.5 million tons, live weight) accounted for 58% and 57% of global mariculture yield, respectively (FAO, 2020).

Accompanying the fast growth of mariculture production and the associated growth of user conflicts around mariculture is the unprecedented modification of the seascape. Previous research has documented associated environmental impacts (e.g., disease spread, water pollution, coastal wetland loss) (Inniss et al., 2016; Smith et al., 2010). For instance, Chile, one of the most highly productive countries in mariculture and also the second largest global producer of farmed salmon, suffered a crisis in 2008 from the spread of the Infectious Salmon Anemia virus (Iizuka & Zanlungo, 2016), followed in 2016 by persistent harmful algal blooms in estuarine and marine ecosystems in southern regions (Montes, Rojas, Artacho, Tello, & Quiñones, 2018). In North Sumatra, aquaculture accounted for almost 50% of the mangrove deforestation during the 1990 s and 2010 s (Basyuni, Fitri, & Harahap, 2018; Basyuni & Sulistiyono, 2018). In Southeast Asia, around 15% to 49% of the shrimp farms were established at the expense of mangrove forest decline (Bui, Maier, & Austin, 2014; Muttitanon & Tripathi, 2005). In coastal Sri Lanka, the conversion of mangrove habitat to shrimp farms has led to 76% loss of the total carbon sequestration caused by land use changes (Bournazel, Kumara, Jayatissa, Viergever, Morel, & Huxham, 2015).

With the systematical improvement during the past three decades, high-resolution images from spaceborne sensors have provided a great opportunity for significant progress of geospatial data collection. High-resolution images also form a robust basis for mapping mariculture types and dynamics comparing to previous remotely-sensed images with coarse spatial and limited temporal resolution (Aasen, Honkavaara, Lucieer, & Zarco-Tejada, 2018; Moser, Serpico, & Benediktsson, 2013). Earlier work has tried to extract mariculture areas from satellites images (e.g., Rapideye, Worldview-2, GF-1/2) (Fu, Ye, et al., 2019b), using various methods such as spatial structure enhanced analysis (Fan, Chu, Geng, & Zhang, 2015; Lu, Li, Du, Wang, & Liu, 2015), object-based image analysis (Wang, Cui, Wang, Ming, & Lv, 2017; Zheng, Wu, Wang, & Chen, 2018), and deep convolutional neural networks (Cui et al., 2019; Shi, Xu, Zou, & Shi, 2018). On the one hand, currently most research efforts of mariculture mapping come from China, and focus on seaweed mariculture or floating rafts at small local scales, while the extraction of animal mariculture farms are largely missing. One the other hand, very few have attempted to explore the spatiotemporal dynamics of mariculture and their driving forces at regional scale or beyond.

To improve marine spatial planning, sustainably manage mariculture, and minimize negative impacts on marine ecosystems, it is essential to systematically understand the spatiotemporal dynamics of mariculture development and the underlying driving mechanisms. Here, we conduct a comprehensive assessment of the mariculture region in a representative coastal city in Southeastern China. We aim to: (1) reveal the spatiotemporal dynamics of mariculture using high-resolution satellite imagery, and (2) identify driving factors that were associated with different types of mariculture expansion. Our study is one of the first to comprehensively assess the dramatic modifications of seascape during a long-term period and precisely fills the gap of research on sea use and sea cover change. High-resolution satellite imagery substantially improves the detection and extraction of different types of sea use and sea cover, the construction of potential driving factors, and the analysis of driving mechanisms. Our analyses provide a sound foundation for marine spatial planning and sustainable mariculture development to fulfill SDGs.

2. Methods

2.1. Study area

Ningde City is located in Fujian Province, Southeastern China, and is the core area of the 21st Century Maritime Silk Road of China's Belt and Road Initiative (Belt and Road Portal, 2017) (Fig. 1a). Ningde is selected as one of China's National Marine Ranching Demonstration Zones from 2017 to 2025 and its "Blue Economy" is dominated by the production and processing of seafoods (MARA, 2017a). The gross output value of mariculture in Ningde reached 1.21 billion USD in 2016. The Ningde mariculture industry provided direct livelihoods to approximately 50,000 people, most of whom conducting small-scale aquaculture at a household level (Wu, Yang, & Yang, 2021). Ningde accounted for 80% and 66% of total cage mariculture area in Fujian and China respectively, and produced 71% of the national yield of large yellow croaker (*Larimichthys crocea*) in 2016 (MARA, National Fisheries Technology Extension Center, & China Society of Fisheries, 2019; Ningde Municipal Statstical Bureau, 2019).

To assess spatiotemporal dynamics of mariculture in Ningde, we define seaweed mariculture areas (SMAs) as areas that farm unfed plant species (e.g., porphyra [*Porphyra* spp., namely nori), laminaria [*Laminaria japonica*, namely kelp], gracilaria [*Gracilaria* spp.]); and animal mariculture areas (AMAs) as areas that farm fed animal species, including finfish (e.g., large yellow croaker [*Larimichthys crocea*]) and marine invertebrates (e.g., abalone [*Haliotis* spp.], sea cucumber [*Apostichopus japonicus*]). Seaweeds are farmed on parallel or perpendicular ropes or bamboo poles held together by floating ropes (also known as raft culture, Fig. 1c). Finfish are farmed in submerged nets attached to floating square frames ($3 \sim 5$ m $\times$ $3 \sim 5$ m) constructed from wooden or plastic board; and invertebrates are farmed in submerged boxes hanging on bamboo poles, also held by floating square frames (also known as cage culture, Fig. 1d).

2.2. Data collection

2.2.1. Mariculture cover mapping

Because of their different farming methods, SMAs and AMAs exhibit different characteristics in satellite imagery, including their spectrums, shapes, and textures. We used high-resolution satellite imagery in 2003 (SPOT-5, 2.5 m), 2010 (SPOT-5), and 2016 (GF-1, 2 m; GF-2, 1 m; ZY-3, 2.1 m). We derived the mariculture cover maps of Ningde City from the high-resolution satellite imagery using the multi-scale based neighbor information classification method (MNIC) (Fu, Deng, et al., 2019a; Fu, Ye, et al., 2019b). These maps included three marine-cover classes (i.e., seaweed mariculture, animal mariculture, and open sea surface) with overall accuracies of 99% for 2003, 99% for 2010, and 97% for 2016, respectively (Table A1).

The specific steps of mariculture cover mapping and accuracy assessment are as follows. First, the multispectral bands image and panchromatic band image were orthorectified into the Universal Transverse Mercator projection system, and fused using Gram-Schmidt pan-sharpening method in ENVI (v5.3, Exelis Visual Information

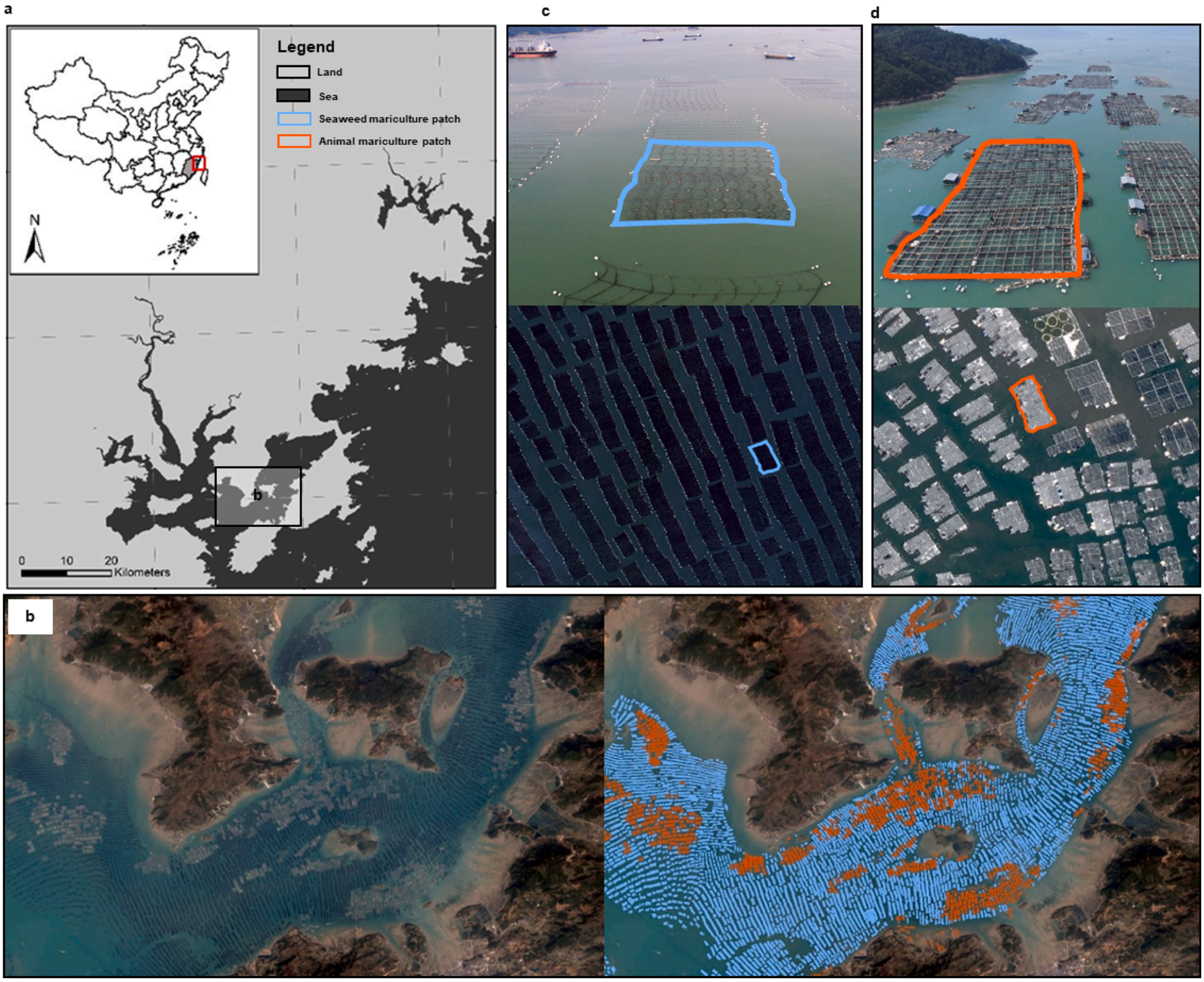

Fig. 1. Mariculture in Ningde marine area, China. a) The location of Ningde City and its marine area. b) Left: A part of Ningde mariculture area in 2016 from GF-2 satellite imagery (1 m resolution). Right: Seaweed and animal mariculture area extracted from GF-2 satellite imagery. c) The seaweed mariculture farms in aerial photographs (top) and in GF-2 satellite imagery (bottom). d) The animal mariculture farms in aerial photographs (top) and in GF-2 satellite imagery (bottom).

Solutions, Boulder, CO, USA, 2015) for preprocessing. Second, we employed the MNIC method to extract animal and seaweed mariculture areas from preprocessed imagery by eCognition software (v9.0, Trimble Germany GmbH, Munich, Germany, 2014) via three steps: (1) the Separability and threshold method to separate land and marine areas; (2) two-level hierarchical segmentation to separate submerged area (animal mariculture area) and unsubmerged area (seaweed mariculture area and open sea surface); and (3) nearest neighbor classification method based on multi-scale segments to identify animal mariculture area, seaweed mariculture area, and open sea surface. Third, we generated random points on the Google Earth satellite imagery as ground truth points in 2003, 2010 and 2016, respectively. Finally, we conducted the accuracy assessment of the obtained mariculture cover maps (Table A1).

2.2.2. Grid cell generation

Considering the driving mechanism may differ from SMA growth to AMA expansion, we constructed different regression models to analyze the driving factors for SMA and AMA. Unlike change detection analysis of terrestrial ecosystems where each land cover pixel is fixed, mariculture cover pixel is floating on the sea surface with the main frame tied to several stakes on the sea floor. In other words, mariculture cover pixels may shift from one year to another. Thus, we cannot conduct change detection analysis using paired pixels. To analyze the driving mechanisms of SMA and AMA expansion, we selected the grid cell as our unit of analysis and generated grid cells of different sizes (e.g., 125 m × 125 m, 250 m × 250 m, and 500 m × 500 m) over the animal and seaweed mariculture maps, respectively (Fig. 2). After comparison of results of spatial dynamics and regression models, we finally selected the best grid cell sizes (seaweed mariculture maps: 500 m × 500 m, animal mariculture maps: 250 m × 250 m) for our results. We calculated the increased mariculture area of each grid cell between each time period to represent the magnitude of mariculture expansion and used as the dependent variable for corresponding regression model.

2.2.3. Available data for potential driving factors

Considering data availability, insights from existing literature (Zhang and Su, 2016), and interactions between SMAs and AMAs, we selected eleven associated factors representing aquacultural, geographical, and anthropogenic aspects of mariculture expansion. Then we calculated the values of these factors for each grid cell of seaweed mariculture and animal mariculture, respectively. The initial mariculture area (area_init) reflects the potential of further expansion in each grid cell. The number of mariculture patches (num_patch) and its change (d_patch) of mariculture patches in each grid cell are included to explore the cluster effect, based on the assumption that with more mariculture

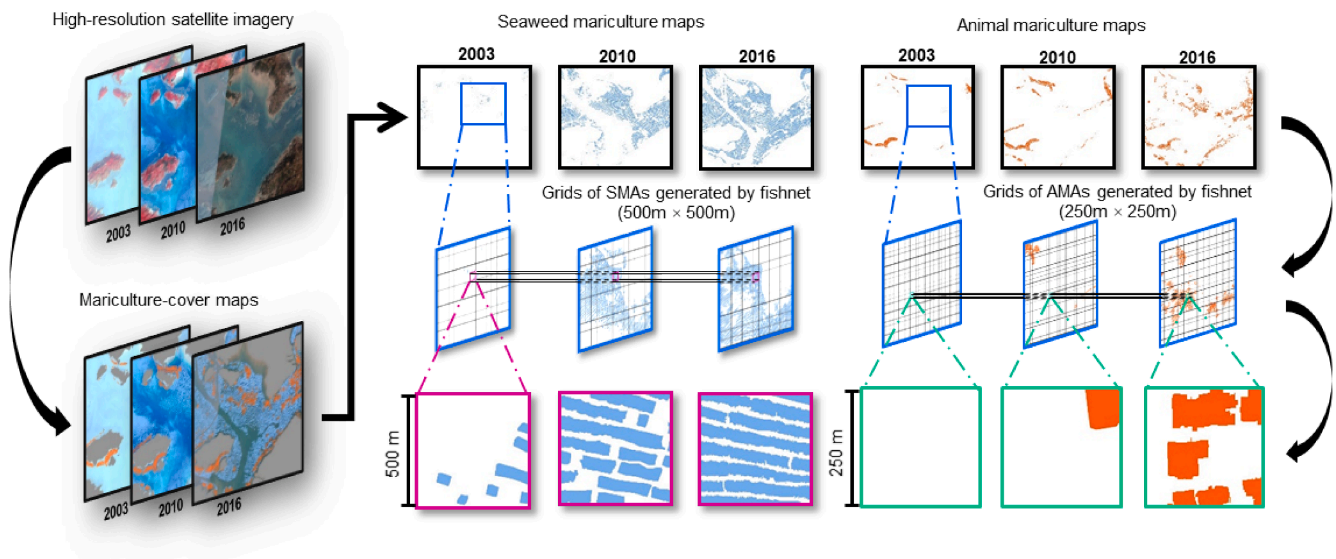

Fig. 2. Units generated for analyzing factors associated with seaweed and animal mariculture expansion. First, we separated the AMAs and SMAs to generated six maps that each only included one type of mariculture, based on the three maps of Ningde marine cover in 2003, 2010, and 2016. Second, we divided the six maps into grid cells of specific sizes (AMAs: 250 m × 250 m, SMAs: 500 m × 500 m), to further analyze the factors associated with seaweed and animal mariculture expansion at the grid cell level.

farms existing in a grid cell, it would attract more mariculture households to practice here. As the distance to the nearest island (dis_island) of each grid cell increases, the site is more exposed to wind and waves and faces stronger hydrodynamics, and mariculture farms that are sensitive to exposure would avoid expand there. Different mariculture types may have different impacts on marine ecosystems. Fed animal mariculture releases organic and inorganic wastes into the environment in the form of uneaten feeds and feces, while seaweed mariculture could benefit the environment by removing and transforming waste materials, lowering the nutrient load, and in turn provide dissolved oxygen when adjacent to animal mariculture. In this case, the distances between each grid cell and its nearest neighbor with the same mariculture type (dis_stype) and, different mariculture type (dis_dtype) and changes in distance (d_dtype) are used to measure the effect of interactions between adjacent mariculture sites on mariculture expansion. We selected anthropogenic variables taking the consideration of from two aspects: user conflicts (i.e., maritime traffic) and onshore activity influence (i.e., human settlements), assuming mariculture site selection would like to avoid or minimize human disturbanceThe data were generated by calculating the number of ports within three kilometers of each grid cell centroid (num_port) and the change (d_port), and the density of the nearest ten human settlements of each grid cell centroid (den_hum) and the growth rate (d_den_human), respectively. Descriptive statistics of selected driving factors are shown in Table A2.

2.3. Data analyses

To understand the spatiotemporal dynamics of seaweed and animal mariculture expansion in Ningde City between 2003 and 2016, we analyzed (1) the total area and annual growth rate of mariculture, (2) the amount, degree, and pattern of expansion for both seaweed and animal mariculture at the grid cell level, and (3) the conversions between different types of mariculture. The expansion degree of each grid cell was calculated as follows:

$$Expansiondegree(\%) = \frac{\Delta y}{S} \times 100 \tag{1}$$

Where Δy refers to the net increase of mariculture area of each grid cell; S is a constant referring to the total area of each sea grid cell (seaweed mariculture grid cell: 0.25 km^2, animal mariculture grid cell: 6.25×10^{-2} km^2).

To assess the effects of driving factors associated with the area expansion of seaweed and animal mariculture, respectively, we constructed six regression models for the periods of 2003–2016, 2003–2010, and 2010–2016 (Table 1, Table A3). The variance inflation factors of our regression models indicate no multicollinearity issue (Table A4).

$$\Delta y = \beta_0 + \beta_1 y_0 + \beta_2 D_0 + \beta_3 \Delta D + \varepsilon \tag{2}$$

where y_0 and Δy refer to the initial mariculture area and net increase of mariculture area of each grid cell, respectively; D_0 and ΔD are the initial and changed value of factors examined for association with expansion of mariculture areas, respectively;β_0 is the intercept term; β_1-β_3 are the corresponding regression coefficients; ε is the error term that has a normal distribution with a mean of zero.

To further understand the differences in expansion rates and patterns between AMAs and SMAs at the pixel level, we established logistic models using the probability of an open seawater pixel (2 m × 2 m) to be turned into AMA or SMA as a function of the geographical and anthropogenic factors (See Appendix B for details of methods and results).

3. Results

3.1. High-resolution spatiotemporal dynamics of mariculture expansion

The resulting marine cover maps reveal a sevenfold expansion of mariculture area between 2003 and 2016 (Fig. 3). Over time, the expansion generally proceeded from the coastline out towards the ocean, surrounded the islands from the inside to the outside, and filled in the inner harbor in a less systematic way (Fig. 3). The net expansion of SMAs surpassed that of AMAs, with SMAs and AMAs increasing in area from 30.25 km^2 to 253.07 km^2 and 8.67 km^2 to 22.86 km^2 between 2003 and 2016, respectively (Fig. 3). In addition, SMAs and AMAs went through different rates and timing of expansion. From an annual growth rate of 95.2% (28.82 km^2/year) between 2003 and 2010 to 1.5% (3.52 km^2/year) between 2010 and 2016, SMAs experienced a rapid onset followed by a steep decline in the rate of expansion. In contrast, AMAs increased steadily in the same two time periods, exhibiting an annual growth rate of 8.2% (0.71 km^2/year) and 11.2% (1.54 km^2/year),

Table 1
Factors associated with animal and seaweed mariculture expansion at the grid cell level during 2003–2016.

Categories	Factors	Animal mariculture (2003–2016) Coefficient (Robust S.E.)	Standardized Coefficient	Seaweed mariculture (2003–2016) Coefficient (Robust S.E.)	Standardized Coefficient
Aquacultural	area_init	−0.383 (0.0967)***	−0.132***	−0.557 (0.0645)***	−0.210***
	num_patch	2028.203 (269.5777)***	0.243***	3379.205 (428.1518)***	0.205***
	d_patch	2647.811 (73.1809)***	0.764***	5209.372 (115.8063)***	0.703***
Geographical	dis_island	−0.366 (0.1423)*	−0.034*	3.014 (0.8157)***	0.062***
	dis_stype	0.450 (0.1836)*	0.045*	−1.158 (0.2701)***	−0.076***
	dis_dtype	−0.416 (0.0693)***	−0.108***	3.277 (0.2793)***	0.275***
	d_dtype	−0.262 (0.0430)***	−0.102***	5.374 (0.9225)***	0.085***
Anthropogenic	num_port	−369.675 (57.4906)***	−0.078***	−889.666 (400.6154)*	−0.025*
	d_port	−105.730 (30.0189)***	−0.059***	−1383.520 (159.9452)***	−0.138***
	den_hum	−3.735 (1.0661)***	−0.028***	−11.593 (5.4875)*	−0.029*
	d_den_hum	−164.082 (87.3340)†	−0.036 †	−3882.505 (991.9866)***	−0.055***
	Constant	2765.798 (633.044)		23356.300 (3001.118)	
		N = 1,942 $R^2 = 0.591$		N = 2,873$R^2 = 0.447$	

Dependent variable is the net increase of mariculture area (m^2). area_init: initial mariculture area of each grid cell (m^2); num_patch: initial number of mariculture patches in each grid cell; d_patch: increase in the number of mariculture patches in each grid cell from 2003 to 2016 ; dis_island: initial distance between each grid cell and the nearest island (m^2); dis_stype: initial distance between each grid cell and its nearest neighbor with the same mariculture type (m^2); dis_dtype: initial distance between each grid cell and its nearest neighbor with the different mariculture type (m^2); d_dtype: change of distance from 2003 to 2016 between each grid cell and its nearest neighbor with the different mariculture type (m^2); num_port: initial number of ports within three kilometers of each grid cell centroid; d_port: change of number of ports from 2003 to 2016 within three kilometers of each grid cell centroid; den_hum: initial density of the nearest ten human settlements of each grid cell centroid; d_den_hum: the growth rate of human settlement density of each grid cell centroid. $^{\dagger}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

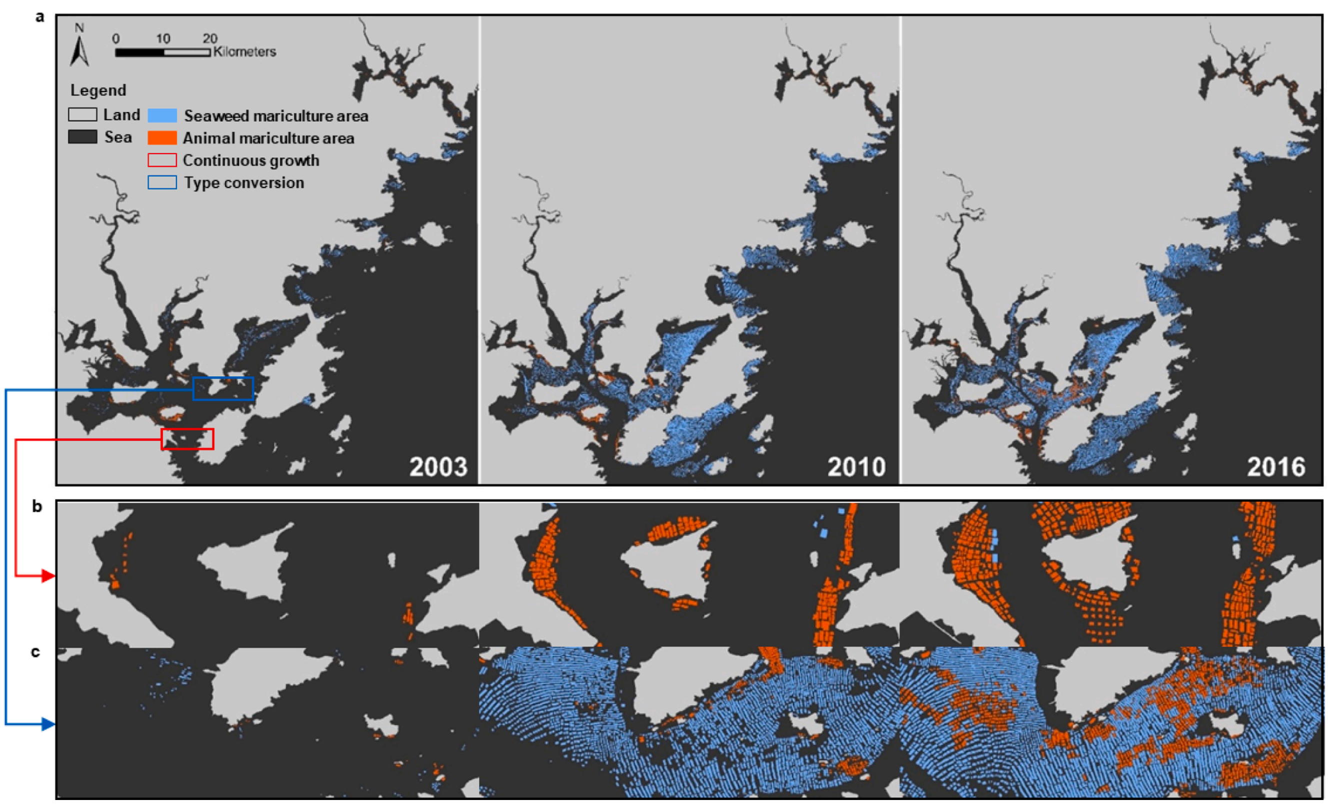

Fig. 3. Dramatic expansion of mariculture in Ningde City between 2003 and 2016. a, The marine cover maps in 2003, 2010 and 2016 depicting seaweed mariculture and animal mariculture area, produced from high-resolution remote sensing imagery observed by GF, ZY and SPOT satellites (1 m to 2.5 m spatial resolution). b, Example of spread of maiculture area during 2003 to 2016. c, Example of spread of the two types of mariculture types in sample years spanning 2003 to 2016.

respectively. Fig. 4 depicts the different spatial pattern and expansion degree between mariculture types and reveals the highest and lowest spots of mariculture expansion at the grid cell level. We also find that both the amount and degree of SMA expansion between 2003 and 2010 exceeded that between 2010 and 2016, while the situation for AMA expansion was the opposite.

Fig. 5 displays transfer flows of marine cover changes over time. Approximately 257.22 km^2 of the sea surface was exploited to develop mariculture between 2003 and 2016, with AMAs covering 4.0% of the exploited sea surface area from 2003 to 2010 and 10.0% from 2010 to 2016. In addition, 14.80 km^2 of initial SMAs (48.9% of SMA area in 2003) and 5.41 km^2 of initial AMAs (62.4% of AMA area in 2003) were abandoned back to open sea surface by 2016. Although <1.0% of SMAs were converted from AMAs during both periods of time, 20.6% (4.71 km^2) of AMAs in 2016 were converted from SMAs in 2010 (See Table A5 of transition matrix for details).

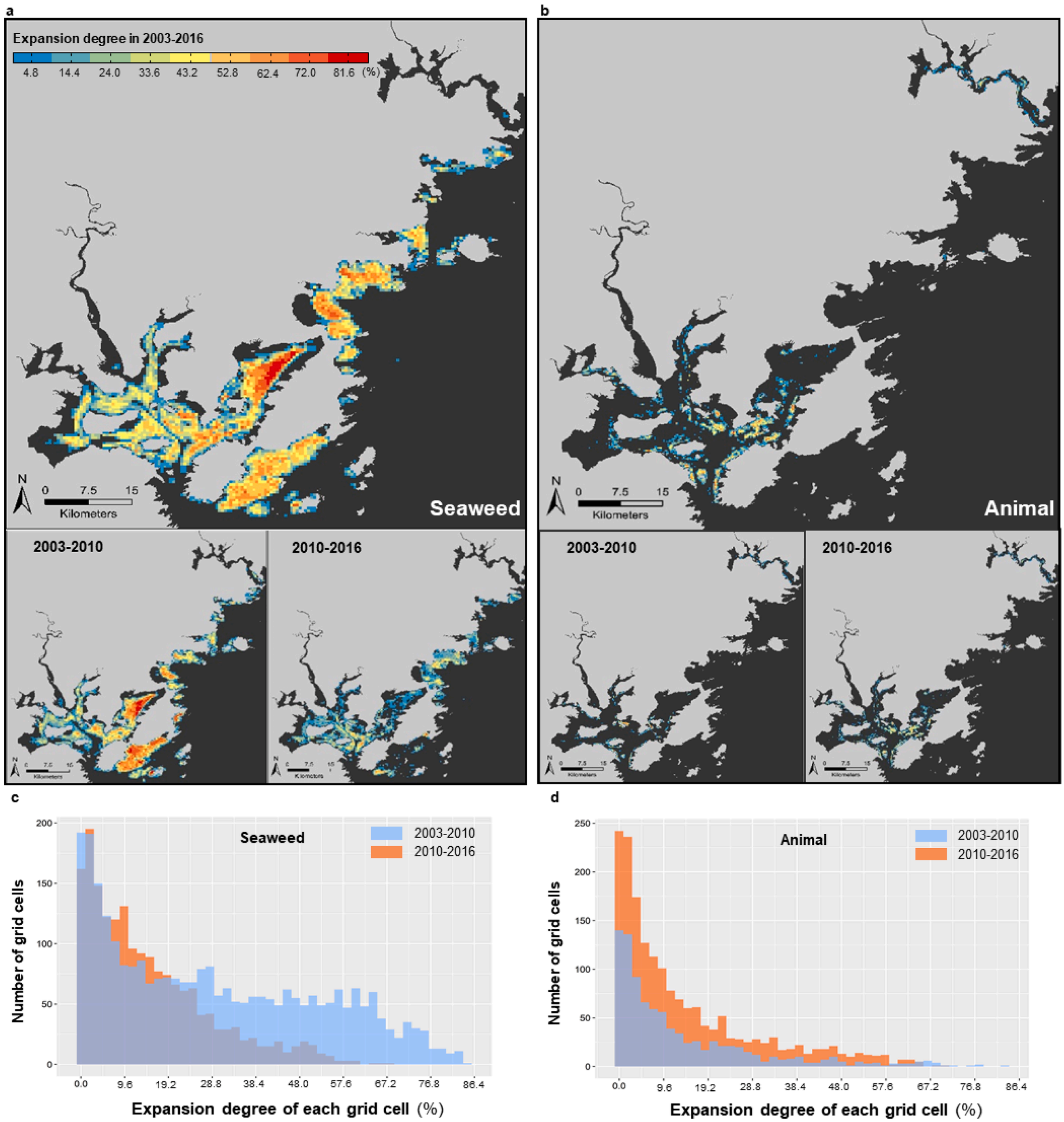

Fig. 4. Spatial pattern and expansion degree of animal and seaweed mariculture in Ningde City during 2003–2016 at the grid cell level. a, Spatial pattern and expansion degree of seaweed mariculture expansion in 2003–2016 at the grid cell level (250 m × 250 m). b, Spatial pattern and expansion degree of animal mariculture expansion in 2003–2016 at the grid cell level (500 m × 500 m). c, Number of seaweed mariculture grid cells to different expansion degree in periods 2003–2010 and 2010–2016. d, Number of animal mariculture grid cells to different expansion degree in periods 2003–2010 and 2010–2016. Gray shaded area in c and d indicates the overlapping parts of the two periods.

3.2. Factors associated with mariculture expansion at the grid cell level

Table 1 shows that aquacultural, geographical, and other anthropogenic factors are associated with mariculture expansion from 2003 to 2016 (See Table A3 for results of periods 2003–2010 and 2010–2016). With each grid cell size fixed, those with smaller initial mariculture area have more potential for further mariculture expansion. The grid cells having more initial mariculture patches also experienced a greater degree of mariculture area growth. The increase in number of patches in each grid cell has the largest positive effect on mariculture area increase. Precisely, while keeping other variables constant, a grid cell with every extra 1000 m^2 initial mariculture area, expanded 383 m^2 less in animal mariculture and 557 m^2 less for seaweed mariculture, respectively; a grid cell with one more mariculture patches, has 2648 m^2 more expansion of AMAs and 5209 m^2 more expansion for SMAs (Table 1). These results are similar to the infilling pattern in urban expansion (Gong, Hu, Chen, Liu, & Wang, 2018), revealing the infilling mode that produces growth patterns encountered inside existing developed mariculture areas in Ningde.

Second, the distances between the same and different types of

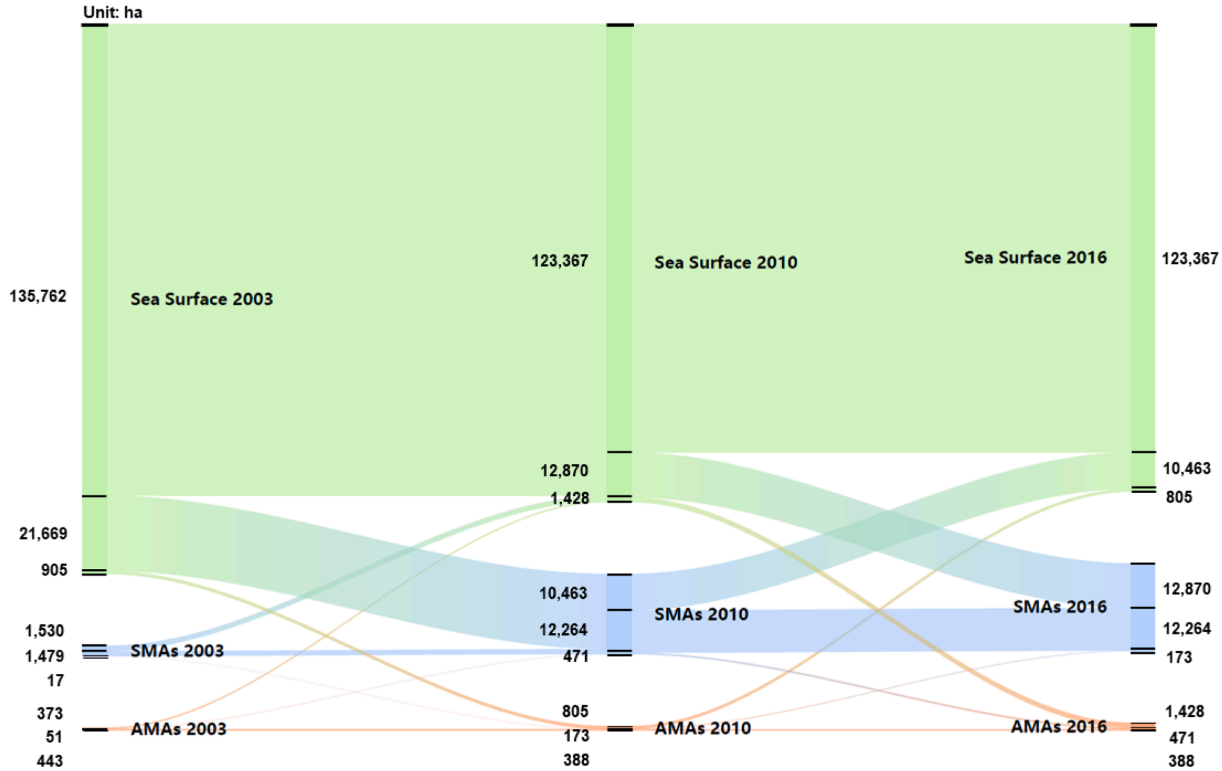

Fig. 5. Sankey diagram of marine cover change during 2003 and 2016. It displays transfer flows of marine cover changes over time (see Supplementary Table 2 of transition matrix for details). The columns in the left, middle, and right indicate the years of 2003, 2010, and 2016, respectively. The colors in green, blue and orange represent open sea surface, seaweed mariculture areas (SMAs), and animal mariculture areas (AMAs), respectively.

mariculture grid cells were significantly associated with the spatiotemporal dynamics of mariculture expansion (Table 1). Both SMAs and AMAs expanded intensively in places near SMAs and those further away from AMAs. Both the initial distance and increase in the distance to the nearest grid cell with a different mariculture type had significantly positive effects on SMA expansion but significantly negative effects on AMA expansion, respectively. Meanwhile, such effects were exactly the opposite for the factor of the initial distance between each grid cell and its nearest neighbor with the same mariculture type (Table 1). Specifically, a grid cell located 1 km further from the nearest neighbor of animal mariculture, expanded 3277 m^2 more for seaweed mariculture and 450 m^2 more for animal mariculture, respectively. In contrast, a grid cell located 1 km further from the nearest neighbor of seaweed mariculture had 1158 m^2 less in area for seaweed mariculture and 416 m^2 less for animal mariculture (Table 1).

Third, anthropogenic factors are also strongly correlated with mariculture expansion. Our results show that both SMAs and AMAs expanded away from port areas and human settlements, likely to minimize the risk of negative impacts of human activities on mariculture production. For example, if a grid cell had one more port within 3 km of its centroid, it would have 890 m^2 less area for seaweed mariculture and 370 m^2 less area for animal mariculture (Table 1). A grid cell with 1% higher human settlement density had 3882 m^2 less area for seaweed mariculture and 164 m^2 less for animal mariculture (Table 1).

Finally, the initial distance between each grid cell and the nearest island had a significantly opposite effect on seaweed and animal mariculture expansion. In other words, SMAs expanded away from islands, whereas AMAs tended to sprawl near islands. Specifically, the grid cell located 1 km further from the nearest island had 366 m^2 less area for animal mariculture and 3014 m^2 more area for seaweed mariculture (Table 1).

4. Discussion

A growing literature has documented land use and land cover changes of terrestrial ecosystems (Foley et al., 2005) as an indication of the dramatic impacts that humans are having on the surface of our planet. In a first ever detailed analysis of nearshore regions, we find unprecedented human modifications of marine ecosystems in China via high-resolution satellite imagery. Our results show an overall 709% increase in total mariculture area in the key production region of Ningde between 2003 and 2016, with an 836% increase of SMAs and 264% growth of AMAs. Although the net expansion area of seaweed mariculture surpasses that of animal mariculture, the expansion rate of AMAs outpaces that of SMAs between 2010 and 2016, with an annual growth rate of 11.2% (1.54 km^2/year) for AMAs and 1.5% (3.52 km^2/year) for SMAs, respectively (Fig. 3). Below we discuss the reasons for such dramatic mariculture expansion and provide insights on the management of sustainable mariculture.

At the macro scale, to meet the escalating seafood demand, Chinese government implemented incentive mariculture policies and promoted artificial propagation and breeding techniques to accelerate the development of mariculture during the twenty-first century (see details in Fig. 6). As the wild fish stocks are declining sharply, aquaculture has been entirely responsible for the continuing growth in the supply of fish and fish products for human consumption since the late 1980 s (FAO, 2020). To meet both domestic and international markets for seafood, China has been leading the world production of both mariculture animals and seaweeds during our research period (FAO, 2020). Our study area, Ningde City, is one of the fastest growing regions in terms of mariculture production (Fig. A1).

At the grid cell level, aquacultural, geographical, and anthropogenic factors all significantly contribute to both animal and seaweed maricuture expansion (Table 1). Both AMAs and SMAs have expanded by increasing density within a cell (Gong, Hu, Chen, Liu, & Wang, 2018).

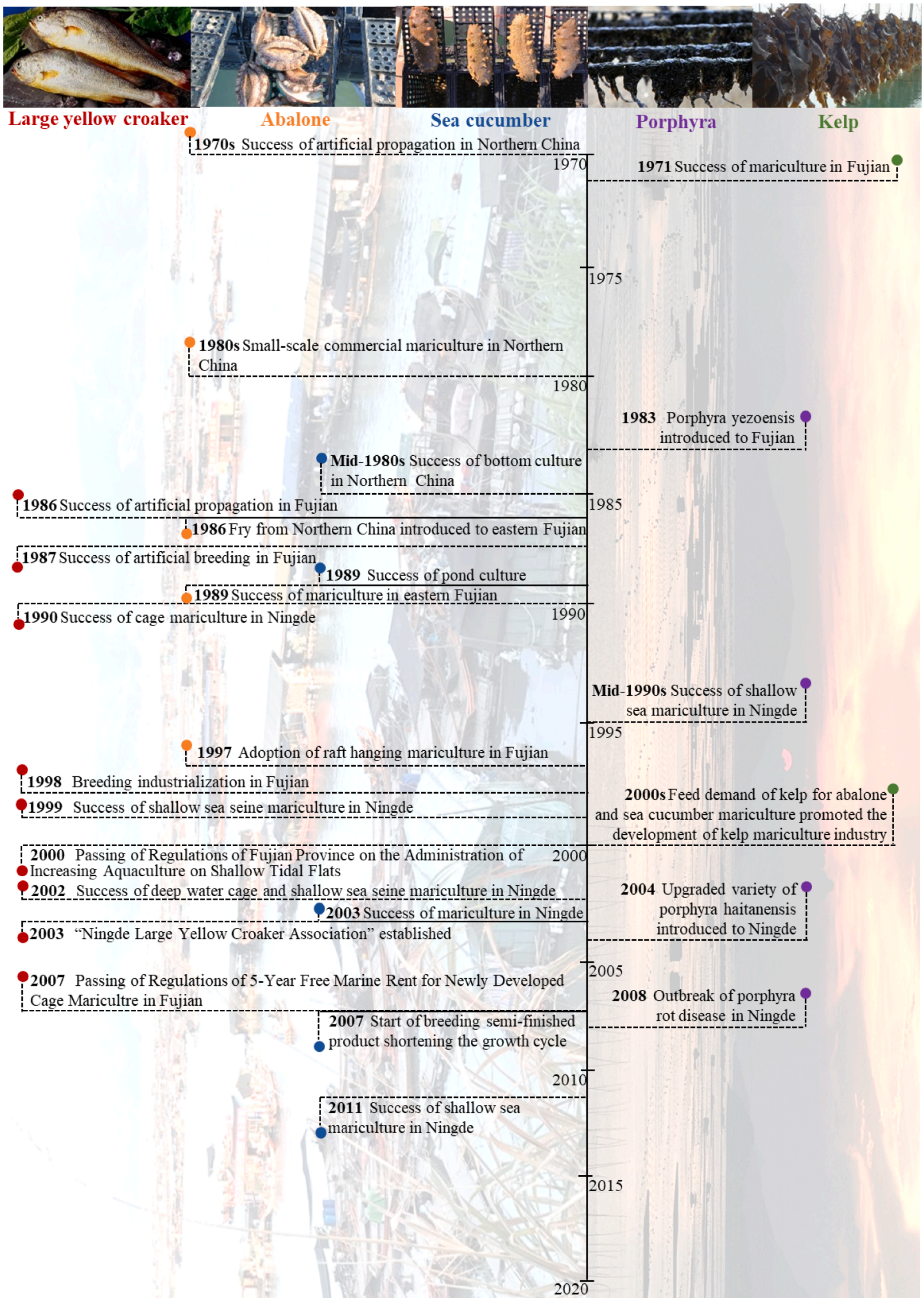

Fig. 6. Milestones in mariculture development of representative varieties. Left and right zones depict the development timelines of animal (i.e., large yellow croaker, abalone, and sea cucumber) and seaweed (i.e., porphyra and kelp) mariculture industry in China, Fujian Province, and Ningde City, respectively. The dot bullets in red, orange, blue, purple, and green colors represent milestones for the large yellow croaker, abalone, sea cucumber, porphyra, and kelp, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Correlates of expansion indicate greater growth in mariculture away from human interference such as disturbance from port areas and water pollution caused by adjacent human settlements. Due to their varying sensitivities to wind and wave exposure (Cardia & Lovatelli, 2015), AMA expansion was greater near islands. In contrast, SMA expansion was greater away from islands, likely because the hydrodynamics are weaker, restricting crucial nutrient supply required by seaweeds. Our results also suggest that seaweed and animal mariculture sites interact with each other and significantly drive the spatiotemporal dynamics of mariculture expansion. Both SMAs and AMAs expanded intensively in places near SMAs and avoided expansion near existing AMAs. This expansion pattern indicates the trial-and-error behavior of Integrated Multi-Trophic Aquaculture (IMTA) (Chopin, Cooper, Reid, Cross, & Moore, 2012) in Ningde mariculture practice. Taking advantages of synergistic interactions between different species, the IMTA refers to cultivation of aquaculture species at different trophic levels, allowing one species' uneaten feed, wastes, and by-products to be recaptured and converted into fertilizer, feed, and energy for other species (Chopin, Cooper, Reid, Cross, & Moore, 2012). Although animal mariculture only accounts for a small portion (8.3% in 2016) of total mariculture area in Ningde, it causes serious environmental impacts, including eutrophication, ocean acidification, and excessive suspended solids and so forth (Zhou, 2012; Zhu et al., 2013). Seaweeds extract inorganic nutrients from the surrounding water through photosynthesis and other metabolic processes. The practice of farming seaweeds adjacent to finfish farms has proven to be a valid alternative for nutrient bioremediation (Buck, Troell, Krause, Angel, Grote, & Chopin, 2018; Xiao et al., 2017). Therefore, the IMTA could be an effective and efficient solution to optimize socioeconomic benefits from mariculture, reducing feed costs, alleviating environmental impacts, and potentially mitigating fish disease risks.

To sustain seafood provision, maintain people's livelihoods, and mitigate environmental impacts, we provide the following recommendations to strengthen coastal and marine ecosystem research and management in China and beyond. First, it is important to take a coupled human and natural systems approach (Halpern et al., 2012; Liu et al., 2015) and regard mariculture systems as coupled human and ocean systems to understand and manage human-nature interactions. Environmental impacts induced by the rapid expansion and intensification of mariculture (e.g., water pollution, biodiversity loss, and decline and degradation of waterbird habitat and coastal wetlands) (Grigorakis & Rigos, 2011; Smith et al., 2010) not only occur locally, but also further away via telecoupling processes (e.g., raw materials of aquaulture feed imported from other countries, and aquactic products produced in China exported to other countries) (Liu et al., 2013). Second, conducting integrated monitoring and assessments of socioeconomic and environmental impacts of mariculture, allows comparison of the impacts and tradeoffs of different aquaculture practices (e.g., mariculture types, feed sources, and IMTA systems) on food production and quality, livelihoods, and ecosystem impacts (Gentry, Alleway, Bishop, Gillies, Waters, & Jones, 2020; Winther et al., 2020). Third, marine spatial planning (Gentry et al., 2017; Lester et al., 2018) is crucial to meet multiple objectives, harmonizing competing uses of marine areas, while also minimizing negative environmental impacts. Particularly, systems modeling and simulation of different scenarios (e.g., business as usual, restricted development, and minimized environmental impact scenarios) are helpful for balancing costs and benefits, and informing proactive measures. While most studies on spatial planning have roughly assessed the technical feasibility (e.g., water depth and temperature) of monoculture farming sites (e.g., finfish, bivalve, and kelp), our study could complement existing research on interactions between mariculture types, suggesting better spatial planning via combinations of certain seaweed and animal sites to reduce environmental impacts. Finally, it is necessary to regulate mariculture behaviors via measures such as environmental awareness education, scientific training of farm design, and management of feed and energy use. For instance, our life cycle assessment suggests that 45–90% of environmental impacts of animal mariculture come from the feed use, while 83–99% of environmental impacts of seaweed mariculture are related to fuel use for operation and maintenance activities (Marín et al., 2019). China has called for sustainable development of mariculture since its 13th Five-Year Plan (2016–2020) (MARA, 2017b). With better understanding and effective management of human-ocean interactions, we can move toward sustainable use of marine ecosystems in the long run.

5. Conclusion

We use high-resolution satellite images to capture the unprecedented expansions of both animal and seaweed mariculture, and identify the associated driving factors and to which extent they contribute to mariculture expansion in a representative coastal city in Southeastern China. Our results suggest the need to conduct spatial planning of mariculture and regulate mariculture behaviors via environmental awareness education, scientific training of farm design, and management of feed and energy use in China and beyond. Our findings also call for a coupled human and ocean systems approach to understand and manage human-ocean interactions and the implementation of integrated monitoring and assessments of socioeconomic and environmental impacts of mariculture.

6. Author statement

J.W. and W.Y. designed the research; J.W., T.M., G.H., and Y.F. collected the data; J.W., T.M., and Y.F. performed the analyses; J.W. and W.Y. wrote the first draft; All authors revised the manuscript together. The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104190.

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