Ocean and Coastal Management 243 (2023) 106729

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Systematizing ecosystem change in coastal social-ecological systems: Perspectives from a multi-stakeholder approach in Nakatsu mudflat, Japan

Shamik Chakraborty [a,*], Takumi Yamamori [b], Jie Su [c], Brian Alan Johnson [d], Pankaj Kumar [d], Yukiko Ashikaga [b], Alexandros Gasparatos [c]

[a] Global Research Center for Advanced Sustainability Science, University of Toyama, 3190, Gofuku, Toyama, Japan
[b] NPO Nakatsu Waterfront Conservation Association, 1151-4, Higashihama, Nakatsu, Oita, Japan
[c] Institute for Future Initiative (IFI), The University of Tokyo, 7-3-1, Hongo, Bunkyo-Ku, Japan
[d] Institute for Global Environmental Strategies, 2108-11, Kamiyamaguchi, Hayama, Kanagawa, Japan

ARTICLE INFO

Keywords:
Traditional and local knowledge (TLK)
Ecosystem services
Social-ecological system
Participatory process
Nakatsu mudflat
Japan

ABSTRACT

Coastal social-ecological systems (SES) are essential for the wellbeing of coastal communities and the wider society. However, in many parts of the world coastal SES face rapid change, and ultimately degradation. In this paper we unravel the mechanisms and implications of change in coastal SESmobilising multiple sources of knowledge, including scientific, expert-based and traditional and local knowledge (TLK). We focus on the rapidly changing Nakatsu mudflat in Japan, and combine primary and secondary data elicited through a mixed-method participatory approach that mobilised local stakeholders with different types of engagement with (and knowledge of) the mudflat. Through 4 expert interviews and 40 questionnaire surveys we identified the main ecosystem services provided by the mudflat that are perceived to be essential to the wellbeing of the local community. Although practically all respondents identified food provision as an important mudflat ecosystem services, many also pointed to the importance of some cultural (e.g. aesthetic beauty, spirituality, education and knowledge) and supporting services (e.g. habitat provision, sediment formation/retention). Through 8 Focus Group Discussions (FGD) and concept mapping we identified and systematized the underlying direct and indirect drivers of ecosystem change in the Nakatsu mudflat. These include population ageing and shrinking, economic diversification, and technological change that have collectively eroded TLK practices associated with the sustainable use of the mudflat. We also identified the mechanisms mediating these drivers and how they unfold in reality. Our study demonstrates that participatory processes engaging multiple stakeholders with different types of knowledge can provide rich and useful information on coastal SES change, which might not be readily obvious from simple headline indicators such as the change in the extent of the SES.

1. Introduction

Intertidal mudflats are an ecosystem type formed in the edges of many tidal estuaries, and are characterized by seawater cover during the high tide and exposure to sun and wind during the low tide (Dyer et al., 2000). They can be found all around the world in very different types of coastlines, and are of exceptional importance for providing habitat, biogeochemical processes and multiple ecosystem services (Gillis et al., 2014; Martinez et al., 2007). Yet these ecosystems have experienced constant degradation in many parts of the world over the past few decades (Murray et al., 2019). Some of the most common pressures include coastal infrastructure development (MA, 2005; Arkema et al., 2013), reduction of sediment input from rivers (Xie et al., 2017), sea level rise (Passeri et al., 2015), subsidence and compaction of coastal sediments, and coastal erosion (Xie et al., 2017; Blum and Roberts, 2009). The degradation of intertidal mudflats also reflects the increasing degradation of coastlines around the world (Murray et al., 2019), which jeopardizes the marine food chain and affects estuarine and marine biodiversity (Dissanayake et al., 2018, IPBES, 2019).

Intertidal mudflats are interconnected with very diverse ecosystems, ranging from shallow coastal areas to deep sea environments (Marley et al., 2019), which makes them particularly crucial for coastal and marine biodiversity. For example, in intertidal mudflat areas, diatoms and seagrass consume sediments (forming the basis of marine food

* Corresponding author.
E-mail address: shamik@eco.u-toyama.ac.jp (S. Chakraborty).

https://doi.org/10.1016/j.ocecoaman.2023.106729
Received 25 July 2022; Received in revised form 30 April 2023; Accepted 26 June 2023

chains), and they are in turn consumed by fish, other aquatic organisms, and birds (Saint-Béat et al., 2013). Intertidal mudflats provide transit routes and hiding/foraging grounds for fish (Barlleta and Blaber, 2007), Furthermore, they are essential for carbon storage, bioremediation, and habitat provision (Paterson et al., 2019; Passarelli et al 2018; Byun et al., 2019). Beyond their ecological importance, mudflats also provide multiple ecosystem services (ES) that support the livelihoods and wellbeing of local communities and broader society (MA, 2005; Datta et al., 2021; Davies, 2021; Passarelli et al 2018). Some of the many examples include important provisioning services associated with food (e.g., fish, seaweed, and other aquatic organisms) (Lebreton et al., 2019) or tangible and intangible cultural services (e.g., cultural events, tourism/recreation, spiritual interactions, inspirational experiences) (Choi et al., 2015; Thomas et al., 2021). Collectively, the multiple ecosystem services provided by these coastal SES can contribute to economic, social, cultural and heritage values to individuals and communities (Sandifer et al., 2015; Newton et al., 2014).

Considering the above, it becomes rather obvious that intertidal mudflats essentially have highly interconnected social and ecological components across multiple scales, and can thus be conceptualized as social-ecological systems (SES) (Hossain et al., 2020; Hossain and Szabo 2017b; Gain et al., 2020). Due to their high biological diversity and their significant contributions to human wellbeing via multiple ecosystem services, many scholars have articulated the need to develop comprehensive strategies for their sustainable management (Rova et al., 2019; Lin et al., 2019; Marley et al., 2020). This echoes similar arguments for other SES around the world (Foley et al., 2010; Berkes, 2012).

There is an emerging consensus in the academic literature about the need to integrate insights from multiple sources of knowledge, when seeking to both understand the functioning of (and changes within) SES, as well as establish approaches for their sustainable management (IPBES, 2022). In many cases this require the critical synthesis of information from modern scientific knowledge, expert-based knowledge and Traditional and Local Knowledge (TLK) (Martin et al., 2022). This need to consider TLK and integrate it with other types of knowledge has also been articulated for coastal SES, as local communities have long experience observing and managing such SES, with the multiple values embedded in local cultures and societies often dictating how resource management is carried out in (Burley et al., 2007; Martin et al., 2016; Kearney et al., 2007). In fact the *"meanings, values, and identities; knowledge and practice; governance and access; livelihoods; and cultural interactions with biophysical environments"* (Poe et al., 2013: 166) are essential for both understanding and assessing how change unfolds in coastal SES, as well as offering insights how to sustainably manage coastal SES (Tengö et al., 2014; Hind, 2015; Adams et al., 2014; Chakraborty and Gasparatos, 2019).

However, TLK is often given less importance (or is even lost) in geographical contexts characterized by rapid economic transformation and growth (Ruddle and Satria, 2010; Assefa and Hans-Rudolf, 2015; Queiroz et al., 2017) or rapidly ageing and shrinking populations (Cetinkaya, 2009; Iniesta-Arandia et al., 2015; Kamiyama et al., 2016; Tattoni et al., 2017). Furthermore, TLK is not always effectively integrated with modern scientific knowledge and expert-based knowledge in contexts experiencing TLK erosion such as the ones outlined above (Iwama et al., 2021). This is despite expectations that this integration could open up possibilities for social learning (Ranger et al., 2016) to facilitate better coastal and marine SES management (Kenter, 2016; Irvine et al., 2016).

Japan offers a very relevant geographical context to explore how change unfolds in coastal SES such as mudflats, mobilising knowledge from different sources. On the one hand, as an island nation Japan contains many coastal SES (including mudflats) of critical ecological and socioeconomic importance, as highlighted by the *satoumi* concept (Yanagi, 2013).[1] Coastal communities in Japan have been managing such coastal SES (incl. mudflats) over centuries using approaches anchored to TLK (Akimichi, 2012; Yanagi, 2013). However, many of these coastal SES, and especially mudflats, have been experiencing rapid change due to various interrelated factors such as dredging, port development, unsustainable fishing, and changes in ecosystem management (Ichikawa et al., 2017). The rapid, and in some areas extreme, ageing and decline of the population has compounded these processes via the erosion and loss of such TLK, with negative subsequent effects for coastal SES (Chakraborty and Gasparatos, 2019). Furthermore, studies have shown that such rapid ecosystem change in coastal SES in Japan (including mudflats), has important ramifications for the provision of multiple ecosystem services that are important for the wellbeing of local communities (Uehara et al., 2019, 2020).

The aim of this study is to understand and unravel how change in coastal SES unfolds mobilising multiple sources of knowledge from users and stakeholders, including TLK. We focus on the rapidly changing Nakatsu mudflat in the western part of the Seto Inland Sea of Japan, which is one the largest mudflats in the region (and Japan more broadly). Beyond its ecological importance, this coastal SES has been shaped by some unique coastal resource management traditions, mediated through long-held community values and TLK practices (that are also fast dwindling). At the same time the Nakatsu mudflat is emblematic of the changes and degradation observed in many similar coastal habitats around Japan and other parts of the world, (including shifts in ecosystem services) with important ramifications for local communities.

In summary, we use a mixed-method participatory approach that elicits and synthesizes insights from multiple mudflat users and stakeholders through interviews, questionnaire surveys and Focus Group Discussions (FGDs). The objectives are to:

(a) Understand the extent and status of the Nakatsu mudflat, and the major human activities therein;
(b) Assess the perceived importance of the ecosystem services provided by the Nakatsu mudflat;
(c) Unravel the factors mediating the change of the Nakatsu mudflat (and how);
(d) Propose and critically discuss priority areas for the sustainable management of the mudflat, and other coastal SES facing similar changes.

Following the framing and the background of this study (Section 1), Section 2 describes the research approach, study area and the data collection and analysis methods. Section 3 outlines the main results, focusing on the ecosystem services provided by the mudflat, the importance of these multiple ecosystem services for the local community, and the drivers of change in the mudflat. Section 4 critically discusses the main findings and identifies key policy/practice implications and recommendations to enhance the sustainability of the mudflat, and other similar coastal SES. Finally, Section 5 concludes the paper by summarising the main finding across the research aims and objectives outlined above.

2. Methods

2.1. Research approach and conceptual framework

To understand the importance of and the changes taking place in the Nakatsu mudflat we use the conceptual framework of the Millennium

[1] *Satoumi* denotes nearshore and shallow marine environments that are actively managed by local coastal communities including fishers and are directly linked to the wellbeing of these coastal communities (Yanagi, 2013).

Ecosystem Assessment (MA, 2005). In this framework, the contribution of ecosystems is viewed through the concept of ecosystem services, which denotes the benefits that humans receive directly and indirectly from nature (MA, 2005). This includes the different provisioning, regulating, cultural and supporting services that collectively reflect the different tangible and intangible benefits humans derive from nature (MA, 2005).

In the MA framework the drivers of environmental change are defined as "*any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. A direct driver unequivocally influences ecosystem processes. An indirect driver operates more diffusely, by altering one or more direct drivers* (MA, 2005: 74). The above include various demographic, economic, sociopolitical, scientific/technological, and cultural/religious indirect drivers. These indirect drivers eventually give rise to five main direct drivers of environmental change, namely land use change, pollution, overexploitation, invasive species and diseases, and climate change. Often these indirect and direct drivers interlink, having compounding effects on environmental change (Babai et al., 2021). To give an example from coastal SES, demographic change due to population ageing and decline (an indirect driver) can cause the decline and loss of traditional farming and fishing practices (indirect driver), which in effects leads to changes in land use (e.g. road development in near coastal areas, concretization of shoreland, port development) (direct driver). Collectively, the combined effect of these drivers of environmental change can alter coastal SES and the ecosystem services they provide.

To meet the four objectives outlined in Section 1 we employ a mixed-method participatory approach that elicits and synthesizes insights from the main users and stakeholders engaged in and have different types of knowledge about the mudflat area. Table 1 outlines the main research tasks and methods, as well as the relevant parts of the manuscript that contain the content for each objective.

2.2. Study site

Japan has experienced the large-scale conversion of most of its coastal mudflats after the Second World War (Uehara et al., 2020), a period characterized by rapid and pronounced economic growth. During that period, mudflat areas around the country, and especially around the Seto Inland sea (where the Nakatsu mudflat is located) have been under constant threat due to dredging and concretization of shorelines, port developments, and construction of upstream dams that cut off sediment supplies to the mudflats (Shibuya et al., 2011). However, despite the high concentration of industrial activity along the coastlines of the Seto inland seas and the pressure from industrial fisheries (Chakraborty and Gasparatos, 2019), the remaining mudflat areas in this area still contribute significantly to the livelihoods and wellbeing of the coastal communities (Uehara and Mineo, 2017).

Table 1
Research tasks and methods for each study objective.

Objective	Research task	Methods	Section
1	• Estimate the mudflat spatial extent and change over time • Identify the main current and historical uses and activities in the mudflat	• Site visits and observation • Geospatial analysis using secondary data • Key informant interviews	3.1
2	• Identify the perceived importance of the benefits provided by the mudflat	• Questionnaire surveys using Likert scales • Statistical analysis	3.2
3	• Identify the direct and indirect drivers of ecosystem change for the mudflats • Identify how drivers unfold and how they affect the mudflat • Identify interlinkages between drivers and mediating factors	• Focus Group Discussions • Conceptual modelling	3.3
4	• Identify policy implications • Propose priority areas for sustainable mudflat management	• Critical synthesis of results	4.4.

The Nakatsu mudflat (1347 ha) (Fig. 1) is the second largest single tract of mudflat in the Seto Inland sea. It is located in the middle of a large stretch of intertidal mudflat areas starting from Buzen City in Fukuoka Prefecture (facing the Suo-nada Sea) to the Kunisaki Peninsula (facing the western part of the Seto Inland Sea) (NWCA, n.d.). The Nakatsu mudflat ecosystem supports hundreds of rare and endangered species (Akimichi, 2012; Ashikaga, 2019) including endangered bird species. In this sense, the mudflat is an important habitat for the ever-decreasing populations of shorebirds and waders in the Seto Inland sea.

Historically, the mudflat was used as a commons resource for recreation and fishing until about 50 years ago (Yanagi, 2013). One of the prevalent fishing practices was bamboo weir fisheries (*sasahibi)*, a type of tidal fishing technique practiced in Japan and Korea that is argued to be sustainable (Akimichi, 2012). However, this system withered following the development of the user rights system by the Japanese Fisheries cooperative Nakatsu branch that designated areas for seaweed cultivation, fishing, port development and coastal reclamations. Nowadays, local communities (including fishers and seaweed cultivators) still continue to have strong attachments to the mudflats through livelihoods activities, historical ties living with the mudflat, and educational activities and research (the latter have arguably helped protect the mudflat).

However, much like other coastal and mudflat areas of Japan, Nakatsu has been experiencing interlinked demographic, socioeconomic and technological changes. For example, Nakatsu city has an already aged population, with 30.6% of its residents being >65 years old, with this fraction expected to increase to more than 32% in the next 20 years (Nakatsu city, 2021). This has contributed to a dwindling fisher population, especially fishers engaged in low-impact fishing through traditional practices. For example, in 2012 there were about 129 fishers cooperative members in Nakatsu city on the average of 61 years old, while residents employed in the tertiary sector were on average 47 years old (Nakatsu city, 2015). These phenomena have also contributed to the erosion of long-standing TLK practices, which has complex feedbacks to the changes observed in the mudflat that are not fully understood by the local stakeholders and communities. Interestingly the area also experiences possible impacts of climate change, with the temperature increasing related to suspected death of Japanese shortnecked clams (Kimura, 2014). .

Due to its ecological importance and high species abundance, the tidal flat has remained a potential candidate for Ramsar Convention status (Ashikaga, 2019). There has been a long process behind the management of the mudflat, with different organisations and stakeholders having different interests. In the late 1990s the national government requested the prefecture to establish a council for the protection and co-existence with the Nakatsu mudflat. This was in response to the Ministry of Transport's initiative ("Aiming for a Port that Coexists with the Environment") and in response to the sand-covering project planned for Nakatsu Port development. The plan centered around the "Waterfront Playing Group" (*Mizube ni asobu kai* in Japanese)' that was established by local residents. This "Waterfront Playing Group" later was named the NPO corporation Nakatsu Waterfront Conservation Association, which plays the major role about conservation efforts in area.

Subsequently, in response to the recommendations of the environmental assessment committee, in the year 2000 the prefecture established the "Nakatsu Port Oshinden Area Environmental Improvement Council". A consensus was formed on the need to improve the revetment of the Maite River to a shape that reflects the ecosystem proposed by the

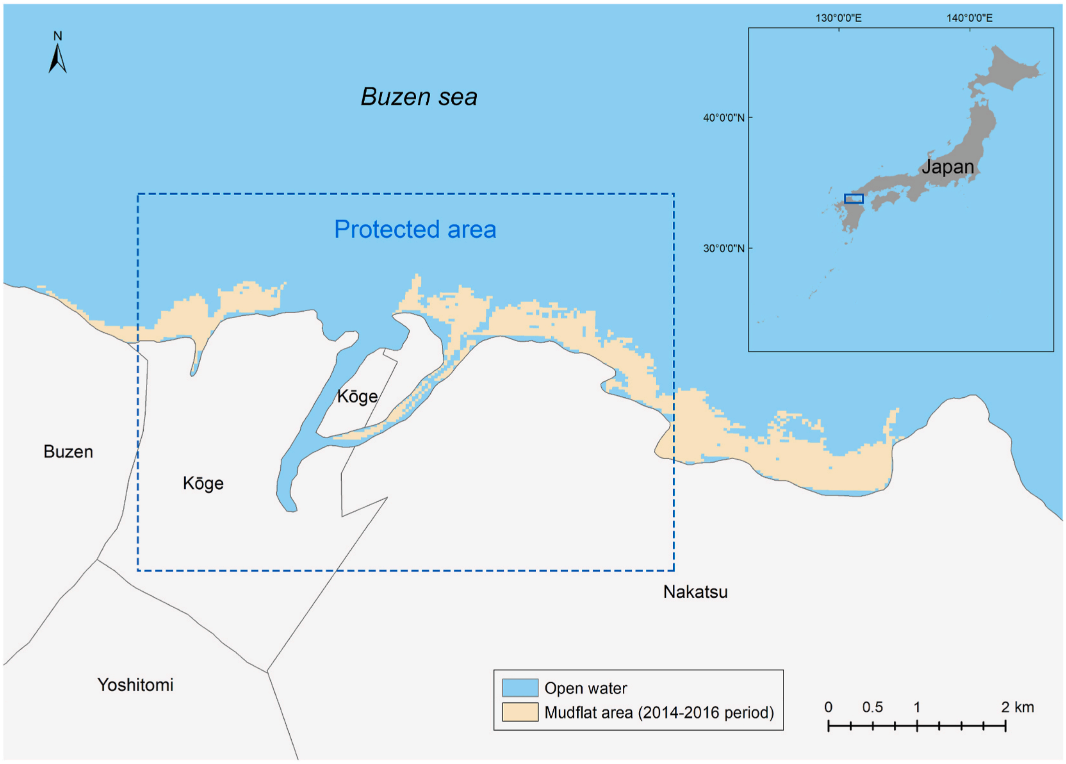

Fig. 1. Location of Nakatsu mudflat in Kyushu, Japan.

local residents. This was achieved through the development of a kind of nature-based solution, where the revetment building in the shoreland could allow waves to pass through the structure, "allowing" the mudflat to expand naturally. The local residents (including the NPO members) who participated in the project recognized the Nakatsu mudflat as their own beach, and took responsibility in monitoring, beach cleaning, and nature observation around the mudflat. These conservation activities are voluntary, with the NPO carrying out research and conservation activities through external grants. Given their central role for the protection and conservation of the mudflat, the NPO members engage with local fishers belonging to the Japan Fisheries Cooperative Nakatsu branch about the rights to use of the Nakatsu mudflat, as well as discuss problems and identify prospects for the conservation of the mudflat. This happens in "*Higara rabo*" or mudflat laboratory that is the main office of the NPO.

Beyond, the NPO and fishers, the private sector also engages in different ways with the mudflat. Toto Nakatsu (toilet manufacturers) and Daihatsu (car manufacturers) are the two biggest companies located in the mudflat (including some partly reclaimed area from the mudflat). Besides them, there are some other smaller manufacturers, as well as transport/logistic companies (e.g. trucking, shipping) and service sector businesses such as restaurants and shops in the mudflat environment.

2.3. Data collection and analysis

2.3.1. Main considerations

To meet the objectives outlined in Section 1 and Table 1 we employed a mixed-method approach for data collection and analysis which consisted of (a) 4 key informant interviews (Section 2.3.1), (b) 8 focus group discussions (FGDs) with 40 different mudflat users and stakeholders (Section 2.3.2), (c) 40 questionnaire surveys (Section 2.3.3), and (d) geospatial analysis (Section 2.3.4). The primary data for (a)-(c) data was collected over 6 fieldwork campaigns between February 2018 and February 2021. As a key aim was to mobilise different types of knowledge, these field visits were instrumental for creating a platform to deepen interactions between relevant users and stakeholders holding different types of knowledge (i.e. scientific, expert, TLK). Furthermore, they were instrumental for understanding better the mudflat SES and collect observations to put some of the findings into perspective.

The participants engaged in each of these data collection exercises were selected following a stakeholder analysis conducted with the input of the NPO Nakatsu Waterfront Conservation Association. This exercise identified all relevant major stakeholders involved or having an active interest in the utilization and/or conservation of the Nakatsu mudflats.

The key informant interviews (Section 2.3.2), FGDs (Section 2.3.3), and questionnaire surveys (Section 2.3.4) were undertaken by the 1st and 2nd author of the article, who are trained in these types of qualitative data elicitation methods. Collectively they have extensive experience in these methods (1st author: 8 years; 2nd author: 10 years). All data collection exercises were conducted in Japanese language, which is the mother tongue of the 2nd author, while the 1st author is at a near native speaking level.

We did not carry out any official research ethics approval procedure, as it is not common practice in Japan for non-medical research. Furthermore, the research did not elicit any confidential or personal information from the participants. Following good research practices, before any data collection process we explained thoroughly to all participants the focus of the research, the expected outcomes, how the findings will be used, and that participants could stop their engagement at any point without having any negative consequence. After this introduction we received the oral consent of all key informants, FGD participants, and survey respondents before embarking in the respective data collection exercises.

2.3.2. Key informant interviews

We initially conducted four key informant interviews with a university professor, a local historian, a fisherman leader residing in the local community, and a retired public service employee. All four were especially knowledgeable on the mudflat, the benefits it provides and how the mudflat has changed over time. The expertise of the four key informants was determined based on peer-referral method from two peers engaged with the NPO Nakatsu Waterfront Conservation Association. Between them they hold different types of knowledge in relation to the main processes within the mudflat, which was regarded important for understanding the ecosystem and its change (see Bélisle et al., 2018).

The interviews were semi-structured and open-ended to allow the interviewees expand on their answers as deemed appropriate. Each interview was conducted in person and lasted 45–60 min. These interviews mainly aimed to understand (a) the status of the mudflat (Section 3.1); (b) how people in local communities are connected to the mudflat and the ecosystem services they provide (Section 3.2); and (c) how the mudflat changed over time and why (Section 3.3). Although we do not formally analyze the key informant interviews for Section 3, the four interviews were instrumental in helping the research team to understand the main processes within the Nakatsu mudflats and develop the questions for the focus group discussions (FGDs) and the questionnaire surveys.

2.3.3. Focus group discussions

The FGDs collectively engaged 40 participants that were selected based on their interests, engagement and knowledge of the Nakatsu mudflat, and spanned four main groups namely NPO members, members of the Japan Fisheries Association (JFA) Nakatsu, researchers/academics, and local businesses. The FGDs sought to provide a platform to understand the main activities happening in the mudflats, the benefits derived from the mudflats (Section 3.2), and most importantly how the mudflat has changed over time (and the processes underpinning change).

The participants were identified in collaboration with the Nakatsu Waterfront Conservation Association, which is the main institution responsible for the management and protection of the mudflat. This consultation for the stakeholder identification exercise was carried out during the first fieldwork campaign (August 2016), and was assisted by the screening of local and regional-level documents related to the management of the mudflat. This institutional analysis offered vital information about the management of the mudflat, and reflected the understanding of institutions as the rules that govern decision-making in a given context (Vatn, 2005).

Following Section 2.2., the main relevant organisations engaged in the mudflat are the Nakatsu Waterfront Conservation Association and the Japan Fisheries Cooperative Nakatsu branch. Essentially any use (or any change in use) of the mudflat needs to go through these two institutions to be approved. However, they are closely collaborating with educational and research institutions (e.g. Oita University, Bunri University), and businesses (e.g. local industries and restaurants). The former undertake research and teaching related to the ecosystem, while the latter use land in the periphery of the mudflats for economic activities (Section 2.2). Research and education provide scientific knowledge about the functioning of the ecosystem and possible instruments to manage it sustainably. Businesses (such as TOTO, Nakatsu in the present case) offer funding for the conservation of the mudflat also, including funding to the NPO Nakatsu Waterfront Conservation Association.

We identified 40 stakeholders from the above institutions, and carried out eight FGDs, each comprising four to six people. Table S1 in the Supplementary Material contains more details about the characteristics of the different participants. Each FGD contained a mix of participants from these institutions. Collectively the participants represent the main interests for the Nakatsu mudflats, and at the same time reflect different types of knowledge (i.e. scientific, expert, TLK).

Each FGD lasted about two-three hours and started with a brief explanation of the activity at hand and the expected outcome. As the main goal of each FGD was to identify the main drivers of ecosystem change in Nakatsu mudflat and how they intersect (Section 1), we used a research approach borrowing from concept mapping (e.g. Moon et al., 2011) and modelling (Reed et al., 2013) to find the connection between the different drivers of change in the mudflat and how they unfold (mechanisms) and intersect. Such approaches have been employed in different ecosystem contexts (Yee et al., 2011; Russell et al., 2011; Gentile et al., 2001; Olander et al., 2018), and is ideal for group settings as it is highly visual and enables participants to understand complicated connections directly.

To facilitate the process, each FGD started with a pre-prepared concept map, which depicted on a large poster the main phenomena and their linkages (Fig. 2). The FGD participants then worked together to identify whether the phenomena and interactions were correctly depicted, as well as if there were phenomena/interactions missing or excessive. Through this collaborative process the conceptual map were consolidated to develop it into a final version that was acceptable to each FGD participant (i.e. consensus on depiction). The draft conceptual map for the first FGD was developed by the first two authors based on the key informant interviews and observations of the mudflats. Subsequently, each finalized and agreed conceptual map from a FGD, was the draft for the next. In other words, the finalized conceptual map from FGD 1, was the input for FGD 2, and so on. The final conceptual map from the FGDs (i.e. FGD 8), was cross-validated through a literature review and individual meetings the four key informants.

2.3.4. Questionnaire surveys

We elicited the perceived importance of the ecosystem services provides by the Nakatsu mudflat for users and stakeholders with different engagement with the mudflat (e.g., Díaz et al. 2015; Scholte et al., 2015; Iniesta-Arandia et al., 2014). Initially we identified the main ecosystem services provided by the mudflat through site observation and key informant interviews and use it to develop a questionnaire survey. We distributed the in-person questionnaire to each FGD participant to rate the perceived importance of the different tangible and intangible ecosystem services through a 5-point Likert scale: (a) 5 = highly important, (b) 4 = important, (c) 3 = nothing special but important, (d) 2 = if anything important, (e) 1 = not important. The draft survey was piloted with three members of the NPO Nakatsu waterfront conservation association, to establish its clarity and ability to elicit properly the stakeholder perceptions. We averaged the scores for the entire sample to assess the mean response for each particular ecosystem service. Subsequently, we identified differences in the perceived importance between groups using ANOVA pairwise comparison method.

2.3.5. Geospatial analysis

To estimate the extent of mudflat area change, we conducted a time series analysis of mudflat cover change in the last ~30 years (1984–2016). We used data from the Global Distribution of Tidal Flat Ecosystems dataset (Murray et al., 2019) (available online at: https://www.intertidal.app/download/direct-download). This dataset consists of 11 global maps of tidal flats extent and spans the period between 1984 and 2016. Each map in the dataset has a spatial resolution of 30 m × 30 m, and was produced through the analysis of Landsat satellite images over three-year periods, i.e. (1984–1986, 1987–1989, and up to 2014–2016). We extracted the portions of these global maps corresponding to our defined study area and analyzed the trend in the mapped tidal flat extent over time.

3. Results

3.1. Extent, status and human activities within the Nakatsu mudflat

Fishing and mariculture have traditionally been the main livelihoods for the local communities along Nakatsu mudflat area. Key informant interviews reveal that fishing in the intertidal mudflat of Nakatsu was characterized by TLK-based techniques (Table 2), such as bamboo weir fisheries that used tides to trap fish within preset bamboo structures during high tide and handheld nets for fishing during retreating high tide (Fig. 3). Other methods of resource harvesting included (a) the use

Fig. 2. FGD meeting (left) and view of the Nakatsu mudflat with retreating tides (right).

of handheld tools to dig for clams, (b) the protection of the seagrass and algae beds through avoiding disturbance from heavy machines, (c) the seasonal control of productive fisheries by creating marine conservation zones, (d) the control of the size of shellfish to support juvenile population increase, and (e) the use of the special types of nets that do not damage the loose bottom sediments of the mudflat (Table 2). Table 3 shows the types of fish and other marine organisms caught throughout one year.

Nowadays the mudflat environments have been adversely affected by the concretization of the shorelines and development of ports (e.g. Nakatsu port), industries (e.g. car manufacturing) and facilities (e.g. toilet systems and garbage burning facilities). During the field visits and key informant interviews with local experts, it was pointed out that these industrial developments near the mudflat had an overall negative impact on the mudflat ecosystem that led to its changes and degradation (see Section 3.3). Moreover, areas beyond this approximately 10 km stretch of intertidal mudflat do not have strict protection and cause concern for the local experts and conservationists including birdwatchers.

Geospatial analysis of tidal flat extent in the past ~30 years (1984–2016) showed the tidal flat extent to be relatively unchanged (Fig. 4; Table S2, Supplementary Material). We calculated the goodness-of-fit (R2 value) of the linear trendline for the time-series data. The result (R2 = 0.03) implies that it is not possible to conclude with certainty any positive or negative change in the tidal flat extent. We believe that the slight fluctuations in the tidal flat extent calculated between adjacent time periods (Fig. 4) is partly due to the erroneous estimation of some tidal flat areas in certain periods (e.g. due to inability of the satellite sensor to image the reef because of frequent cloud cover, high tide levels, or other types of obstructions). This seems particularly evident for the map of the 1999–2001 period.

3.2. Perceived importance of ecosystem services from the Nakatsu mudflat

Through the key informant interviews and site observation we identified 12 tangible and intangible ecosystem services provided by the Nakatsu mudflat (Table 4). These are food provision, climate regulation, water purification, disaster reduction, aesthetic, spiritual, marine art and culture, education and knowledge, recreation and tourism, biomass production, sediment formation and retention, and habitat provision.

When we estimate the perceived importance of these ecosystem services between stakeholder groups, we find some interesting convergences and divergences between groups (Fig. 5). For example, for respondents from the private sector all ecosystem services had generally lower perceived importance compared to all other groups, with the exception of water purification and disaster risk reduction. In most cases these differences were statistically significant, and possibly indicate the low actual engagement of this stakeholder group with the mudflat. Furthermore, the relatively high perceived importance for water purification and disaster risk reduction possibly indicate the fact that they perceive such services as important for their businesses. Another interesting finding is the significant difference in the perceived importance of climate regulation between respondents from education/research organisations and other groups. This possibly suggests their better understanding of climate change issues, and how the mudflat can help reduce some of its impacts for local communities.

3.3. Drivers of ecosystem change in the Nakatsu mudflat

3.3.1. General patterns

Overall, the FGDs identified five direct drivers, two indirect drivers and 39 (positive/negative) mechanisms that mediate these drivers and lead to ecosystem change in the Nakatsu mudflat. The five direct drivers include overexploitation (n = 30), habitat change (n = 27), invasive species (n = 21) pollution (n = 13), and climate change (n = 8) (see also Table 4). The two indirect drivers are population ageing and shrinking (n = 34) and technology and institution related to fishing (n = 25) (see also Table 5).

Fig. 6 visualises (a) the positive and negative linkages between the direct and indirect drivers, (b) the interaction between the drivers and mechanisms underlying them, and (c) the frequency that each driver/mechanisms was mentioned by the respondents. It is worth noting that ecosystem change in Nakatsu mudflat can be attributed to negative mechanisms, such as the lack of environmental awareness and port development, but also positive mechanisms, such as NPO-led conservation and education on the mudflat. The most mentioned negative mechanisms include erosion of TLK and its transfer (n = 34), followed by increased dredging for port development and shipping (n = 32), market development (n = 27), and lack of environmental awareness (n = 26). Conversely mechanisms related to the natural environment, such as the increasing water temperature, or changes in typhoon patterns changes in sand/grit cycles were recognized by comparatively fewer respondents (n = 8).

3.3.2. Direct drivers

3.3.2.1. Overexploitation. Overexploitation was the most commonly mentioned direct drivers of ecosystem change in the Nakatsu mudflat ecosystem (n = 30), with the main underlying mechanism being the changes in the prices of fish and other aquatic organisms (n = 21).

Local stakeholders argued that constant fish prices would lead to less overexploitation, as there would be fewer incentives to increase extraction. However, the price elasticity in the local market, the wish of fishers to rely on fisheries for their livelihoods (rather than other occupations), and the availability of fish stock cause the decrease in the price of fish and other aquatic organisms. This in turn drives fishers to opt for increasing their catches, targeting species that have good market value and adopting advanced fishing technologies. In the Nakatsu area, seaweed, daggertooth pike conger (*Muraenesox cinereu*), gazami crab,

Table 2
Major human activities in the Nakatsu mudflat and their effect.

Activity	Implementation approach	Effect to mudflat	Current prevalence of activity
Bamboo weir fisheries	• Use of handheld nets and tools (see Fig. 3 for example)	• Depends on fisheries reliant on the tidal actions of estuarine areas • Represents active conservation through fishing with high input of TLK	• No (existed in 1940s)
Active conservation of tidal flats	• Hand tilling of tidal flat	• Increases oxygen in the tidal mudflats • Conserves clam habitats and habitats for migratory birds	• Yes (but only by a few TLK holders)
Seasonal control of productive fisheries	• Decrease the number of fishers through fisheries permits of *Gyogyoken*, • Create marine conservation zones • Control types of nets, time and/or season of catch	• Enables sustainable marine resource harvesting	• Yes
Control harvest size	• Prohibit harvesting of marine species above a certain size: 15 cm for gazami crab; 2.5 cm for short necked clam; 10 cm for tiger prawn; 4 cm for redilated trough-shell; 200 g for octopus • Regulated through the Oita Prefecture Fisheries Coordination Regulations Article 37 (*Oita ken gyogyo chousei kisoku dai 37 jo*)	• Supports juvenile population for reproduction	• Yes
Use special net types	• Use *Kakoi sashiami* nets (for whiting, Japanese seabass, Japanese spanish mackerel)	• Prevents overcatch and discard of fish species with economic value	• Yes
Conservation through education and research	• Promote active learning and recreation of mudflat environment to local children and their families, • Research and monitoring of mudflat environment among different stakeholders	• Creates appreciation of the mudflat environment and the benefits it provides • Creates collaboration with local fishers and other users to enable evidence-based management of the mudflat environment	• Yes

and flower crab (*Portunus armatus*) are the species with high market values that are captured the most. The adoption of sophisticated fishing technologies such as GPS and sonar-equipped fishing vessels also increases the amount of fish catch, as it improves the ability of fishers to spot fish stocks.

Fig. 3. Bamboo weir fisheries. Photo courtesy Nakatsu Waterfront Conservation Association.

3.3.2.2. Habitat change. Many FGD participants identified habitat change as a major driver of ecosystem change in the Nakatsu mudflat (n = 27). The main underlying mechanisms mediating habitat change include (a) dredging and concretization of shorelines, including expansion of concretized breakwaters, dams and piers (n = 32), (b) seaweed mariculture (n = 17), and (c) overexploitation of freshwater resources (n = 14).

According to 32 FGD participants the dredging and concretization undertaken during the port development in the late 1990s has damaged intertidal mudflat areas in Nakatsu significantly. Large ships with heavy loads were allowed to enter the Nakatsu mudflat, which caused the increasingly sludgy conditions at the bottom of the mudflat, while the continuation of shipping routes still causes damage to the mudflat habitat. It was estimated by local experts that the dredging for the port construction was up to 8 m, which needs a system of concretized surfaces and seawalls to hold the eastward flow of sediments and stop it at the seawall. Beyond dredging, the shoreline has experienced extensive port development and concretization, including concretized breakwaters, dams and piers.

These dredging and concretization activities have affected significantly the prime mudflat environments between the Yamakuni river and the Maite river estuary. On the one hand, dredging leads to more sludge and lower oxygen levels (n = 18), which is not suitable for mudflat creatures and has been mentioned as possibly the primary cause of the decline in short-necked clams populations across the Nakatsu mudflat. At the same time the silt and mud from the intact mudflat constantly tries to occupy the dredged areas, creating a vicious cycle of mudflat loss and reclamation (n = 32). However, according to local experts the populations of species preferring sludgy conditions such as Japanese ivory shell (*Babylonia japonica*), seem to be increasing. On the other hand, the concretized shores (including concrete breakwaters, dams and piers) lead to the loss of habitats for hiding, resting and foraging for fish and other aquatic organisms (n = 32). These setback walls also cause stronger wave patterns and a decrease in swash and backwash. This creates a challenging environment for some species of fish and other aquatic organisms, for which the swash and backwash generated by natural shorelines is essential for their growth and survival.

Seaweed mariculture seems to have a mixed effect for habitat change in the area. Mariculture is backed by the Nakatsu Fisheries Cooperative, and has a long tradition in the Nakatsu area that was recently boosted through a contract with 7-Eleven convenience stores to use Nakatsu seaweed. Seaweed is often affected by algae, which makes seaweed cultivators clear algae beds near cultivation structures (n = 17). However, according to some FGD participants (n = 11) the current fish and clam stocks are partially secured due to seaweed cultivation, as due to seaweed cultivation, any other type of activities such as dredging in the

Table 3
Types of fish and other marine organisms harvested at Nakatsu mudflat throughout the year.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seaweed (*Porphyra yezoensis*)										seeding	seeding	
Daggertooth pike conger (*Muraenesox cinereus*)							Peak	Peak	Peak			
Tongefish (*Cynoglossus joyneri*)	Peak	Peak									Peak	Peak
Gazami crab (*Portunus trituberculatus*)										Peak	Peak	Peak
Queen crab (*Chionoecetes opilio*)												
Flower crab (*Portunus pelagicus*)									Peak			
Japanese black bream (*Acanthopagrus schlegelii*)												
Japanese halfbeak (*Hyporhamphus sajori*)												
Fltahead grey mullet (*Mugil cephalus*)				Peak								
Japanese seabass (*Lateolabrax japonicus*)							Peak	Peak				
Octopus (*Octopus vulgaris*)							Peak	Peak				
Webfoor octopus (*Amphioctopus fangsiao*)												
Top shell (*Rapana venosa*)												
Japanese oyster (*Crassostrea gigas*)												
Congere eel (*Conger myriaster*)												Peak
Broad squid (*Sepioteuthis lessoniana*)												
Firefly squid (*Watasenia scintillans*)												
Silver pomfret (*Pampus punctatissimus*)												
Japanese spanish mackerel (*Scomberomorus niphonius*)							Peak	Peak				
Japanese flounder (*Paralichthys olivaceus*)												
Pacific needlefish (*Strongylura anastomella*)												
Marbled sole, Flounder (*Pseudopleuronectes*)												
Bustard halibut (*Paralichthys olivaceus*)												
Sillago (*Sillaginidae*)							Peak	Peak				
Sillago, Baywhiting (*Sillago parvisquamis*)				Peak	Peak							
Rockfish (*Sebastes inermis*)												
Redspotted grouper (*Epinephelus akaara*)												
Black rockfish (*Sebastes schlegelii*)												
Bartail flathead (*Platycephalus sp*)												
Japanese barracuda (*Sphyraenidae*)												
Dotted gizzard shad (*Konosirus punctatus*)												
Kiji shrimp (*Pandalopsis japonica Balss*)												
Cocktail shrimp (*Metapenaeopsis barbata*)												
Greasyback shrimp (*Metapenaeus ensis*)												
Longheaded eagle Ray (*Aetobatus narutobiei*)												
Sea cucumber (*Apostichopus armata*)												

Note: 'peak' refers to the month of the year when the catching of the specific species is at its peak. Source: (Survey data by the authors).

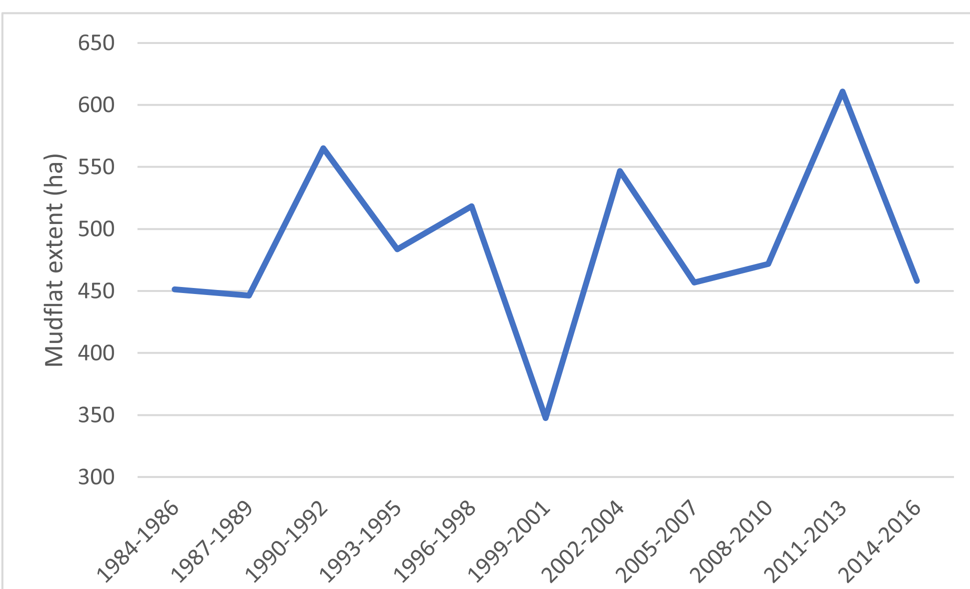

Fig. 4. Change in the spatial extent of the Nakatsu tidal flat.

mudflat area is not allowed. Also, according to some participants (n = 11), seaweed cultivation can slow the concretization and dredging of shorelines, as these are not possible in areas of seaweed cultivation as the user rights for seaweed cultivators would not allow concretization and dredging of shorelines.

Furthermore, industrial freshwater use from inland rivers flowing towards the coast can also lead to habitat change according to some FGD participants (n = 15). The Daihatsu car manufacturing industry (a heavy industry) is currently one of the largest industrial users of freshwater. The overexploitation of freshwater does damage to mudflat habitats, by

Table 4
Perceived importance of the ecosystem services provided by the Nakatsu mudflat.

Question	Average score	Ecosystem service	Category
Nakatsu mudflats is important to me because it provides seafood including seafood that are representative of local culture	4.64	Food	Provisioning service
Nakatsu mudflats is important to me because it provides water purification function	3.6	Water purification	Regulating service
Nakatsu mudflats is important to me because it protects the land area from wave actions due to typhoons	2.42	Disaster reduction	Regulating service
Nakatsu mudflats is important to me because it provides a sink of CO2 that can mitigate global warming	2	Climate regulation	Regulating service
Nakatsu mudflats is important to me because it provides unique scenery of the mudflats	4.64	Aesthetic	Cultural service
Nakatsu mudflats is important to me because it provides spiritual satisfaction, stress release and hope	4.64	Spiritual	Cultural service
Nakatsu mudflats is important to me because it provides knowledge about creatures that live in tidal flats and mud, sand, sea currents and their movements	4.07	Education and knowledge	Cultural service
Nakatsu mudflats is important to me because it provides recreation and tourism opportunities	2.92	Recreation and tourism	Cultural service
Nakatsu mudflats is important to me because it provides unique art and culture of the locality	2.28	Marine art and culture	Cultural service
Nakatsu mudflats is important to me because the silt and mud support the diversity of life forms	4.21	Sediment formation and retention	Supporting service
Nakatsu mudflats is important to me because it harbor endangered species	4.14	Habitat provision	Supporting service
Nakatsu mudflats is important to me because a diversity of plants and animals for the marine food chain are formed here	4	Biomass production	Supporting service

reduction of freshwater input, which can adversely affect primary productivity as found on other estuarine and mudflat areas (Burford et al., 2011).

3.3.2.3. Invasive species. Invasive species was another identified driver of direct ecosystem change in the Nakatsu mudflats (n = 21). The main mechanisms here relates to the increased population of moon jellyfish (*Aurelia aurita*), which predates on juvenile and small fish/calms, reducing their stocks. The population of other invasive species such as Naru eagle ray (*Aetobatus narutobiei*) and hammerhead sharks (*Sphyrnidae*) has also increased (the latter within the past three years according to local fisher's records), having a similarly detrimental effect on fish and clam stocks, as has been found in other studies (Fukuda and Zenitani 2009; Ashikaga 2015).

3.3.2.4. Pollution. Mudflat pollution is another major direct driver responsible of ecosystem change in the Nakatsu mudflat. The sources of pollution include sewage disposal due to the expansion of residential areas, seaweed mariculture, and runoff from agricultural areas.

In total 15 FGD participants pointed out that the construction of new houses and apartments near the shoreline has increased substantially in the past years due to low land prices and farmland loss due to the aging and shrinking population (n = 18). These residential areas have straightened concrete drainage facilities that pour sewage into the mudflat, causing low levels of pollution in the area.

Seaweed mariculture is another source of pollution in the mudflat (n = 17). On the one hand, the use of new technologies of seaweed production at an industrial scale (e.g. automated seaweed dryers) and disease (e.g. pathogenic bacteria and fungi) and artificial seaweed structures may have a negative influence on the mudflat habitats (see also Bhuyan, 2023; Adegbeye et al., 2020). On the other hand, according to respondents the fertilizer used for seaweed production contains ammonium sulphate can be toxic to marine ecosystems such as seagrass meadows (see also Moreno-Marín et al., 2016).

Finally, 21 respondents observed that local and small-scale pollution from agricultural runoff (e.g. from fertilisers and agrochemicals) also affects local ecosystems. However, there is some degree of uncertainty about the extent of this pollution damage, which in their opinion is meager compared to the physical changes of the mudflat environments due to anthropogenic activities. One interesting mechanism of pollution relates to the introduced Channeled apple snail (*Pomacea canaliculata)*.[2] However, according to many respondents (n = 21) it became a pest eating crops in the rice land, eventually requiring heavy pesticide application to stop its spread (see also Joshi 2007). This application in the past 20 years has polluted the runoff water into the mudflat, and according to some FGD participants may have contributed to the decrease of Manila clams.

3.3.2.5. Climate change. Climate change was also observed some FGD participants as one of the direct drivers of ecosystem changes in the Nakatsu mudflat (n = 8). There are two major underlying mechanisms here: (a) an increase in water temperature, and (b) changes in typhoon patterns.

According to local experts, the increased water temperature (Section 2.2) has negatively affected species such as the *Gazami* crab (*Portunus trituberculatus*), while affect positively species such as the Flower crab (*Portunus armatus, Platylambrus validus)* that have higher temperature tolerance.

The other mechanism of ecosystem change associated with climate change relates to the increased intensity and frequency of rainfall during storms (n = 8), as well as the changing pattern of typhoons (see also MOE, 2012). Typhoons were identified by FGD participants as natural disturbances that are essential for mixing the shallow seas around the mudflat, which is beneficial for mixing nutrients (see also Chai et al., 2021). According to local experts, and fishers, the number of typhoons has decreased over the decade at Nakatsu, which may be a possible effect of climate change. This decrease can lead to lesser mixing of shallow seas and mixing of nutrients in the Seto Inland sea, especially in its shallow areas like the mudflat (n = 8).

3.3.3. Indirect drivers

3.3.3.1. Population ageing and shrinking. The vast majority of FGD participants (n = 34) identified the ageing and shrinking population as an indirect driver of ecosystem change, mainly via (a) loss of TLK for sustainable fisheries management (n = 34); (b) changes in economic/livelihood activities in the mudflat areas (n = 26).

The ageing and shrinking population was associated with the erosion

[2] This snail species has been introduced in different parts of Japan (including Nakatsu) from South America as a species for food and weed control (see Hidaka et al., 2007).

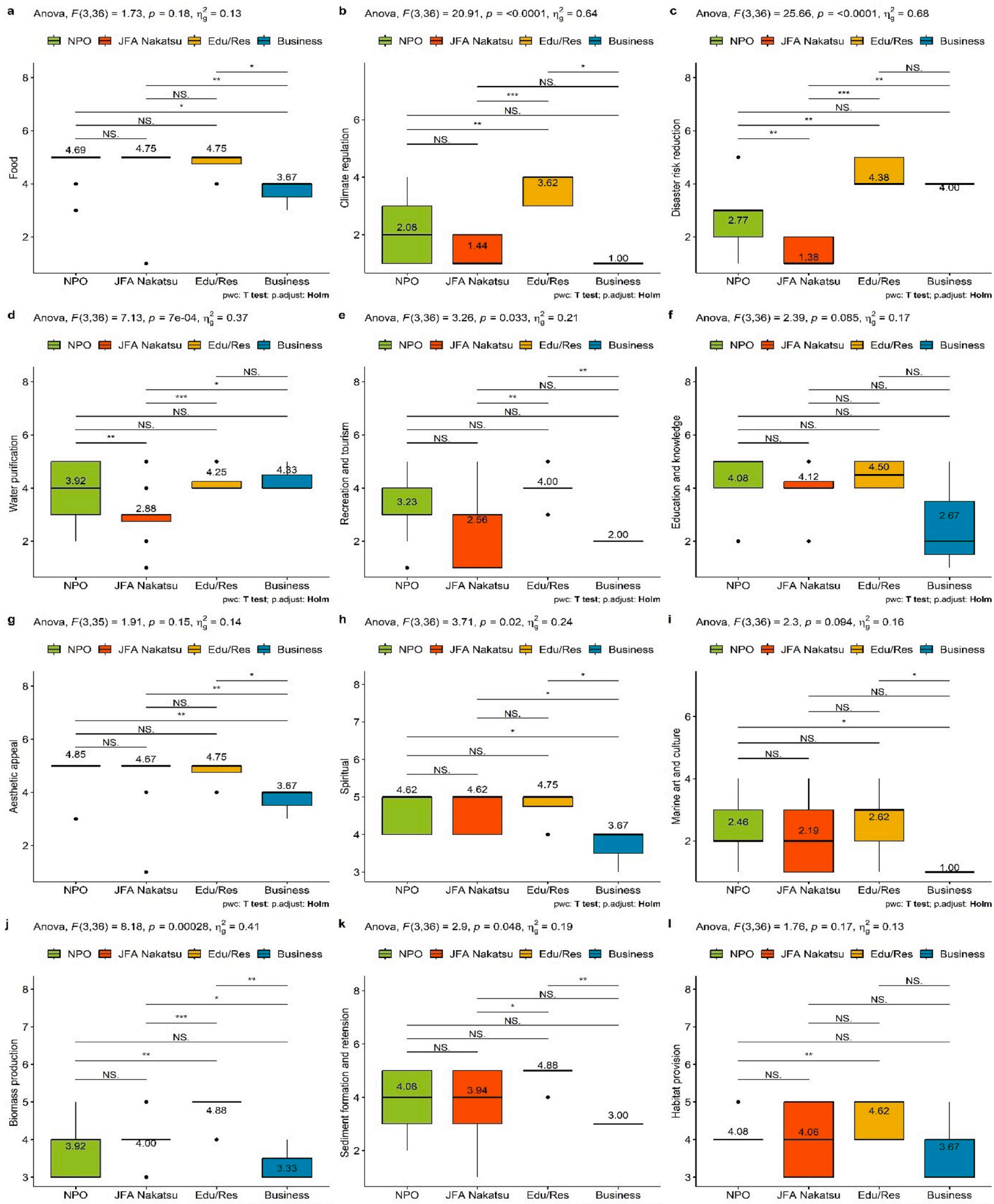

Fig. 5. Pairwise comparisons of perceived ecosystem service importance between stakeholder groups. *Note:* The midlines in box-whisker plots represent the median values and the numbers the mean values. The bottom and top edges of each box indicate the 25th and 75th percentiles, respectively. The whiskers extend to 1.5 times the interquartile range and outliers are marked using dots: ***$p < 0.01$; **$p < 0.5$; *$p < 0.1$; NS denotes non-significant difference.

and loss of TLK on the sustainable use of the mudflat. For instance, a traditional method was the use of handheld tools to harvest clams, which prevented the solidification of the mudflat and enabled oxygen circulation to the mudflat area, which is essential for many mudflat species. However, nowadays, handheld tools are replaced by heavy machinery that dig deeper into the mudflat for clams, increasing both the disturbance to the mudflat and also might increase overexploitation. Furthermore, the expansion of seaweed and oyster mariculture, and

Table 5
Drivers of change and their mechanisms and outcomes in the Nakatsu mudflat.

Drivers of change	Main mechanisms	Outcome
Habitat change	• Dredging and sediment extraction causes erosion	• Loss of continuous mudflat stretches, which is important for habitat connectivity • Increased prevalence of muddy bottom conditions with low oxygen content in the sediments, which is important for the survival for fish and clams
Pollution	• Increased sewage causes increased toxicity (including in seagrass meadows) • Dredging and mudflat erosion, causes low oxygen in sediments	• Decline of fish and clam stocks • Increased prevalence of muddy bottom conditions with low oxygen content within the mudflat
Climate change	• Changing patterns of typhoons (in terms of intensity and numbers) • Increase in water temperature	• Increase of water temperature may have led to increase prevalence of invasive species • Change in typhoon patterns may have affected the constant mixing of the shallow seas, and as an extent nutrient distribution
Invasive species	• Increased predation on juveniles, clams and small fish stocks	• Decrease of fish and clam stocks
Overexploitation	• Prioritization and increased harvesting of species with higher economic value through modern fishing techniques	• Decrease of fish and clam stocks • Degradation of mudflat condition due to bottom dragnets
Population ageing and shrinking	• Lack of environmental awareness and TLK use among younger generations contributes to more dredging, port development and lower active use of the mudflat for provisioning services • Decline of farming livelihoods causes farmland loss, and conversion to built up land	• Loss of TLK alters fishing practices, contributing to decrease of fish and clam stocks • Habitat change from increased dredging, port development and construction
Fishing-related technology and institutions	• Increased prevalence of sophisticated boats (with GPS and sonar) and more powerful engines enables commercialized and intensive fishing	• Commercialized and intensive fishing practices contribute to overexploitation

demand for some particular types of fish has reduced the multi-species fishing in the Nakatsu mudflat, which was considered as a strategy to prevent overexploitation. It is worth noting that some respondents (n = 5) pointed to the possibly positive effects that population shrinking might have on fish demand and thus fisheries overexploitation, which could possibly increase fish stock in the long-term, though this is still a hypothetical scenario.

Several respondents also mentioned that population ageing and shrinking can have indirect effects to ecosystem change via changes in livelihoods. First, with most of the younger generation involved in the tertiary sector (i.e. service sector), those depending on fisheries for their livelihood tend to be more elderly (Section 2.2). These changes in livelihood were mentioned by 26 FGD participants as a vital mechanism influencing (as well as be influenced by) the loss of TLK. An allied issues here is that due to the population ageing and shrinking landholders and fishers feel difficult to continue working on the mudflat environment, and decide to sell their lands and mudflat areas for development projects, which further leads to the issue of dredging and port development (Section 3.3.2.2).

3.3.3.2. Technology and institutions related to fishing. The changes and developments in fishing technology and institutions were identified as another major indirect driver of ecosystem changes in the Nakatsu mudflat (n = 25). This relates to both changes in the user right system in the Nakatsu mudflat, as well as the in the increased used advanced fishing technologies rather than traditional fishing methods (Table 2).

The user rights in the Nakatsu mudflat changed from common property to a strict user right system with set areas for short neck clam harvesting, seaweed cultivation, octopus catching through pots, fishing with set nets and bottom drag nets, and port development. These rights are set by the Japanese Fisheries cooperative Nakatsu branch, which is a part of the Japanese Fisheries cooperative Oita branch (see Section 2.2). This change of user right in the mudflat has important ramifications for change in the mudflat, particularly in the context of TLK loss (see previous section).

On the one hand, these user rights in the mudflat "essentially dictate" whether the catch from the mudflat environments is going to be sustainable or will lead to overexploitation (see Section 3.3.2.1). For instance, the size of the mesh of the nets was decided following the user rights in the mudflat and fishers' livelihoods, and once set cannot be changed easily, which makes it a particularly important decision for the sustainability of fish stocks. Similarly, 26 FGD participants pointed that the increased use of bottom drag nets causes damages to the mudflat environment.

On the other hand, the transfer or change of rights in mudflat uses was also associated with ecosystem change. Twenty-six FGD respondents mentioned that fishers sold their user rights and fishing areas to port development for exchange of money, which paved the way for dredging and concretization through the development of ports and factories, leading to habitat loss (Section 3.3.2.2). With this decline in fishing areas, the fishing rights have been made stricter and strongly controlled by fishers and seaweed cultivators. As a result locals (even children) cannot enter the mudflat and the sea for other activities such as recreational fishing or birdwatching. Similarly, user rights for seaweed production in Nakatsu reduced the opportunity for oyster farming, which has been argued by participants as having lower impact on the mudflat. Fortunately, the Japan Fisheries cooperative, Nakatsu started trying to revive the oyster cultivation system by giving it the brand name *higata-bijin* literally meaning "mudflat beauty" (for more information, see https://higata.thebase.in).

Finally, a major mechanisms mediating ecosystem change is the fact that the traditional fishing methods (Table 2) are replaced by modern fishing tools, such as (a) fishing boats with higher engine power (n = 25), (b) bottom trawling nets, GPS, sonar (n = 19), and (c) highly resistant materials like nylon nets (n = 26). The fishing boats currently used in the Nakatsu area are made of fiber reinforced plastics and have more powerful engines which allows them to travel longer distances and have stronger trawling system. These technological advents in the trawling systems were essentially the reason that the indigenous bamboo weir structures were removed from the mudflat areas (Section 3.1). Furthermore GPS use increased among fishers after 1973 due to a decrease in the associated cost via market support of the market (n = 27). These radar and GPS systems have enabled fishers to both venture out to sea even when visibility is poor and revisit in short intervals areas with large schools of fish. Meanwhile, fishers now also use cordless devices and mobile phones to share information about the location of large fish schools (n = 14), contributing to the overexploitation of fish stocks. Those modern fishing tools have contributed to the decrease and phase out of TLK-based fishing in the mudflat areas (Section 3.1).

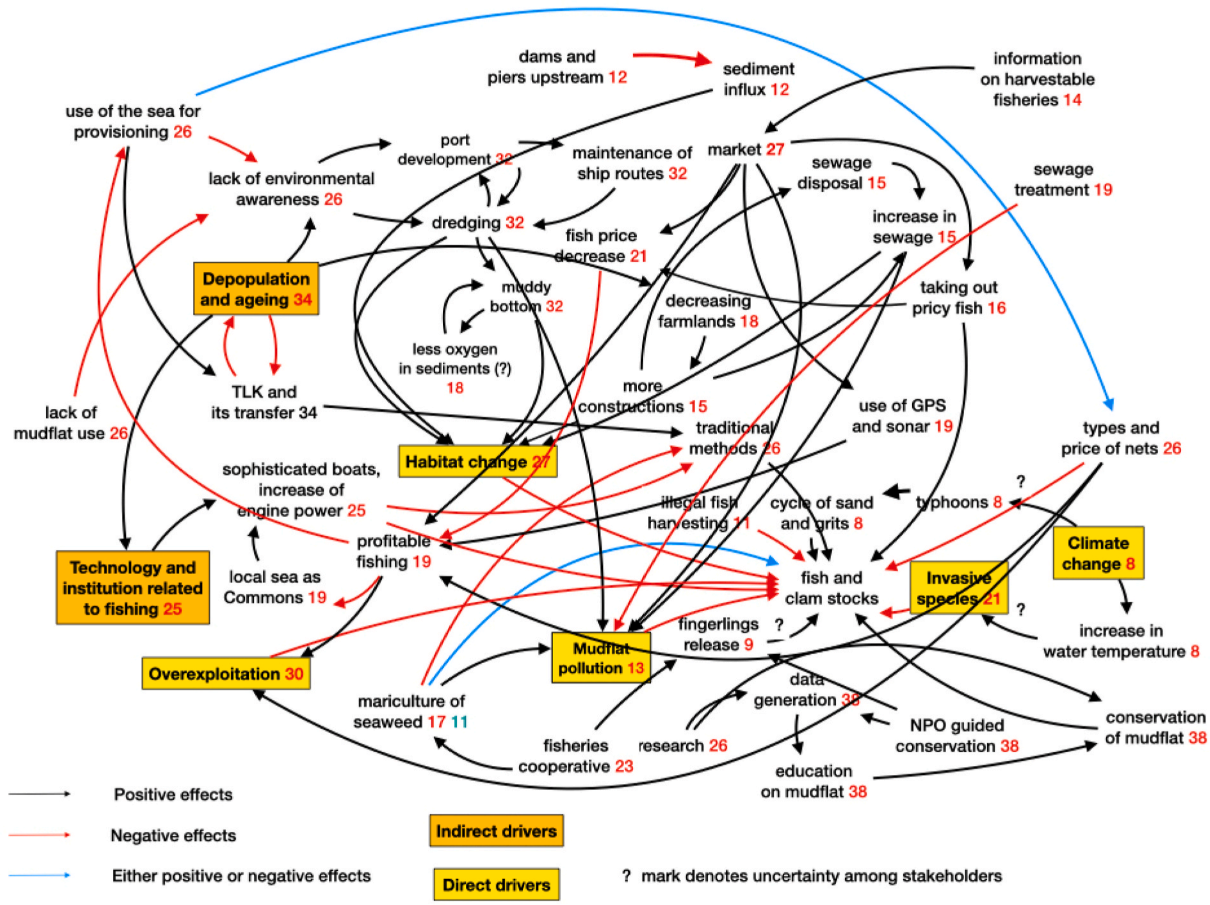

Fig. 6. Conceptual map/model of the drivers and mechanisms of ecosystem change in Nakatsu mudflat. *Note:* This qualitative information is elicited from the FGDs. Major direct and indirect drivers are denoted in boxes. Arrows denote the positive (black arrows), negative (red arrows) or bidirectional effects (blue arrows) of the mechanisms. Question marks (?) denote uncertainty about the effects of the mechanisms. Numbers indicate how many respondents mentioned each specific driver or mechanism.

4. Discussion

4.1. Reflections on knowledge integration

In this study, we applied a mixed-method approach that sought to elicit and synthesize the knowledge about the drivers of ecosystem change in a coastal environment (i.e. Nakatsu mudflat), and how it unfolded (i.e. mechanisms) (Section 1). To achieve this, we used a mixed-method approach that combined key informant interviews, FGDs, questionnaire surveys and geospatial analysis (Table 1). The FGDs was the main method to understand how change has unfolded in the mudflats, and brought together users and stakeholders with different types of knowledge (i.e. scientific, expert, TLK). Following the implementation of the different research methods, we can make certain reflections about knowledge integration and synthesis.

In more detail, the iterative and deliberative approach followed for the FGDs enabled on the one hand for the reflection and integration of different types of knowledge (deliberative component) and for the gradual enrichment of the concept map using these diverse knowledge types (iterative component).

Regarding the deliberative component, each individual FGD essentially provided a platform for dialogue and collaboration between stakeholders and users with different values, interests towards and understandings of the mudflat. This essentially provided a platform for co-production of research (Lopes and Videira 2016), as has been observed in various similar participatory and transdisciplinary research designs (Reed et al., 2013). However, it is very prone to inserting certain errors and biases about the depicted phenomena, or certain participants/voices/lenses dominating the process (Lawrence et al., 2022). We tried to minimize this through multiple rounds of consultations within each individual FGD, where each participant could articulate their opinion/knowledge (especially for some of the more controversial or poorly understood phenomena) and the final "requirement" for a consensus concept map from each FGD (see also Richards et al., 2004; Reed et al., 2013).

Regarding the iterative component, by using the output of each FGD as the input of the next FGD (Section 2.3.2) enabled for the gradual "evolution" of the conceptual map. This type of design prevented the research team from synthesizing on its own simply the consensus outputs of the eight individual FGDs, which would have likely inserted biases or errors. Instead, it enabled for the consistent input of different types of knowledge from the participants of each sub-sequent workshop, ensuring the minimal interference of the research team with the final output beyond the initial first draft and the moderation of the FGDs. It is worth noting here that the FGDs made some major changes in the input concept map, but progressively fewer and fewer changes were made. In fact, very few proposed changes were made in the last FGDs (i.e. FGD7 and FGD8), and no proposed changes were made during the final cross-checking with the four key informants (Section 2.3.2).

4.2. Mudflat ecosystem services and their perceived importance

Food provision is considered one of the most important ecosystem services provided by the mudflat (Table 4). This result is within expectation as the local fishers catch a variety of fish and other marine species (e.g. crabs, octopus, crustaceans, seaweed) throughout the year (Table 3). It is worth noting that seafood was not only considered a provisioning service but had also strong cultural significance, as most of this seafood is associated with unique preparation and eating methods that contribute to a specific local food culture. This has been identified also in other coastal/marine SES in Japan (Chakraborty and Gasparatos, 2019), as well as other parts of the world (Liu et al., 2019).

Regulating services related to climate regulation, water purification, and disaster risk were perceived as least important by respondents (Table 4), despite these ecosystem services were considered as some of the vital ecosystem services provided by mudflats (Sasmito et al., 2020; King and Lester, 1995; Wang and Wall, 2010). The underestimation of regulating services by the local respondents can be attributed to the invisible and slow process of changes (Groot et al., 2010) and lack of awareness and a better understanding of the importance of these services (Mengist et al., 2020), which also observed in other similar contexts in Japan (Shoyama and Yamagata, 2016) and elsewhere (Gouwakinnou et al., 2019). It is worth noting that the lower understanding and perceived importance of regulating services by local communities and stakeholders can contribute to further degradation of these services through shore concretization and port development (see Fig. 6) (Shibuya et al., 2011).

Interestingly, respondents have diverse perceptions toward cultural services, with aesthetic, spiritual, and education and knowledge. Respondents showed a strong aesthetic appreciation (Table 4) of the beauty of the mudflats during low tide at sunrise and sunsets where runnels are visible and provide pleasant scenery. Migratory birds and their activities here hold another part of the aesthetic beauty of the mudflats. A few studies also have discussed the aesthetic values of mudflats (Passarelli et al 2018). Interestingly, the mudflats are not directly related to art and culture, such as dances and festivals based on the sea and its creatures, as seen in other nearby coastal areas (Chakraborty and Gasparatos 2019). The perception of recreation and tourism opportunities is also of low importance by respondents. This is inconsistent with studies that have discussed the importance of recreation and tourism potential of mudflat areas (Wang and Wall, 2010; Choi et al., 2015). It should be noted that forty years ago, the pine forests of Nakatsu mudflats were picnic spots for recreation. The low perceived importance of recreation and tourism may be a factor of lifestyle change (also mentioned in the FGDs). We must note here that cultural ecosystem services cannot always be identified or assessed easily, as they are often intersecting and intangible (Huynh et al., 2022). In this study we verified the elicited cultural ecosystem services through a combination of (a) examples/explanations of how respondents perceive a given cultural service, (b) reviews of similar studies that have also focused on the cultural appreciation of mudflats (see, Passarelli et al 2018), and (c) cross-checking with locally available secondary literature. For instance, the study participants often linked the aesthetic beauty of the mudflat, to the vast expanse of the sea in the area and the features of the runnels that reflect the light of the setting sun. Similarly, when discussing cultural ecosystem services associated with recreation the respondents mentioned several migratory bird species (including rare and endangered species) that they observe in the mudflat. The data about migratory birds was further reconfirmed with the "Nakatsu Tidal Flat Report" for the year 2018 (Nakatsu Waterfront Conservation Association, 2018) published annually by the Nakatsu Waterfront Conservation Association.[3] Such triangulation exercises were necessary to ensure that cultural ecosystem services were understood by the respondents that their perceived importance was elicited properly.

It is somewhat unexpected that local stakeholders assigned high importance on supporting services (i.e. biomass production, habitat provision, and sediment formation and retention), which is relatively inconsistent with evidence in other global contexts (Aryal et al., 2021). This suggests that the local stakeholders involved in our study likely have high ecological knowledge of the mudflat ecosystem in general. This is not necessarily impossible as some studies have argued in such cases of high perceived importance of supporting services the respondent perceptions generally parallel scientific knowledge, which could represent a good starting point for ecosystem conservation and restoration (Smith and Sullivan, 2014). However, we also should consider that this high perceived importance of supporting services may not be representative of the entire population of the area (refer to Section 2.3 for sampling). Also, in our case, there are strict conservation rules for the use of the Nakatsu mudflat, as well as various educational and knowledge-sharing activities carried out by the Nakatsu Waterfront Conservation Association. It is possible that for some respondents these perceptions have been shaped by the active use of the ecosystem and/or engagement in educational/cultural activities in a strict conservation area where knowledge about these ecosystem services is shared.

Finally, most respondents suggested that the intact and unaltered mudflat areas had high bequest values, associated with satisfaction for preserving it for future generations to have access to the benefits it provides (TEEB, 2010). These bequest values are associated with provisioning for future generations (i.e., food from the mudflat) and aesthetic value (see Table 4) which is a source of pride and cohesion for the local community, as observed in other coastal/marine SES including Japan (Kvarnström and Boström, 2018; Chakraborty and Gasparatos, 2019). Social cohesion can help increase SES resilience through collective decision-making anchored on a shared understanding of coastal resources, particularly in areas characterized by population ageing (McElduff et al., 2016, Jurjonas and Seekamp, 2018).

4.3. Systematizing ecosystem change

The FGDs identified 5 direct drivers and 2 indirect drivers that are responsible for the change observed in the mudflat ecosystem in Nakatsu (Table 5). These drivers are highly interconnected through various mechanisms. Below we critically discuss the drivers and mechanisms most commonly mentioned by the FGD participants, namely population ageing and shrinking, loss of TLK, overexploitation, habitat change, and economic and infrastructure development.

Overall, there is no single driver or mechanism that is solely responsible for ecosystem change in Nakatsu mudflat (Table 5, Fig. 6, Section 3.3). Instead we found a series of drivers and mechanisms, which interact strongly and in complex ways due to the underlying environmental and societal dynamics. This strong interaction and complexity in ecosystem change is in line with other research on dryland ecosystem change (Zeng et al., 2021), peatland degradation (Dohong et al., 2017), and mangrove degradation (Yando et al., 2021). These drivers and mechanisms interacted temporally (e.g. population ageing and shrinking interacted with technological development and changes in user right system leading to the loss of TLK-based practices), spatially (e.g. farmland decrease interacted with land-based sewage disposal leading to mudflat pollution), and institutionally (e.g. local fishermen sold their rights to the development department leading to habitat loss). Such types of interactions are also reported in studies related to ecological land degradation-restoration (Feng et al., 2021), vegetation change (Kang et al., 2021), and species invasion (Elmhagen et al., 2015).

It is also interesting to note that the aforementioned interactions/effects can be either negative or positive or both. For instance, seaweed mariculture could, on the one hand, protect the mudflat area from appropriated for development and concretization, which could eventually have positive effects for fish and clam stock. On the other hand, the pollution from seaweed cultivation (e.g., eutrophication) could have negative impacts on fish stock and reproduction (Hasselström et al., 2018). A similar argument has been made that technological change has

[3] This is an annual collaborative report on bird species identification and population count conducted by the Nakatsu Waterfront Conservation Association and members of Wild Bird Society of Japan (*Nihon yacho no kai*).

both positive (i.e. increasing the productivity or efficiency with which ecosystem services are obtained) and negative effects (i.e. increasing pressure on ecosystems) for ecosystem change (Petschel-Held et al., 2005).

According to Section 3.3.2.1 fisheries overexploitation is a major driver of ecosystem change in the mudflat, which is a typical driver of change for ocean and coastal ecosystems, such as mangroves (Polidoro et al., 2010), saltmarshes (Altieri et al., 2012), and coral reefs (Newton et al., 2007). However, studies on how the linkages between fisheries overexploitation and mudflat ecosystem degradation unfold are relatively scarce compared to the other types of ecosystems mentioned above. Here we find that fisheries overexploitation was the most commonly identified direct driver for mudflat ecosystem change in the Nakatsu area through the experience-based understanding of the FGD participants (Section 3.3.2.1). On the one hand, the use of modern fishing tools contributed to the decrease and phase out of low intensive TLK-based fishing practices in the mudflat areas, which reflects tensions between traditional and highly modernized intensive fishing practices elsewhere (see Longo et al., 2011; Longo and Clark, 2012). On the other hand, the unregulated nature and high elasticity of the local fish market was indicated to be influencing fishers' incentives to catch more fish. Similar concerns have been identifying in studies applying bioeconomic models to estimate the relationship between price and yield in order to find the equilibria of sustainable fisheries (Auger et al., 2010; Mansal et al., 2014; Rodriguez et al., 2021). It has been argued that under reasonable prices, costs, and discount rates it is not economically viable/beneficial to overexploit fisheries even with very low growth rates (Grafton et al., 2007). This is arguably reflected in the perspectives of local FGD participants that the local fisheries cooperative should apply better economic means to control the fish prices change with fish availability on that day, as a means of better regulating the fish market and price.

According to many FGD participants, habitat loss is a direct driver that is strongly connected to the coastal economic development (Section 3.3.2.2), which is consistent with studies tracking the loss of natural coastal wetlands through land conversion, dredging and infrastructure development (Lin and Yu, 2018; Cunning et al., 2019). On the one hand, the increase in economic development activities and shoreline concretization have changed the mudflat habitat, which has been noted in other mudflat areas next to major development activities such as at Isahaya Bay in Japan, and Saemangeum in South Korea (Sato, 2006). This conflict and the trade-off that needs to be made between habitat conservation and economic growth is crucial in areas undergoing economic development and in particularly sensitive systems with high biodiversity (Dietze and Adger, 2003; Pagani-Núñez et al., 2022). On the other hand, coastal concretization is a common trend in Japan, with artificial shorelines increasing by about 2500 km between 1978 and 1996 (Yanagi, 2007). The main purpose of the expansion is to mitigate the impact of waves especially during natural disasters such as typhoons and tsunamis (e.g., structures observed in the Oshinden area in the Nakatsu mudflat). However, it is interesting to note that despite the observed declines in the frequency of typhoons in Nakatsu according to the FGD participants (Section 3.3.2.5), local communities still prioritized traditional concrete walls for typhoon and tsunami protection. Still many studies have suggested that the construction of coastal revetments can have adverse effects on the land-sea interface, as it decreases ecological connectivity between coastal areas (Dugan et al., 2011), as reported in different types of coastal and marine ecosystems (Chapman, 2003; Bozek and Burdick, 2005).

Finally, the loss of TLK (and its transfer) due to population ageing and shrinking is considered by local stakeholders as a very critical indirect driver of change in the Nakatsu mudflat ecosystem (Section 3.3.3.1). TLK loss often intersects with overfishing as outlined above, as the TLK-based practices in the Nakatsu mudflat used by many households (Section 3.1, Table 2) tended to have a comparatively low impact on the coastal fisheries, by putting lower pressure on fish and shellfish stocks, and reducing the capture of juvenile fish and the discard of captured fish. These types of resource harvesting activities (Table 2) have been argued to be methods of active conservation within heavily used coastal areas, and cannot be maintained without a rich pool of TLK held, practiced and improved through livelihood practices (Aswani and Hamilton, 2004; Aswani and Lauer, 2006). The loss of TLK-based ecosystem management practices due to population ageing and shrinking has been identified as a serious problem contributing to the degradation of SES in developed (Cetinkaya, 2009; Iniesta-Arandia et al., 2015; Kamiyama et al., 2016; Tattoni et al., 2017), and in developing contexts (Assefa and Hans-Rudolf, 2015; Reyes-García et al., 2013; Queiroz et al., 2017). We need to point that in some contexts population ageing and shrinking can reduce human pressure on ecosystems (Davidson and Andrews, 2013; Davidson et al., 2014). However, in our case study the ecosystem outcomes of these demographic changes are not that straightforward (see also Jarzebski et al., 2021), as many respondents suggested that these demographic processes couple with the loss of TLK, and the alternative use of the mudflat (with dredging and port developments) to have adverse changes to the nearshore environment in the long-term. Such synergistic and cascading effects have been identified also in other contexts (Shiraishi, 2001; Unger, n.d.; Jansuwan and Zander, 2021).

4.4. Implications, recommendations and future research

When looking at the greater picture, the information synthesized from the expert interviews and FGDs suggests the loss of connectivity (in the broadest sense) within the mudflat system due to the multiple processes of ecosystem change discussed in the previous sections. As the Nakatsu mudflat is part of a greater mudflat system spanning from the Sone mudflat in Fukuoka to the Northern part of the Kunisaki peninsula (Otsuka et al., 2020), our findings might explain better some of the broader ecosystem change processes observed in the region.

Although, dredging and concretization have been identified as the two major factors behind the loss of ecological connectivity locally (Section 3.3) (and possibly regionally), our study suggests that this direct driver of change closely intersects with multiple other indirect demographic and socioeconomic drivers of change (Section 3.3, 4.3). Parallel to these landscape modification processes contributing to the loss of ecological connectivity, participants also identified a significant societal disconnect with the mudflat. This has manifested via changes in mudflat uses and associated practices (Section 3.1) and related TLK (Section 3.3), which arguably has had a negative feedback effect for the societal connectivity with the mudflat. In this sense, while the conservation/protection actions helped to some extent to avoid some of the landscape degradation processes (i.e., stable mudflat extent) (Section 2.2, 3.1), there were still changes in the perceived benefits from (and livelihoods connections with) the mudflat (Section 3.2-3.3), as well as TLK erosion for the sustainable management of the mudflat (Section 3.3).

Considering the above, we argue that to ensure mudflat sustainability there is a need to move beyond its conservation/protection, by reinvigorating existing and forging new social connections with the mudflat. In this respect further to continuing the current conservation/ protection efforts, we identify four interlinked policy and practice priority areas to achieve this: (a) ensure the delivery and valorisation of the multiple ecosystem services provided by the mudflat, (b) promote an adaptive approach to understanding how change unfolds and identifying sustainable solutions, (c) re-invigorate TLK practices for the sustainable management of critical mudflat areas, (d) increase the awareness of local stakeholders and visitors for the ecological importance, multiple benefits, and intersecting change processes within the mudflat.

First, Section 3.2 shows that the mudflat does not only provide multiple ecosystem services, but also that their importance is perceived differently across different stakeholder groups. This clearly indicates that there are different interests and values for the mudflat, which need to be acknowledged in future management efforts. Ensuring the delivery of multiple ecosystem services and avoiding (to the extent possible) ecosystem service tradeoffs could create broader incentives and a common interest space among stakeholders to enable the sustainable management of this coastal ecosystem (Lebreton et al., 2019).

Second, Section 3.3 shows that there are multiple factors affecting ecosystem change in the Nakatsu mudflats. In fact, demographic drivers such as population aging and shrinking, contribute to the loss of TLK and the deployment of technologies and institutional mechanisms that degrade the mudflat and intersect with broader development processes in the area (Section 3.3). This means that it is highly unlikely that a single solution could feasibly solve the sustainability challenges in the mudflat, and/or that some of the processes are beyond the capacity of local stakeholders to tackle. This would most likely require adaptive processes to understand change in this coastal ecosystem and identify and implement appropriate solutions (Nichols et al., 2019; Bahri et al, 2021).

Third, there are concerns about the sustainable use of the mudflat considering the gradual loss of several traditional activities/practices (Section 3.1) and TLK (Section 3.3) such as bamboo wier fisheries and use of handheld fishing tools for clam extraction. We argue that the re-invigoration of such practices, at least in the most critical areas of this ecosystem, can help promote its sustainable management. However, we need to be also mindful that given the multiple interests at play and the lower economic viability of such techniques there might be certain limits to such re-invigoration. Possible zoning of the mudflat for such practices and linkage to recreational and educational activities (e.g. through agrotourism) can possibly enhance their viability in critical ecological areas outside the conservation/protection zone (Choi et al., 2015; Lee, 2022).

Fourth, there is a need to continue raising awareness about the importance and change of the mudflat among stakeholders and local communities. Studies have shown that awareness-raising efforts can forge public support and consensus among different interests on how to approach coastal ecosystem management (Duarte et al., 2008; Lagbas and Habito, 2016). The current awareness-raising and education efforts of the NPO can form a solid foundation to build upon, but considering the multiple vested users and interests, achieving wider-reaching effects would likely require leveraging further support. For example, awareness-raising efforts can be linked with the ongoing corporate sustainability actions of the major private sector players or efforts to engage local fishers to demonstrate TLK practices for visitors (see above).

We believe that central to all of the above recommendation would be the development of a multi-stakeholder platform where the different understandings and interests about the mudflat can be articulated and used to identify solutions through the mobilization of the different types of knowledge held by the stakeholders.

This study aimed to be a first step by eliciting through qualitative research the multi-dimensional knowledge of how ecosystem change unfolds, and reflect on its implications. Although we discovered multiple factors and drivers that are responsible for mudflat change, we did not capture in a quantitative manner how these factors operate or interact, but instead identified possible variables that can be used for future research to understand the magnitude of these phenomena. Two important aspects would be to (a) move beyond the perceived importance of ecosystem services outlined here (Section 3.2) to assess actual ecosystem services provision within the SES, (b) quantify the relative effects of the different drivers of change (Section 3.3). This future research in Nakatsu mudflats and similar coastal ecosystems in Japan should be the foundation for developing testable hypotheses about the magnitude and directions of these linkages, and identifying which have the greatest effect and potential to reverse ecosystem change if targeted by appropriate response options. Participatory scenario analyses can help create shared visions of the mudflat and identify possible and mutually acceptable pathways and responses to achieve the sustainable management of the coastal SES (Palomo et al., 2011; Oteros-Rozas et al., 2015; Gourguet et al., 2021).

5. Conclusion

In this study we combined primary and secondary data through a mixed-method approach to understand the extent, status and main human activities in the Nakatsu mudflat, Japan, as well as the perceived importance and the change processes therein. We critically synthesized this information to identify priority areas for the sustainable management of the mudflat. This process mobilised local stakeholders with different types of engagement with (and knowledge of) the mudflat. The results suggest that the mudflat provides very diverse ecosystem services, which have, however, very diverse perceived importance between stakeholder groups (Section 3.2). Although the geospatial analysis indicated no significant change in mudflat extent over the last 30 years (Section 3.1), the different participants identified significant changes in this coastal ecosystem that contribute to its gradual degradation (Section 3.3). Some of the main changes relate to dredging, port developments, and fisheries overexploitation due to the adoption of new fishing technologies. These drivers are exacerbated by the loss of TLK (particularly through population ageing and shrinking) and the securitization and selling of fishing rights.

The paper highlights that participatory processes which can effectively mobilise stakeholders with complementary understandings and types of knowledge can indeed provide rich information about the interlinked factors affecting coastal ecosystem change. In this sense the combination of scientific, expert-based and TLK-based knowledge can offer a more comprehensive and nuanced picture of coastal SES change and conservation. In our case the knowledge about the change and loss of vital mudflat functions, combined with the radically differentiated perceived importance of multiple ecosystem services among stakeholder groups, provides useful information on how this coastal ecosystem degrades, as well as who is likely to be affected. This is not necessarily obvious when looking simply at the lack of change in the spatial extent of the mudflat. It is here that this combination of different types of knowledge can help in identifying mutually acceptable approaches for the sustainable management and use of coastal SES.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Acknowledgements

We thank the stakeholders in the study area for their inputs in the Focus Group Discussions. The authors acknowledge the Hosei University Internal Research Fund (*Kojin Kenkyu-hi*), which funded part of the research. AG acknowledges the financial support of the Japan Society for the Promotion of Science (JSPS) for a Grant-in-Aid for Scientific Research A (22H00567).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106729.

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