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A capital-based framework for assessing coastal and marine social–ecological dynamics and natural resource management: A case study of Penghu archipelago

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Abstract Human behavior and the environment interact reciprocally. It is necessary to understand social and ecological systems as an integrated co-evolving social–ecological system (SES) to reveal why an environment is in its current condition and how humans have impacted upon and been influenced by the dynamics of natural system. Many societies in coastal and marine SESs rely on marine natural capital for their livelihoods. They have adjusted to changes in natural capital by utilizing human-made capital (i.e., physical, human, and social capital), and their behavior is simultaneously influencing the natural capital. This study conceptualizes a capital-based framework for investigating the adaptation and transformation of a social–ecological system on temporal scale and provides a case study of Penghu Archipelago, Taiwan, with a 110-year historical review of the period of 1900–2010. It is furthermore examined how human society adapts to marine natural resource problems in order to understand the coping strategies. The results show human-made capital is inadequate with respect to sustaining marine natural resources. Appropriate investment in human-made capital is required for solving the problem. The challenge is to invest in social capital so as to form functional institutions that employ physical and human capital in a sustainable manner.

Introduction

Humans affect and are affected by the natural environment. In order to understand their interactions and the dynamic processes, an increasing number of studies have emphasized social systems and ecological systems as an integrated social–ecological system (SES) and placed focus on their co-evolution

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trajectories (Olsson et al., 2004; Folke, 2006; Liu et al., 2007; Brondizio et al., 2009; Glaeser et al., 2009; Ostrom, 2009; Norgaard, 1994). As defined by Glaser et al. (2012), an SES "consists of a bio-geo-physical unit and its associated social actors and institutions". It can be "delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context". It is composed of resources, actors, and its governance (Holdschlag and Ratter, 2013; Ostrom, 2009). In a coastal and marine SES (CM-SES), ecosystems provide extensive services that support the livelihood of human beings (Glaser et al., 2012; Ferrol-Schulte et al., 2013). The amount of coastal and marine natural resources directly influences those whose livelihoods depend on it. Since the coastal and marine environment and its associated natural resources are highly uncertain, societies must adapt to the dynamics of the system not only to sustain but also to develop their livelihoods (Marshall, 2013). In addition, adaptation is a dynamic process involving actions of an individual or a group of people to better cope with social and ecological change (Chakravarthy, 1982; Smit and Wandel, 2006; Nelson et al., 2007; Marshall, 2013). These actions simultaneously change the environment and require further adaptation. This study focuses on the adaptation process of human society in this complex interaction on a temporal scale and proposes a capital-based framework using natural and human-made capital to explore the complex interactions within a CM-SES. A case study of the Penghu Archipelago, a regional CM-SES, is used for understanding the main research question: how a society adapts to the dynamics of an CM-SES for sustaining livelihoods using human-made capital. The focus on Penghu helps provide a general picture of the causes and effects of current problems as well as their linkages upward to national and downward to community levels in the globalized world (Glaser and Glaeser, 2014). This paper sets out the concept of the capital-based framework and the rationale for using natural capital, human-made capital, and their interaction for understanding the reciprocal dynamics of a CM-SES. The roles that human-made capital play in societal adaptation and transformation in light of SES dynamics are discussed following a historical overview of the Penghu CM-SES. Bearing in mind the current marine natural resource crisis, which threatens people's livelihoods, suggestions are made for appropriately constructing human-made capital for sustainable use of natural capital.

A capital-based framework: interactions between natural and human-made capital

Costanza and Daly (1992) define natural capital as "the stock of natural ecosystems that yields a flow of valuable ecosystem goods or services into the future". Natural resources are stocks that generate ecosystem services and benefit human beings. For an example, fish stocks are natural capital utilized by fishermen for their livelihoods (Hein et al., 2006). For fishermen, fish cannot only be food but must also be goods that can be exchanged for other needs. The combination of fish stocks, fishermen, and governance (institutions regulating fishing activities) comprise a fishery SES (Ostrom, 2009; Holdschlag and Ratter, 2013), which is a subsystem of a CM-SES on a functional scale (Wu, 2013). Compared with natural capital, human-made capital is seen as the ability of societies to adapt to changes (Walker et al., 2006). Different components of human-made capital have been utilized for different purposes. In the sustainable livelihood (SL) framework used for poverty reduction, human, physical, financial, and social capital are regarded as human-made capital interacting with natural capital (Ellis, 1999; Krantz, 2001). To understanding how to sustainably use natural capital, Berkes and Folke (1994) do not discuss the forms of human-made capital *per se* but instead utilize the concept of cultural capital, which links natural capital and human-made capital. In a capital assets framework, Bennett et al. (2012) regard human, physical, social, financial, cultural, and political capital as human-made capital for assessing tourism development capacit0079. In contrast, Ostrom (1999, p.174) adopts human, physical, and social capital as components of human-made capital, which is "created by individuals spending time and effort in transaction and transformation activities to build tools or assets today that will increase individual and social welfare in the future". Although human, physical, and social capital are the only human-made capital elements in Ostrom's concept, financial, cultural, and political aspects are elements composed by her three human-made capitals or are produced by their interactions.

In this study we adopte the Social-Ecological System Framework conducted by Resilience Alliance (2007, p.8) (Fig. 1) as a basis and conceptualize the 'capital-based' framework for assessing social-ecological dynamics (Fig. 2). In the capital-based framework, this study uses a more inclusive notion of human-made capital, presenting human, physical, and social aspects as a whole (human-made capital) for investigating their interactions with natural capital (Fig. 2). The concepts of human, physical, and social capital are examined as followed:

Human capital

Schultz (1961) claims that human capital includes not just the labor force but also the knowledge and skills of individuals, which can facilitate productive activities and help people change themselves to fit their changing surroundings (Coleman, 1988). This study discusses human capital in the form of number of fishermen, outsourced labor, increasing knowledge, and fishery sector skills. Social capital can influence human capital through information distribution and cooperation between individuals or groups (Brondizio et al., 2009; Cash et al., 2006).

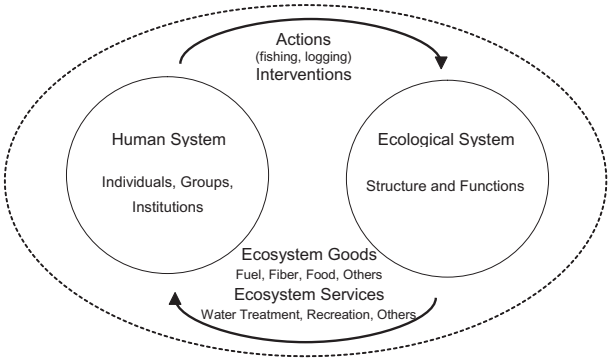

Fig. 1 Conceptual diagram of a social-ecological system (Resilience Alliance, 2007, p.8).

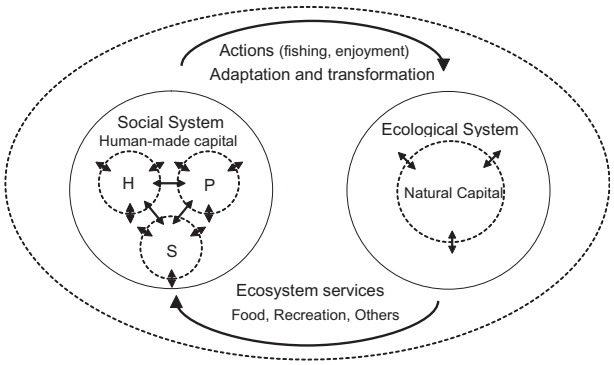

Fig. 2 Conceptual diagram of the capital-based framework for assessing social–ecological dynamics. There are interactions between social system and ecological system as well as between human-made capital and natural capital. (H: human capital, P: physical capital, S: social capital, arrows represent the dynamics of capital and their interrelationships) (Adopted and modified from Resilience Alliance (2007, p.8)).

Physical capital

In Coleman's definition (Coleman, 1988), physical capital is a stock of human-made material resources that can be used to produce a flow of future income. Physical capital exists a wide varity of forms, including tools, equipment, techniques, and facilities that can be used for developing future production (Brondizio et al., 2009). The physical capital discussed in this study is composed of technologies that improve marine natural resource utilization such as improved vessels, gears, facilities, and fishery equipment. Besides, in the absence of human capital in the form of knowledge, skills, and workforce, physical capital cannot be generated or operated for increasing production and income. When physical capital is used for the benefit of a group or society rather than of an individual, social capital is also necessary for linking the network and regulating its use (Ostrom, 1999).

Social capital

Putnam et al. (1994, p. 167) defines social capital as "features of social organization, such as trust, norms, and networks, that can improve the efficiency of society by facilitating coordinated actions". It is an important human-made capital that can facilitate collective action and influence adaptive capacity (Adger, 2003; Woolcock and Narayan, 2000). In its many forms, Ostrom (1999) suggests it is "the shared knowledge, understandings, norms, rules, and expectations about patterns of interactions that groups of individuals bring to a recurrent activity". Brondizio et al. (2009) furthermore connect social capital in the form of institutional arrangement for natural resource management, emphasizing social capital's function on linking governance systems across different level SESs. Institutions are the formal or informal rules for regulating human behavior (North, 1990; Leach et al., 1999). Social capital is crucial for a society's ability to provide appropriate and effective institutions for governing natural resources and adapting to the dynamics of SESs (Ostrom, 1990; Young, 1996; Berkes et al., 2000). Institutions appropriate to the SESs can help build social capital for society to adapt to system changes (Upton, 2008).

Social adaptation occurs through institutional transformation within SESs. Top-down and bottom-up approaches are both important for governing natural resources. This study emphasizes the analysis of governmental institutions for three reasons. First, governmental institutions are crucial for framing society's adaptation path and for shaping an SES to its current state (Pike et al., 2010; Reed and Bruyneel, 2010). Second, though many community-based institutions were generated in Penghu, they were legalized through governmental institutions. Since community-level institutions encountered mismatch problems caused by rapid, globalization-driven changes, their adaptation to these changes required the help of other enforcement (Wu, 2013). Functional government institutions thus become a key factor in supporting community-level institutions. Third, a society's social capital for developing sustainable livelihoods is strongly affected by governmental institutions. Institutions that suit the SES could contribute to social capital, which can further facilitate institutional adjustment to change. In contrast, mismatched institutions could harm social capital and thus decrease adaptive capacity (Brondizio et al., 2009; Marshall, 2013; Ostrom, 1999; Adger, 2003).

Methods

In order to understand the co-evolution of a CM-SES, a review with long time frame is necessary: this reveals why an environment is in its current condition and how humans have influenced and been influenced by the dynamics of the system. It helps explain the path-dependent co-evolutionary trajectory of the specific SES and the changes in the relationship between social and ecological systems over time (Hughes, 2009, p. 4; Reed and Bruyneel, 2010). Olsen et al. (2009) propose a 100-year timeline as essential for examining the trajectory of long-term trends of ecosystem change. This study provides a historical review of the period 1900–2010 in Taiwan's Penghu Archipelago as a case study to investigate the adaptation and transformation of the CM-SES over this 110-year period. Fishery represents the starting point, for this is the most fundamental means by which marine ecosystem services contribute to livelihoods in the form of income. In Taiwan, fishery is categorized as coastal (within 12 nautical miles), offshore (12–200 nautical miles), distant water (> 200 nautical miles or high seas), and aquaculture. Since the aim of this study is to understand the direct exploitation of wild stock and there is no distant water fishery conducted around Penghu, focus rests on coastal and offshore fishery. Coastal and offshore fishery production, number of people employed in the fishery, and the transformation of governance systems were investigated to understand the dynamics of the CM-SES over these 110 years. While governance system is critical for shaping the co-evolution trajectory of an SES (Pike et al., 2010; Reed and Bruyneel, 2010), emphasis is placed on the role of institutions in facilitating societal adaptation in the SES.

Historical review of Penghu

Ecological system of Penghu

The Penghu Archipelago also known as the Pescadores (from the Portuguese word for "fishermen"), consists of 90 small islands with a total land area of approximately 127 square kilometers. Lying in the middle of the Taiwan Strait (Fig. 3), it is about 50 km from the west coast of Taiwan and about 145 km from the east coast of China. It consists of 90 islands and numerous wave-swept rocks. The islands were formed by a

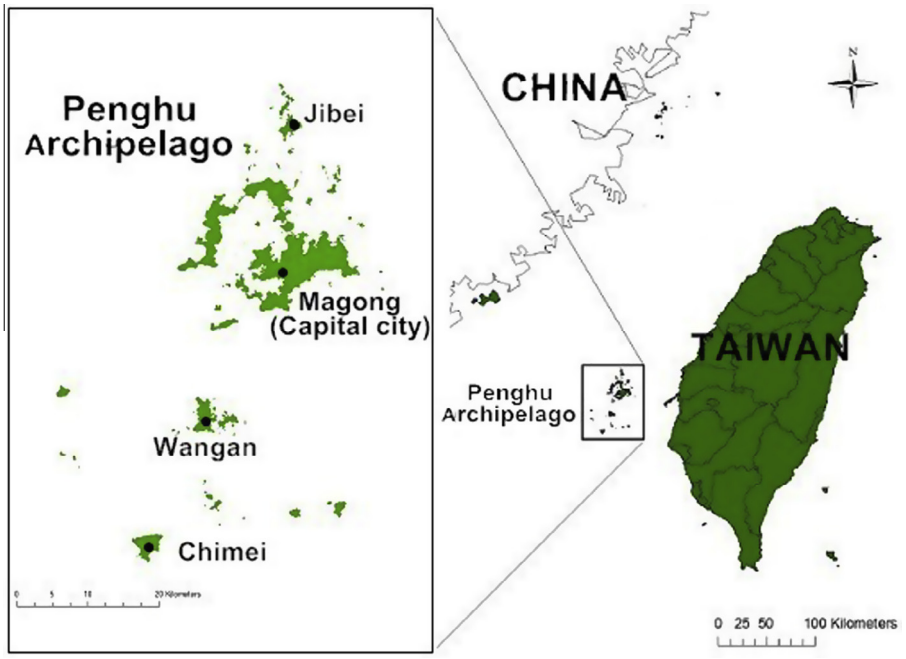

Fig. 3 Map of the Penghu Archipelago.

mass of basalt rising from the sea through volcanic action, which resulted in a spectacular landscape. Currently, 19 of the 90 islands are inhabited (Tsai, 2009). The archipelago is a county with 96 villages as administrative subunits.

Crossed by the Tropic of Cancer, the archipelago's climate is in the transition between the tropical and sub-tropical zone and is characterized by hot summers and windy winters. The strong northeast monsoon wind in winter can reach typhoon level (Hsu, 2005, p. 200). The area receives an average annual rainfall of about 1000 mm, which falls mainly in the summer. However, the hot summers and strong winter winds mean that evaporation is higher than precipitation. The development of agriculture has been hindered by limited land, lack of fresh water, and severe weather conditions during winter.

The sea surrounding Penghu is part of the South China Sea eco-region in the Central Indo-Pacific (Spalding et al., 2007). Several upwelling zones in this area have been identified as important fishing grounds (Tang et al., 2002). The ocean environment is influenced by the Kuroshio Current and the China Coastal Current. These currents bring nutrients to Penghu and disperse larvae and juveniles of various marine organisms (Hsieh et al., 2007).

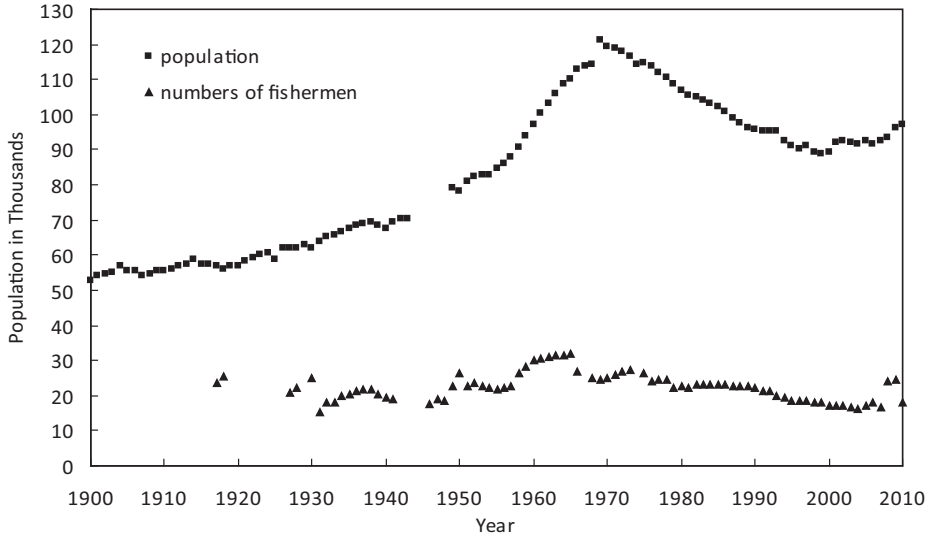

Fig. 4 Dynamics of population and number of fishers in Penghu County from 1900 to 2010. Data not shown in the diagram is unavailable from the sources. Sources: Taiwan Governor-General (1900–1943) and Budget, Accounting and Statistics Office, Penghu (1949–2010).

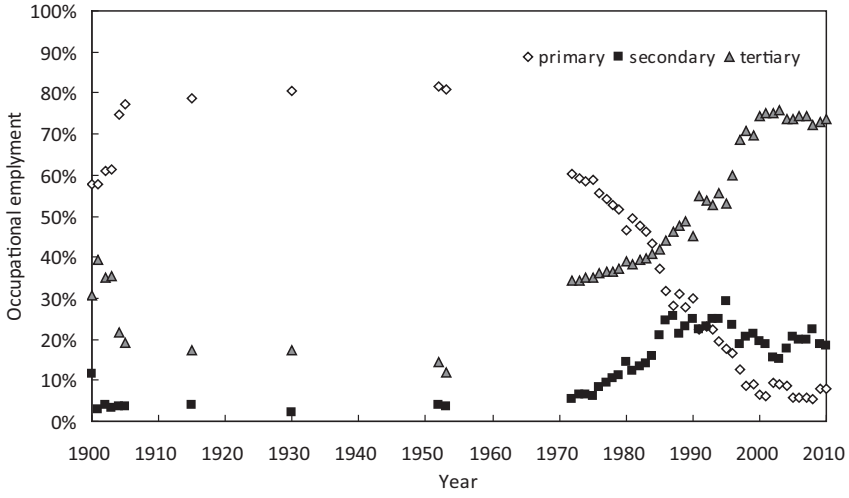

Fig. 5 Economic structure by the percentage of people employed in primary, secondary, and tertiary industries (%) in Penghu County from 1900 to 2010. Data not shown in the diagram is unavailable from the sources. Sources: Taiwan Governor-General (1900–1930) and Budget, Accounting and Statistics Office, Penghu (1952–2010).

Social system of Penghu

Population dynamics in Penghu

The number of inhabitants of Penghu rose slowly during the Japanese colonial period at the beginning of the 20th Century (Fig. 4). After the end of Japanese colonization in 1945, the population increased rapidly and almost doubled within 20 years, peaking at 121,026 in 1969 and then starting to decline. With rapid economic development in Taiwan in the mid-20th Century, people from Penghu migrated to mainland Taiwan, especially to big cities, under the influence of industrialization and urbanization (Yin, 1969). Moreover, marine natural resource degradation and the rapid drop in the production of this CM-SES could not support the population (Yin, 1969; Tsai, 2009). The number of people who migrated annually from Penghu to the Taiwanese main island increased greatly from 920 to 2,572 from 1964 to 1965 and remained high into the late 20th Century (Yin, 1969). As a result, Penghu's local population dropped rapidly after 1970 (Fig. 4).

Economic transformation in Penghu

Fishery used to be a main primary economic sector[1] in Penghu. With the degradation of marine natural capital, however, the number of people employed in coastal and offshore fishery has dropped since 1966 (Fig. 4), and the archipelago's economic structure gradually shifted from primary to tertiary industry[2] (Fig. 5). By 1985, the percentage of people employed in the tertiary sector exceeded that in the primary sector, accounting for 41.9% and 37.2%, respectively. By 2010, the percentage of people employed in the tertiary sector had risen to 73.7% while primary sector employment dropped to 7.9%. Considering the decline in fishery, tourism development represents a key goal of Penghu's long-term administrative plan for economic progress (Penghu County Government, 1994–2010).

[1] Primary economic sector is the economic sector making direct use of natural resources, such as agriculture, forestry, fishing, and mining.

[2] Tertiary economic sector is the economic sector providing services, such as transportation, maintenance, and tourism.

Coastal and offshore fishery development in Penghu

Japanese colonization (1900–1945)

Taiwan modernized and entered the large-scale commercial fishery era during the Japanese colonial period (1895–1945). The Japanese made institutional and technological contributions to society (Hu, 2003; Chen, 2007), with the national development agenda at the time focusing on agricultural modernization, which rapidly increased productivity through modern technologies (Liu and Tung, 2003). The Fishery Act (1910) regulated the practice of different fisheries. New equipment and effective fishing methods were developed, and motorized fishing vessels were first introduced in the Taiwanese main island and Penghu in 1912 and 1916, respectively (Hsu, 2005; Hu, 2003). Later, in 1920, the national government initiated a subsidy policy to encourage fishermen to build motorized fishing vessels. With motorized power, fishery was extended from coastal area to offshore. In addition to new methods such as longlining and trawling, fishing became more efficient (Hsu, 2005). The colonial government also established research and education organizations to provide training courses for local fishermen in building knowledge and skills that would allow them to fish more efficiently (Hsu, 2005; Hu, 2003). According to the available statistical data, although the number of fishermen did not increase significantly during this period (Fig. 4), the fishery production more than tripled over the course of two decades, going from 1900 metric tons in 1916 to 6482 metric tons in 1933 (Fig. 6). This was a consequence of the policy-driven impacts on increasing catching capacity. However, the fisheries industry strongly declined during the World War II (1939–1945) when the vessels and labor were forced to be used by Japanese army for the Asia–Pacific War (Hsu, 2005).

Increasing catching capacity (1945–1965)

After World War II, the jurisdiction of Penghu Archipelago returned to Taiwanese government. Fishery revived in the 1950s when the national government used funding from the United States Agency for International Development (USAID) (1948–1965) to construct new vessels for the

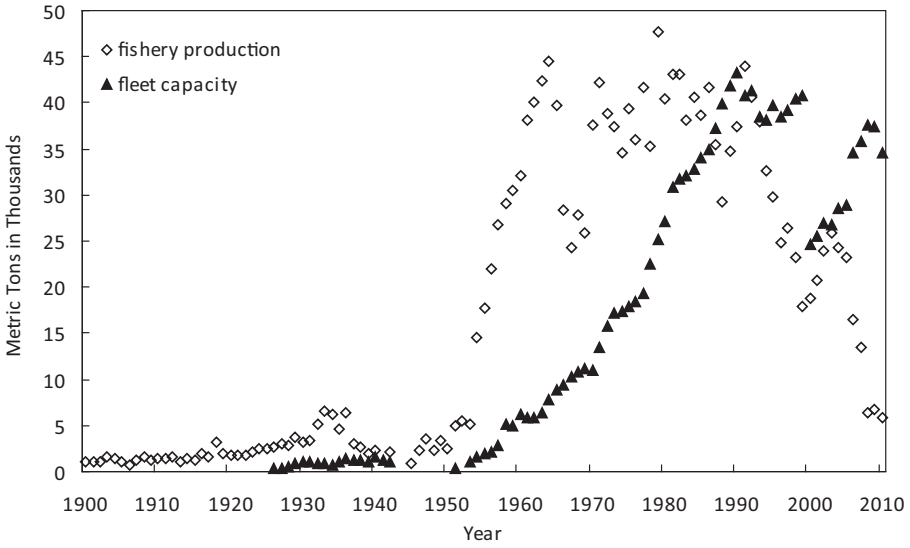

Fig. 6 Coastal and offshore fishery production and fleet capacity in Penghu from 1900 to 2010. Data not shown in the diagram is unavailable from the sources. Source: Taiwan Governor-General (1900–1942) and Budget, Accounting and Statistics Office, Penghu (1945–2010).

fishermen (the loans were paid back in installments (Chang et al., 2010). Fishing fleet capacity was also greatly enhanced by the construction of motorized vessels. During this period, the number of fishers and amount of fishery production increased (Fig. 4 and Fig. 6), with enhanced fleet capacity rapidly advancing production in particular (Fig. 6). The research and education organizations for fishery development established by the Japanese continued to conduct fishery resource studies as well as research into techniques development and skills training, which enhanced the fishing capacity and fishermen's abilities. In addition, fuel subsidies introduced in 1954 had significantly reduced costs for local fishermen (Hsu, 2005). Fishery production nearly tripled (5200–14,600 metric tons) from 1953 to 1954. Production peaked at 44,500 metric tons in 1964, though catching capacity continued to increase (Fig. 6).

Control of growing catching capacity and conservation (1965–2010)

The rapid increase in fleet capacity in the coastal and offshore fishery did, however, cause problems in terms of sustaining fishery production. After the 1964 peak, production dropped (Fig. 6), revealing the first signs of marine natural resource overuse in the waters surrounding Penghu (Hsu, 2005; Yin, 1969). The number of Penghu fishers has declined since 1965 as the overall population has declined. At the same time, more powerful equipment (such as fish finders and automatic direction finders) were subsidized, greatly enhancing catching capacity. Production rose again in 1970 and remained at about 40,000 metric tons for 20 years but did not increase with the increasing fishing capacity as it did from the mid-1950s to the mid-1960 (Fig. 6). Though the fishery sector was in decline, the government provided subsidies for all fishing villages to build their own harbors. Most harbors were constructed in the 1990s after the fleet capacity had begun to drop (Fig. 6). At present, Penghu's 69 harbors represent 30% of the Taiwanese total, and the density of harbors in Penghu is the highest in the country (Tsai, 2009).

Nevertheless, as indications of overfishing became impossible to ignore, governmental fishing policy shifted from increasing catching capacity to controlling capacity (Hu, 2003). In the 1960s, the national government began a series of licensing programs for limited entry aimed at controlling the growing fishing capacity. In 1967, restriction was first targeted at fishing trawlers under 300 metric tons. The limitations increased with each policy, and total number and tonnage of all fishing vessels were controlled within a designated limit in 1991 (Shao, 2003; Huang and Chuang, 2010). In addition, buyback programs were implemented in 1991, with the government purchasing excess catching capacity in the form of fishing vessels, leading to a drop in fleet capacity (Fig. 6). Moreover, government programs providing compensation to fishers for temporary suspension of fishing activities have been implemented since 2002 (Chen, 2010). Most of these efforts to reduce fishing capacities were made when fishing production was still high. However, a decline in yields occurred again after 1991, and the peak of over 40,000 metric tons per year has never been reached since. Even though well-developed technologies existed, costal and offshore fishery production continued to decline after the 1990s (Fig. 6) due to overfishing (Shih and Chiau, 2009).

Since fishery was a labor-intensive industry, and decreased production disincentivized attempts to make a living in this sector, there was a nationwide shortage in fishery labor. The national government sought to cope with this shortage in 1992 by crafting institutions for importing labor from neighboring countries.

Regarding the depleted marine natural capital, the Penghu local government introduced input controls and technical measures in the 1970s in order to sustain fish stocks. With the switching of target species and new methods developed in the fishery, the list of protected species and prohibited methods kept increasing in order to facilitate adaptation to the transforming fishing activities (Wu, 2013). Marine Protected Areas (MPAs) were introduced to Penghu from 1983 onwards as an ecosystem-based management measure. In 2010, there were nine MPAs in Penghu, yet they are proving ineffective since

they lack support from resource users, who are concerned that MPAs will harm their livelihoods. In addition, the government provides insufficient enforcement put the MPAs into practice (Hsieh et al., 2007; Shih and Chiau, 2009).

Coastal and marine social–ecological dynamics and societal adaptation in Penghu

When natural capital of marine origins was abundant in the Penghu fishery SES, the adapataion strategy of the society was to use natural capital more efficiently. Human-made capital contributed to dramatic increases in fishery production from 1950 to 1964. However, the abundant marine natural resources were not inexhaustible and were depleted by this intensive utilization. In order to cope with this change, society acquired human-made capital to sustain production. Human capital in the form of knowledge, methods, and skills for utilizing marine natural resources have been increased in the three fishery-development phases for fishermen to implement more efficient practices. However, the earlier training emphasized on efficient fishing rather than the acquired knowledge of natural capital limitation and the uncertainty of environmental changes. When signs of overfishing appeared in the reduced fishery production in the 1960s, human capital in the form of labor decreased as number of fishermen in the population decreased (Fig. 4). The society of this coastal fishery SES responded to labor shortages by importing workers from neighboring countries.

In this case study, physical capital employed for consuming natural capital grew in three phases. The first was the introduction of motorized vessels and new fishing methods in the Japanese colonial period. The second came after World War II as a greatly increased number of fishing vessels engaged in the industry. The third happened in the late 20th Century, with the invention and introduction of high-tech assistive equipment such as fish finders and automatic direction finders. Physical capital provided sophisticated technologies that allowed fishermen to utilize marine natural capital for profit and to compensate for the labor employment shortage in the fishing sector. The adaptation to the dynamic CM-SES through the consumption of physical capital, however, concealed the extent of the decline in fishery resources relative to the false impression of high production before 1964. Fleet capacity kept growing rapidly after 1964 (Fig. 6), though production no longer increased with the capacity. The government conducted catching capacity controls when production dropped, but the advanced technologies had left the fish no place to hide.

Governmental institutions have shaped the co-evolution trajectory of the Penghu CM-SES through strategies of increasing human and physical capital such as knowledge development and technical improvement. In the first and second phases of fishery development, the top-down institutions were production-oriented, driving society into an adaptation process for deriving maximum short-term economic benefit from marine natural capital. Fishery production continued rising between 1900 and 1964 and was maintained at high levels from 1970 to 1990 by human-made capital. However, in the ecological system, natural capital was depleted by intensive utilization. When the overfishing crisis arrived in the 1960s, institutions controlling access to marine natural resources were generated from the top-down (e.g. catching capacity control and Marine Protected Areas). The transformation of the institutional goals from increasing to controlling catching capacity in the third phase shows that the path of adaptation had changed.

Moreover, social capital assisted the adaptation of the Penghu fishery SES by linking it to other SES levels on spatial and functional scales. Through institutional arrangement, social capital helped to link the Penghu fishery SES to the national SES and the international level in order to acquire subsidies for increasing physical capital, such as fishing vessels in the first and second phases, and to acquire human capital by importing labor from neighboring countries. It also helped link to the tourism SES by transforming Penghu's economic structure from fishery to fishery-tourism. However, within the Penghu fishery SES, such adaptation neither sustains production nor conserves fish stocks.

Adaptation processes in the 110-year timeline

In a time when natural capital was abundant, human-made capital was used to increase production. With the catch exceeding sustainable use, society may not anticipate the overfishing problem because the problem was concealed by increasing physical capital, which maintained absolute production levels despite falling CPUE (catch per unit effort) (Fig. 6). When production dropped, society perceived the problem since the number of people employed in fishery decreased with the decreasing fishery production. The decline of population in Penghu demonstrates many people migrated outside the geographical boundary of the SES (Fig. 4) and the transformation of the economic structure indicates people transformed their livelihoods from primary to tertiary industry (Fig. 5). Social capital has involved transforming the main livelihood of society from fishery to fishery-tourism in the context pressure from decreasing natural capital. However, adaptation to the overfishing problem through transformation of societal economic structure did not solve the marine natural resource depletion crisis.

In Penghu, though many governmental institutions generated in the third phase in order to regulate marine natural resource utilization, they failed to recover and sustain the resources. The decline of the fishery sector, institutional failure to prevent a decrease in marine natural capital, and conflicts between utilization and conservation may have eroded the social capital of Penghu's social system. The condition of the social system in Penghu resembles that seen in many common pool resource studies (see Ostrom, 1990; Costanza et al., 1997; Berkes, 2004; Eide, 2009; Conrad, 2010) in which societies have a high discount rate for utilizing natural resources and ignore the long-term value marine natural resources. When users of marine natural resources tend to pursuit short-term profit rather than longer-term sustainability, rapid resource depletion has often been ignored and the capacity to form functional or proper institutions for governing marine natural resources is weak.

This results show that the acquisition of human-made capital for adapting society to the dynamics of the Penghu fishery SES is both the cause and the consequence of decreasing natural capital in the marine ecological system. However, in order to solve the problem of marine natural resources depletion, appropriate human-made capital is required for sustainable livelihoods. It is also important to improve human capital in the form of knowledge and awareness in recognizing the

common interests of utilizing marine natural resources sustainably, as well as the necessity to regulate access. At the same time, it is necessary to enable a shift in livelihoods. While there is overcapacity in the fishery, investment in physical capital should focus on controlling and reducing – rather than increasing – the fishery. Investment should also be made in facilities of different sectors, such as aquaculture and tourism, to create opportunities for diversifying livelihoods. Moreover, social capital is required for collective participation and the deployment of physical and human capital to adapt to the dynamics of the Penghu fishery SES by facilitating knowledge flow and cooperation for sustainable development.

Conclusions

In light of the rapid depletion of marine natural resources around the world, this case study of the Penghu Archipelago provides a 110-year historical review (1900–2010) to assist in understanding the interactions between natural and societal resources as well as between natural and human-made capital. By using a capital-based framework that contributes to the understanding of societal adaptation processes in a dynamic CM-SES, this study focuses on the role of human-made capital in generating adaptation and governance strategies. The long-term examination of Penghu fishery SES dynamics provides a holistic view of how society adapts to change from 1900–2010. It brings with it an understanding of how the present problematic condition of the CM-SES is caused by co-evolutionary trajectory. The results show that human and physical capital are limited in responding to resource depletion crises since the problem encountered by a complex CM-SES worsens alongside technological sophistication. Social capital successfully contributes to adaptation by linking the Penghu fishery SES to other SES levels on spatial and functional scales through workforce migration and livelihood transformation. This is, however, inadequate for forming functional governance of marine natural resources. The challenge is how to further appropriately invest in human-made capital to better society in adapting the dynamics and the uncertainty of the CM-SES.

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