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Asia-Pacific Network for Global Change Research

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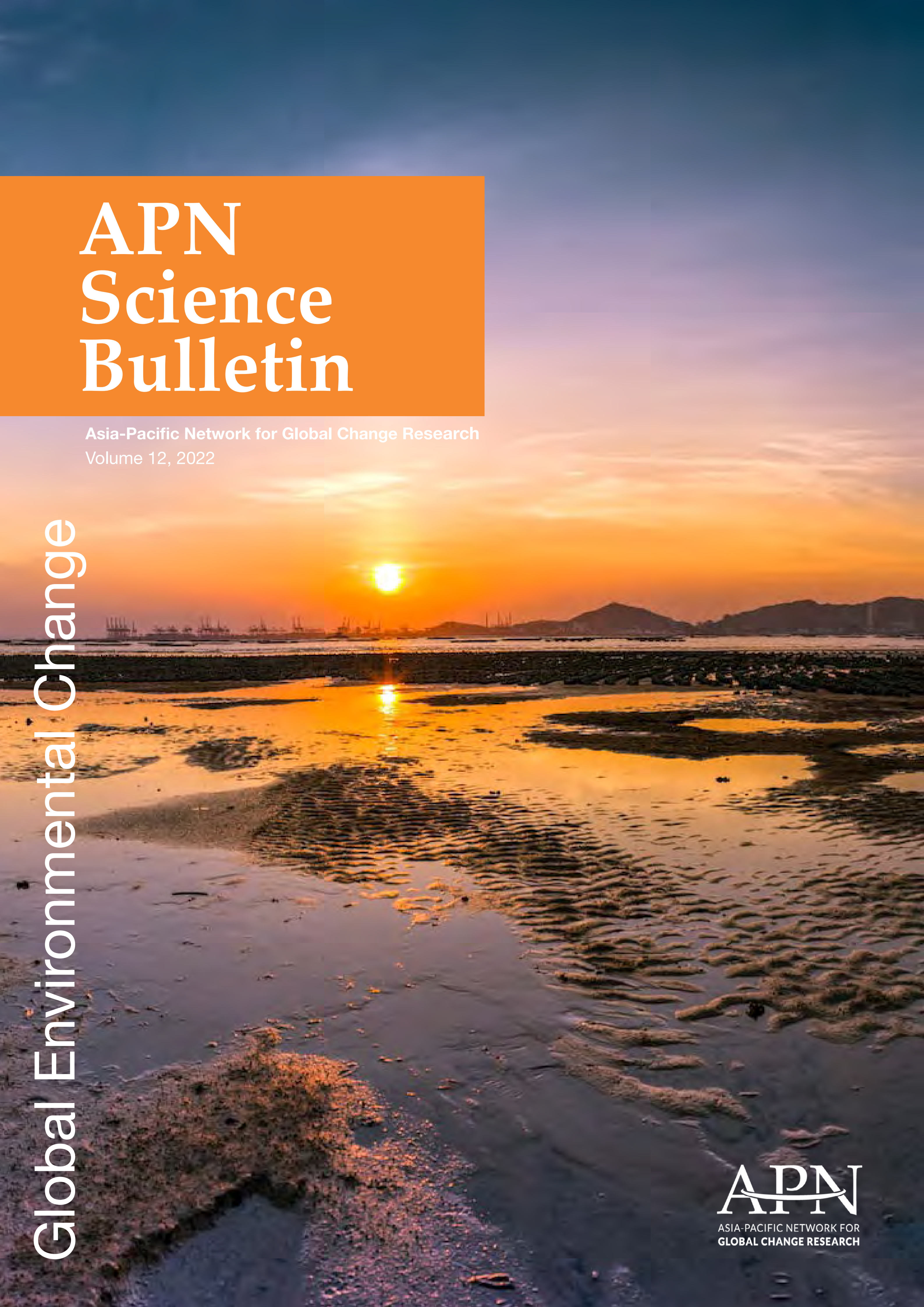
Global Environmental Change



ASIA-PACIFIC NETWORK FOR GLOBAL CHANGE RESEARCH

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Preface

There has been a notable shift in the COVID-19 Pandemic, and we are seeing a semblance of normality again. This has been evident in our work, and most of our projects were back on track in 2022, resulting in more articles being published in the APN Science Bulletin. This year we published a total of 17 articles, up 30% from the previous year. The compilation is available in the current edition of the APN Science Bulletin, our 12th volume, and on the APN website https://www.apn-gcr.org/bulletin/.

The 17 articles featured in the 2022 edition are regionally balanced articles published from projects under APN's Comprehensive Regional Research Programme (CRRP), Capacity Development Programme (CAPaBLE) and Early Career Science Communication (ECSC) Programme. By type, the 2022 compilation comprises ten original articles, five technical reports, one review and one editorial.

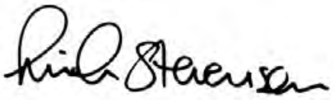
There is continued focus on the vulnerability and impacts of climate change and ways in which to address these for a more resilient Asia-Pacific. These include climate-smart agriculture, mangrove and other forests as ecosystem services, and sustainable and resilient food systems. Capacity building is critical for a more climate-resilient region, and we have collaborated with the World Climate Research Programme (WCRP) to train early-career professionals in climate science, communication and knowledge sharing. Other equally important aspects of global change are also addressed, such as transboundary air pollution, the adverse impacts of microplastics, and increased water and energy needs to meet the demands of a growing population.

At the time of publishing this compilation, we have had a total of 31,196 page views on the Science Bulletin site in the past calendar year alone, with 2,163 downloads of PDF articles, 240 of which were for articles published in 2022. These represent an increase of 31% and 11%, respectively, on numbers published in 2021. Crossref reported that our articles have been cited 228 times, an 84% increase on November 2021 numbers, reaffirming the credibility of the APN Science Bulletin as an international peer-review source of scientific literature on global environmental change.

APN continues its quest to ensure open access for all policy-relevant peer-reviewed articles, scientific resources, capacity building tools, policy briefs and other communications materials through our publications library, a growing database of knowledge products that are openly accessible to all. Our Knowledge Management team promptly brings you project and activity outputs to stay abreast of the international global change and sustainability agendas.

The credibility proffered to the Science Bulletin would be impossible without the 17 contributing authors and 54 reviewers on the 2022 Editorial Board, and on behalf of the Science Bulletin Editorial Management team and the Scientific Planning Group Co-Chairs, I would like to extend our greatest appreciation for your contributions to the 12th volume.

Linda Anne Stevenson



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Contents

Original article

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Microplastics pollution in selected rivers from Southeast Asia

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ABSTRACT

Microplastics have been found in all hemispheres of the world. However, studies on microplastics are mainly conducted in Europe, North America, and East Asia. Few studies are reported in the Southeast Asian region, where a large number of plastic waste is disposed of improperly into the water. This study investigated the abundance and characteristics of microplastics in the surface water of the Chao Phraya River (Thailand), Citarum River (Indonesia), and Saigon River (Viet Nam). Samples were collected at urban and estuary zones of these rivers. The numbers of microplastics at the urban zones were 80±60, 12±6, and 68±20 items/m^3 at the Chao Phraya, Citarum, and Saigon River, respectively. At the estuary zones, the numbers of microplastics were 48±8, 0±0 (0.08±0), and 42±5 items/m^3 at the Chao Phraya, Citarum, and Saigon River, respectively. Microplastics with morphologies of fragments and fibres were mainly found in the rivers. Polypropylene and polyethylene particles were the most abundant in all collected samples. Since the selected rivers play important roles in water supply and aquaculture activities, the presence of microplastics in these rivers may negatively impact aquaculture and human health. Potential plastic management strategies to minimize microplastic problems in the selected rivers were also proposed in this study.

KEYWORDS

Microplastics, Chao Phraya River, Citarum River, Saigon River

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HIGHLIGHTS

- Microplastics were found in samples collected from Chao Phraya, Citarum and Saigon rivers.
- Number of microplastics in urban zones are much higher than in estuary zones.
- Abundance of microplastics increases with increasing population.
- Most microplastics were polypropylene (PP) and polyethylene (PE), with the predominance of fragments and fibres.
- Policies on waste separation at source and ban on single-use plastic products are suggested.

1. INTRODUCTION

Southeast Asia (SEA) region remains the world's most vulnerable region to water insecurity. Countries in the region are growing, and their water management is a matter of concern (Strazzabosco, 2020). Along with long-standing problems, recent concerns are growing on the abundance of microplastics (MPs) in the water environment. MPs have been found in all hemispheres of the world (Mishra, Singh, & Mishra, 2021). However, studies on MPs are mainly conducted in the Northern Hemisphere (Europe, North America, and East Asia). Few studies are reported in SEA countries where a large number of plastic wastes are improperly disposed into the water.

Previous studies have found 5 countries in the SEA region as the top countries that have mismanaged plastic waste (Lebreton & Andrady, 2019; Jambeck et al., 2015). Thailand, Indonesia, and Viet Nam are the main contributors of ocean plastic waste, with 0.15–1.29 million tonnes per year (Jambeck et al., 2015). Also, a study by Meijer, Van Emmerik, Lebreton, Schmidt, and Van Der Ent (2019) estimated that rivers (including the Chao Phraya River, Citarum River, and Saigon River) in these countries are the top rivers in the world emitting plastics into oceans. However, knowledge on the occurrence of MPs in these rivers is insufficient (based on the literature search on Clarivate's ISI Web of Science).

The Chao Phraya River is a major river in Thailand, with a length of about 372 km flowing through 9 provinces and exits in the Gulf of Thailand. The river is also the major raw water supply for water treatment plants that provide tap water for more than 10 million residents. However, the Pollution Control Department of Thailand (PCD) reported that the water quality of the river has seriously deteriorated in the past decade due to the discharge of wastes from urban activities. The Citarum River is in Majalaya Basin, West Java, Indonesia. This river plays a vital role in the water supply, agriculture, electricity, fishery, and industries of the region. However, this river is listed as the most polluted river in the world (Sembiring, Fareza, Suendo, & Reza, 2020). As the Citarum River supplies several cities with their raw water supply, it is essential to understand the occurrence and distribution of MPs on this river. The Saigon River is the longest in Ho Chi Minh City, with a length of 256 km. This river is also an essential source of water for water treatment plants and agricultural and industrial activities. Nevertheless, recent reports found that 882 to 1,552 tonnes of plastic wastes were collected from the Saigon River each day (No. 3 Enterprise 2016).

Based on the above situation, this study investigated the occurrence of MPs in the Chao Phraya

River (Thailand), Citarum River (Indonesia), and Saigon River (Viet Nam). The main objective is to monitor the status of MPs in surface water of these rivers in urban and estuary zones. Characteristics and polymer types of MPs were also investigated for tracking their origin. Since these rivers play important roles in the economy and society in their own countries, study results will provide baseline data about MPs pollution for further studies and management strategies.

2. METHODOLOGY

2.1. Study area

Study sites were selected at urban and estuary zones of major rivers in selected developing countries (Thailand, Indonesia, and Viet Nam) of the SEA region. At the Chao Phraya River, samples were collected at the Tha Pra Chan and Pak Nam zones on September 19 and May 18, 2019. For the Citarum River, samples were collected at the Oxbow Dayeuhkolot and Muara Gembong zones on October 8 and 13, 2020, respectively. At the Saigon River, samples were also collected near the mouth of Nhieu Loc—Thi Nghe canal (urban zone) and Giong Ong To Creek (estuary zone) to the Saigon River in August 24 and October 10, 2019, respectively.

2.2. Sampling

The methods used in this study were consistent between three research partners. The methods for collecting samples in this study were adopted from Ta and Babel (2020). At the Chao Phraya River, samples were collected and analyzed by researchers at Sirindhorn International Institute of Technology, Thammasat University. For the Citarum River, samples were collected and analyzed by researchers at the Bandung Institute of Technology, and at the Saigon River, samples were collected and analyzed by researchers at Van Lang University.

Water samples at these three rivers were collected by manta trawls. These trawls were fabricated with the same design, which included a rectangular aluminium frame (20 cm high x 50 cm wide) and a 2-m long net. The net with an aperture size of 300 μm was connected with a cod-end (25 cm high x 10 cm diameter). Trawling tracks were recorded via Global Positioning System (GPS) devices. The trawling speed was from 5 to 12 km/h, depending on the river currents. The volume of filtered water was measured by a flow meter mounted at the manta trawl opening. The trawled area and volume were calculated by multiplying the recorded distance with the width and height of the manta opening, respectively.

2.3. Sample analysis

A procedure designed for the analysis of MPs concentration in the marine environment by Masura, Baker, Foster, Arthur, and Herring (2015) was adopted with modifications for this study. Water samples were first sieved through stainless steel aperture sizes of 0.05, 0.3, 0.5, 1.0 and 5.0 mm. All solids were transferred to sieves and rinsed with deionized water. In sieves of 5.0 mm, organic materials such as leaves, bugs, larger algae and wood were carefully rinsed with deionized water and removed from the samples with tweezers. This procedure resulted in size fractions: 0.05–0.3 mm, 0.3–0.5 mm, 0.5–1.0 mm and 1.0–5.0 mm. The fractions containing particles larger than 0.5 mm (i.e., retained in sieves with aperture sizes of 0.5 and 1.0 mm) could be examined visually without instruments. Therefore, suspected plastic debris in this size range were placed on Petri dishes using stainless steel tweezers. The total mass for these particles was determined by drying them in an oven at 60°C for 24 hours. Suspected plastics were inspected by an optical microscope. Under the microscope, MPs were inspected for the number, morphology and colour. After visual sorting, all particles were inspected by an attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy (Thermo Fisher Scientific). Polymer types of MPs were confirmed based on comparison with the standard spectra on the OMNIC™ Specta Software. The match factor threshold was set to 70% to identify the accuracy of the polymer.

The fractions containing particles smaller than 0.5 mm (i.e., retained on sieve aperture sizes of 0.05 and 0.3 mm) were transferred into different beakers by deionized water. Fractions in these size ranges are difficult to examine visually because they carry much sediment and organic debris. Thus, hydrogen peroxide (30%) with iron (II) as a catalyst was used to remove organic material. Moreover, sodium iodide (NaI) with a density of 1.5 g/cm^3 was also used to remove sediment and some organics from the samples in these size ranges. The remaining solids after density separation were filtered on cellulose nitrate membrane filters (0.45 μm, cellulose nitrate, Whatman) by vacuum filtration and dried in an oven at 60°C. After drying, the size fraction of 0.3–0.5 mm was inspected by an optical microscope and FTIR, similar to the particles larger than 0.5 mm.

3. RESULTS AND DISCUSSION

3.1. Number of MPs

3.1.1. MPs in urban zones

At the Chao Phraya River, samples were collected in downtown Bangkok (Tha Pra Chan area), which is the largest city in Thailand. The study site is highly populated, along with many tourist attractions located nearby. Figure 1 (A) shows sampling points and the surrounding area at the urban zone of the Chao Phraya River. In the study area, MPs were found in all collected samples. The numbers of MPs at the site are presented in Table 1. The number of MPs in water samples are 48±11, 38±30, and 155±16 items/m^3 for bank 1, bank 2, and the middle position, respectively. The mean number of MPs in all water samples at the study area is 80±60 items/m^3. This difference in MPs numbers at these positions may be explained by the turbulence and morphology of the river in the study area (Ta & Babel, 2020). As shown in Figure 1 (A), before the sampling points, the river has a curve that affects the river flow. Moreover, the busy activities of boats at the banks may also make materials flow into the middle position of the river. However, further studies are needed to confirm and explain the differences in MPs concentrations at different positions in the river.

At the Citarum River, samples were collected in the urban zone of Oxbow Dayeukolot. The abundance of MPs in this area is associated with population density and the resident's activity. The tributaries flow from denser residential and industrial areas. At Oxbow, there is a flood control channel, and the shape is like a horseshoe. In this channel, the water is stagnant; thus, it can trap the MPs. The sampling points on the Citarum River is shown in Figure 1 (B). The concentration of MPs on the left, centre and right sides from the urban zone were 16 items/m^3, 15 items/m^3, and 4 items/m^3, respectively. The mean number of MPs in the study area was 12±6 items/m^3(Table 1).

At the urban zone of the Saigon River, the width of the river is about 322 m, with a buffer zone of trees on the left bank and right bank, including Tan Thuan port, residential areas, along with small and medium industrial facilities. The sampling points of the Saigon River are shown in Figure 1 (C). The concentration of MPs on the left, centre and right banks from the urban zone were 60 items/m^3, 53 items/m^3, and 90 items/m^3, respectively. The mean number of MPs was 68±20 items/m^3. The number of detected MPs was the highest at the right bank of the river. The reason is that raw sewage from the central districts of Ho Chi Minh City drains via combined sewers and by Doi—Te canal to the Saigon River at the right bank. While the left bank of the river is a buffer zone with trees thus, the number of MPs in the left bank was lower than the right bank. The Saigon River is one of the main waterway transportations of Ho Chi Minh City and the South of Viet Nam. Also, this study site is nearby the Tan Thuan Port, with many ships carrying large tonnage are moving in the middle of the river. So, the water stream often tends to be pushed into two banks carrying suspended solid/particulate to the banks. Thus, the number of MPs at the two banks was found higher than at the middle stream.

3.1.2. MPs in estuary zones

At the Chao Phraya River, sampling points at the estuary zone are shown in Figure 1 (A). The total surface area of the river estuary is about 37.8 km^2. As shown in the figure, in this area, most land on bank 1 is used for aquaculture, while bank 2 is used for small industrial and residential zones.

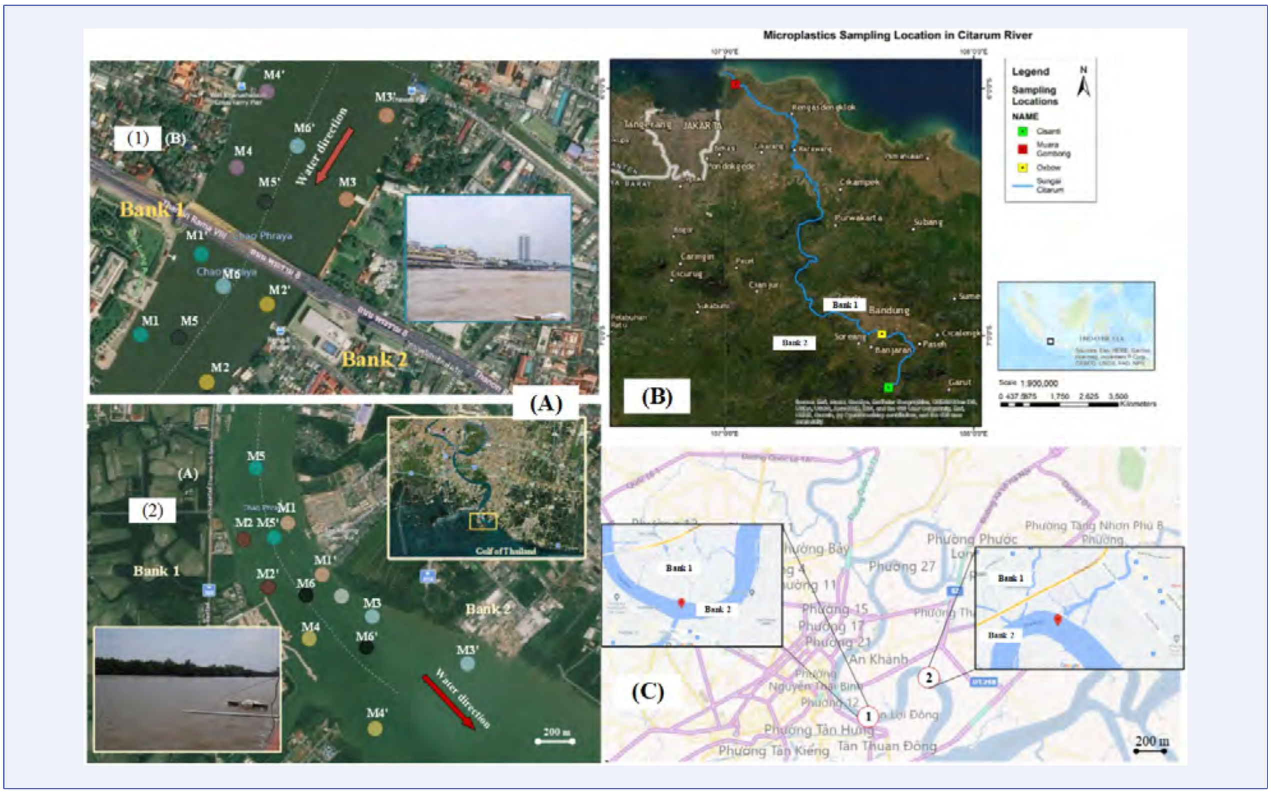

FIGURE 1. Sampling sites at selected rivers: (A) the Chao Phraya River, Thailand: (1) Bangkok (Tha Pra Chan area), (2) Pak Nam, Samut Prakan; (B) Citarum River, Indonesia, (C) Saigon River, Viet Nam: (1) urban zone, (2) estuary zone.

MPs were found in all water samples collected from the estuary zone of the Chao Phraya River (Pak Nam, Samut Prakan). In total, about 5,000 particles were counted, photographed, and categorized in all water samples for the two sampling times. The numbers of MPs in water samples are 46±5, 35±5, and 63±12 items/m^3 for the bank 1, bank 2, and middle position, respectively. The mean number of MPs in all water samples at the study area is 48±8 items/m^3 (Table 1).

At the Citarum River, samples were collected at the estuary zone of the Muara Gembong area. The number of MPs found in this study site was much lower than that of the urban zone. The number of MPs on the left, centre and right banks is 0.098, 0.086 and 0.046 items/m^3, respectively. The mean number of MPs in all water samples at the study area is 0.08±0 items/m^3. The source of plastic and microplastics in Muara Gembong is mainly from industries, fisheries and fish harvesting on the banks of the river. In this location, waste management and wastewater treatment are lacking. Nearby housing and community tend to dump their waste directly into the river. This behaviour was also found from the middle stream to downstream areas of the Citarum River.

At the estuary zone of the Saigon River, the river is about 380 m wide which is the most expansive site among all study sites. At the site, the river receives water from the Giong Ong To Creek, which contains wastewater from residential areas of the urban zone. The left bank river is new residential zones with a low population density and a part of agricultural areas. The number of MPs on the left, centre and right banks are 46.3, 42.9, and 37.1 items/m^3, respectively. The mean number of MPs in all water samples at the study area is 42±5 items/m^3. The number of MPs at the left bank was higher than that of the right bank and middle stream of the river. This may be due to the influence of canal water of the Giong Ong To Creek, which partly carried raw sewage and flows to the left bank at the study site.

When comparing the three rivers, the number of MPs was found in the same trend. The number of MPs found in urban zones was higher than that of the estuary zones. This demonstrated that the

Number of MPs (items/m^3)	**Thailand** (Chao Phraya River)	**Indonesia** (Citarum River)	**Viet Nam** (Saigon River)
Urban zones	80 ± 60	12 ± 6	68 ± 20
Estuary zones	48 ± 8	0 ± 0 (0.08 ± 0)	42 ± 5

TABLE 1. Mean number of MPs in surface water samples at three selected rivers.

abundance of MPs increases with the increase of the urbanization rate. Also, the number of MPs found at the Chao Phraya River (Thailand) and the Saigon River (Viet Nam) is comparable. However, the number of MPs at the Citarum River (Indonesia) is much lower than the Chao Phraya and Saigon River in both urban and estuary zones (Table 1).

3.2. Characteristics of MPs

3.2.1. Size of MPs

The percent distribution of MPs by size was computed using the numbers of MPs. For surface water samples, the percent distribution of MPs by size is not significantly different between the urban and estuary zones of the Chao Phraya River. The size distribution of MPs was similar at all study zones with the predominance of 0.05–0.3 mm. However, it can be realized that the percentage of MPs with the size range of 0.05–0.3 mm in the urban zone is lower than in the estuary zones. According to Boyle and Örmeci (2020), the size of MPs decreases with the time that plastic has been exposed to the natural environment. Control experiments by Song et al. (2017) showed that polymers of PP, PE and EPS need about 2 to 12 months to degrade into MPs smaller than 0.3 mm. Thus, the lower percentage of large MPs (>0.3 mm) in the urban zone of the Chao Phraya River indicates that the plastic debris in this zone may be exposed to the environment for a shorter time than that of estuary zones. Therefore, plastics do not have enough time to degrade into smaller sizes.

At the Citarum River, the size distribution of MPs at the urban (Oxbow) and estuary zones (Muara Gembong) is not significantly different. The most dominant size of MPs was 1.0–5.0 mm at these two study sites with the percentages of 42%–85%. MPs with the size of 0.3–0.5 mm account for the lowest percentages of 3%–17%. As shown in Figure 4 , MPs with the size of 0.3–1.0 mm at the estuary zone were much higher than that of the urban zone.

At the Saigon River, the size distribution of MPs was not very different between the urban and estuary zone. Small sizes of MPs were predominant in all collected samples at the river. At the urban zone, MPs with the size of 0.05–0.3 mm were found with the highest percentage (27%). However, the variation between size ranges was not much different. At the estuary zone, MPs with the size of 0.3–0.5 mm were predominant in all samples (37%). As shown in Figure 4, the size distribution of MPs at the Chao Phraya (Thailand) and Saigon (Viet Nam) is comparable. At these rivers, MPs with small sizes were predominant in urban and estuary zones. However, at the Citarum River, MPs were mainly found with the size of 1.0–5.0 mm in all study zones.

3.2.2. Polymer types

At the Chao Phraya River, the proportion of polymer types is similar in the urban and estuary zones. Polypropylene (PP) was the most abundant polymer type in all surface water samples ranging from 44% to 67%. Polyethylene (PE) (ranging from 26%–36%) was the second abundant polymer at all study zones. PP-PE copolymer was observed with a smaller amount. Moreover, other polymers such as polyester (PES), polyurethane, cellophane, and polybutylene were detected with a total proportion of less than 5%.

At the Citarum River, MPs found in Oxbow and Muara Gembong areas were also mainly PP and PE. The source of MPs in these study sites may come from daily-use plastic, food packaging, and industrial waste in these locations. The high concentration of MPs is related to the high population and resident activities on the land (Alam, Sembiring, Muntalif, & Suendo, 2019). These findings emphasize the urgency to mitigate the MPs contamination of the aquatic environment in the near future.

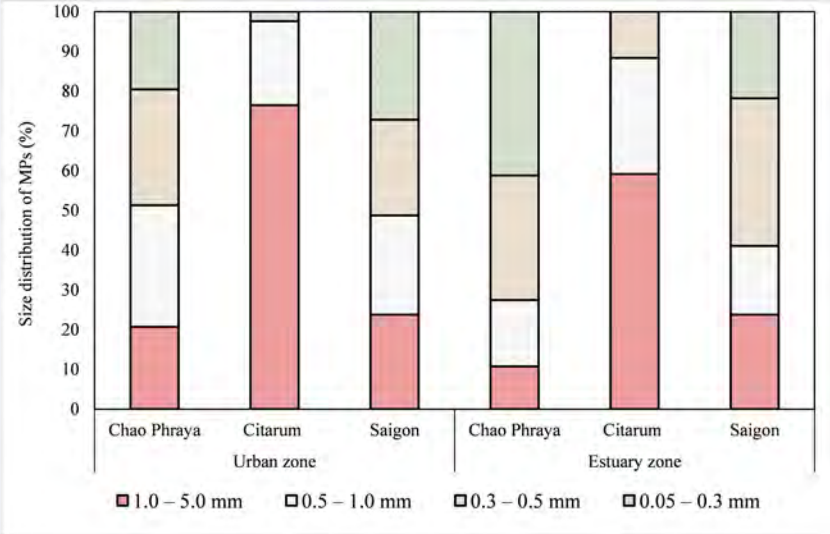

FIGURE 2. Variability of MP sizes at the Chao Phraya River (Thailand), Citarum River (Indonesia), Saigon River (Viet Nam) in urban and estuary zones.

At Saigon River, polymer types of MPs were also similar between urban and estuary zones. MPs at the study sites were mainly detected with four polymer types, including PP, PE, polystyrene (PS), and polyethylene terephthalate (PET). PP was found with the highest percentage (65%–70%), followed by PE (24%–37%). PET was found with the lowest percentage.

The high abundance of PP and PE in the surface water of the Chao Phraya River, Saigon River, and Citarum River could be due to their higher consumption in Thailand, Viet Nam, and Indonesia (Wichai-Utcha & Chavalparit, 2019; VPAS, 2019). These polymers are commonly used to produce consumer products such as containers, bottles, plastic bags, and tableware (Cole, Lindeque, Halsband, & Galloway, 2011). PP and PE polymers are also used in personal care and cosmetics products (Leslie, 2014). According to Plastics Europe (2018), PP and PE are the most widely produced polymers around the world and are also the most frequently detected MPs in the marine and freshwater environment (Wu, Zhang, & Xiong, 2018). Moreover, the densities of the two polymers are lower than water (PP: 0.91 g/cm^3, PE: 0.95 g/cm^3), which makes them float easily on the surface water. The existence of denser polymers such as PES (1.40 g/cm^3) in the surface water can be explained by the following reasons. First, the weathering process can decrease the density of these MPs. According to Guo and Wang (2019), weathering changes the crystallinity of MPs by reducing the density. Moreover, the molecular weight of plastic would decrease due to polymer chain cleavage and oxidation during the weathering process (Lv, Huang, Kong, Yang, & Li, 2017). Second, the higher surface-to-volume ratio enabled the MPs to be suspended in the surface water. In addition, the tides and waves could resuspend the dense MPs from the bottom sediment.

3.2.3. *Morphology of MPs*

Morphologies of MPs were categorized into fibres, fragments, pellets, and films. In brief, pellets are spherical, ovoid, disk-shaped, or cylindrical particles. Fibres are thin and long items, films are thin pieces of plastic debris, and fragments are unidentified morphology. As shown in Figure 4, morphologies of MPs were not significantly different between the Chao Phraya and Citarum River with the predominance of fragments. However, at the Saigon River, fibre was found with the highest percentage. In general, the morphology of MPs is related to their origins. Fibres may be generated from textile materials, fishing gear, and the deposition of airborne matter (Cesa, Turra, & Baruque-Ramos, 2017). Plastic bags and packaging

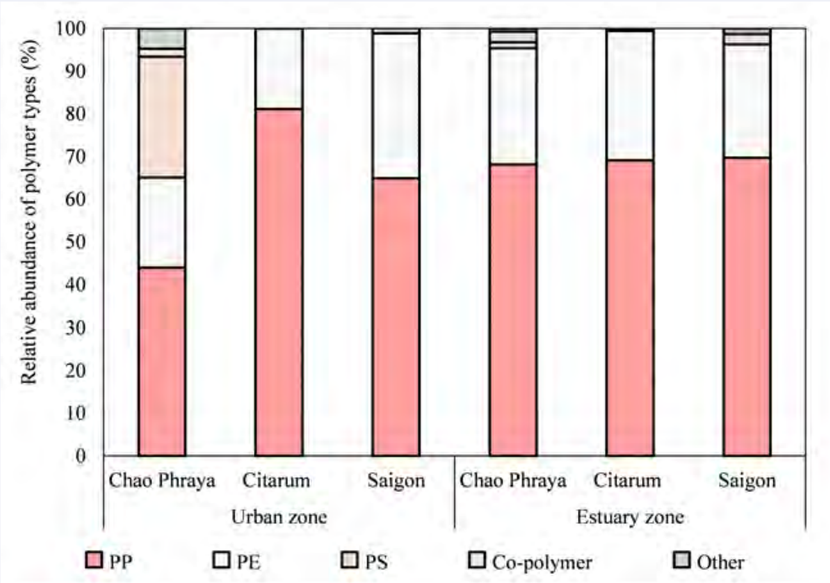

FIGURE 3. Variability of MP polymers at Chao Phraya River (Thailand), Citarum River (Indonesia), Saigon River (Viet Nam) in urban and estuary zones.

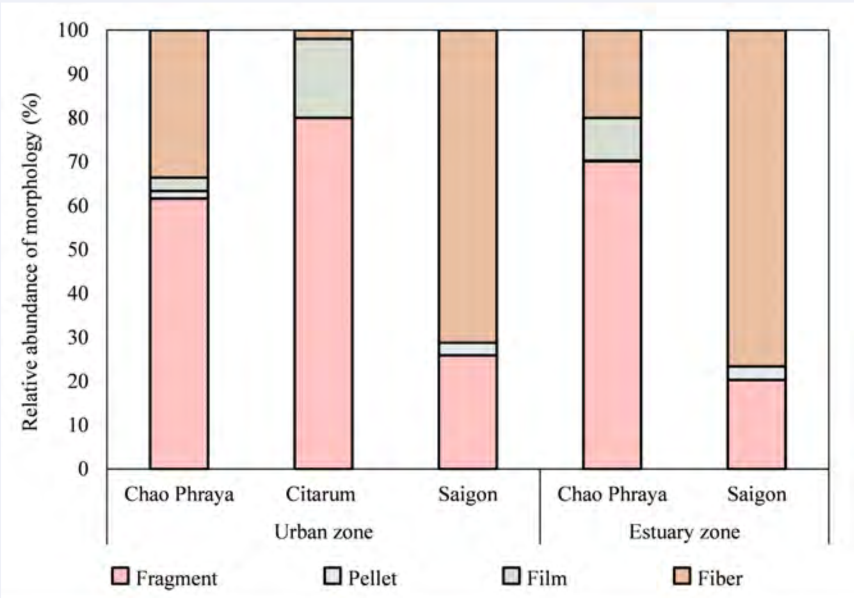

FIGURE 4. Variability of morphology at Chao Phraya River (Thailand), Citarum River (Indonesia), Saigon River (Viet Nam) in urban and estuary zones.

materials, which are thinner and softer, are the primary sources of film-shaped MPs. Pellets can be derived from plastic resin or microbeads in personal care products (Ta & Babel, 2020). Fragments are likely degraded from larger plastic goods (i.e. plastic containers, tableware, furniture, and toys) through mechanical and UV radiation (Horton, Walton, Spurgeon, Lahive, & Svendsen, 2017). Thus, the higher percentage of fragments in this study indicates that MPs found in the Chao Phraya, Citarum, and Saigon River are mainly secondary MPs.

3.2.4. Comparison to other studies

Since the standards for the collection, identification, and evaluation of MPs are still not developed, the units of MPs abundance vary among the studies. Therefore, the results in this study are only compared with studies using the same units. A comparison of MPs levels between the Chao Phraya River, Citarum River, Saigon River and other rivers in the world is presented in Table 2. These studies are classified based on the land-use functions such as urban and estuary zones.

Urban zone

As presented in Table 2, the MPs numbers in the surface water of the Chao Phraya River (Bangkok), Citarum River (Oxbow Dayeukolot), and Saigon River (Nhieu Loc—Thi Nghe) are lower compared to other urban zones. The level of MPs in these studied rivers is comparable with the urban zone of Tamsui River (Taiwan) (Wong, Löwemark, & Kunz, 2020) and Milwaukee River (USA) (Lenaker et al., 2019). Most of the studies on rivers in China, such as the Suzhou River (Luo et al., 2019) and the Hanjiang River (Wang, Ndungu, Li, & Wang, 2017), have higher MPs than the Chao Phraya, Citarum and Saigon River. In the Nakdong River (South Korea), the number of MPs was 293±83–4760±5242 items/m^3 (Eo, Hong, Song, Han, & Shim, 2019), which is much higher than that of the studied rivers. Table 2 also depicted the number of MPs in urban zones of rivers in North America and European countries, such as the Ottawa River (Canada) (Vermaire, Pomeroy, Herczegh, Haggart, & Murphy, 2017) and Danube River (Austria) (Lechner et al., 2014) and have lower numbers of MPs than this study. According to Lambert and Wagner (2018), waste management practices and high population density are directly related to the high level of MPs pollution in regions. Therefore, the number of MPs in this study and other studies may demonstrate the level of waste management systems in each study area. Moreover, the data also highlight the unsound waste management systems in Asian countries compared to European countries (Wu et al., 2018).

Estuary zone

In comparison to other studies using the same metrics, the abundance of MPs in the estuary zone of the Chao Phraya River (Samut Prakan), Citarum River (Muara Gembong) and Saigon River (Giong Ong To Creek) are among the lowest recorded for estuaries. As shown in Table 2, the abundance of MPs in this study is comparable to the Clyde Estuary of Australia. It has similar activities of land uses as in the current study (Hitchcock & Mitrovic, 2019). However, it is lower than that in most estuaries globally. For example, MPs abundance in the Yangtze Estuary (Zhao, Zhu, Wang, & Li, 2014) and Bohai Bay (Wu et al., 2019) of China and the Hunter Estuary of Australia (Hitchcock & Mitrovic, 2019) are found to be 8 to 300 times higher than this study. The significant differences in MPs levels among this study and others may be due to the following reasons. Firstly, the sampling areas in the current study are suburban zones, where land is used for aquaculture, factories and residential zones. Other studies were conducted in densely populated areas with activities of industry, tourism, commerce and recreation. For example, the Yangtze Estuary, estuaries in Bohai Bay and Hunter Estuary are in the metropolitan areas of Shanghai, Tianjin, and Newcastle, respectively. Secondly, different methodologies for sampling and analysis of MPs are applied in the studies. In the Yangtze Estuary and Bohai Bay of China, MPs from the surface water were collected by pumps (Wu et al., 2019). The study at the South Carolina estuaries used a sea surface microlayer collection apparatus with a 2-mm stainless steel mesh to collect MPs samples (Gray, Wertz, Leads, & Weinstein, 2018). The study at Hunter Estuary used a plankton net with a mesh size of 37 mm (Hitchcock & Mitrovic, 2019).

3.3. Potential plastic management strategies to minimize MPs problem in the selected rivers

As mentioned above, Thailand, Indonesia and Viet Nam were the top countries that have mismanaged plastic waste and are the main contributors of ocean plastic waste (Jambeck et al., 2015; Lebreton & Andrady, 2019). With the presence of MPs found in the Chao Phraya River, Citarum River and Saigon River, plastic management strategies are necessary to minimize MPs pollution problems. The following strategies are suggested to reduce MPs levels in the

Location	Abundance (items/m^3)	Reference
Urban zones		
Hanjiang River, China	933±305.5	Wang et al. (2017)
Suzhou River and Huangpu River, China	1,800–2,400	Luo et al. (2019)
Tamsui River, Taiwan	10.1–70.5	Wong et al. (2020)
Nakdong River, South Korea	293±83–4,760±5,242	Eo et al. (2019)
Ottawa River, Canada	0.71–1.99	Vermaire et al. (2017)
Milwaukee River, USA	0.54–11.6	Lenaker et al. (2019)
Danube River, Austria	0.317±4.665	Lechner et al. (2014)
Chao Phraya River, Thailand	80±60	Present study
Citarum, Indonesia	12±6	
Saigon, Viet Nam	68±20	
Estuary zones		
Yangtze Estuary, China	4,137.3±2,461.5	Zhao et al. (2014)
Jiaojiang Estuary	955.6±848.7	Zhao et al. (2015)
Oujiang Estuary	680.0±284.6	
Minjiang Estuary, china	1,245.8±531.5	
Changjiang Estuary	231±182	Xu et al. (2018)
Yondingxinhe River	788.0±464.2	Wu et al. (2019)
Haihe River, China	1,333.3±782.1	
Hunter Estuary	1,032	Hitchcock & Mitrovic (2019)
Clyde Estuary, Australia	98	
Chao Phraya River, Thailand	48±8	Present Study
Citarum, Indonesia	0.08±0	
Saigon, Viet Nam	42±5	

TABLE 2. Abundance of MPs in the selected rivers as compared to other rivers in the world by their land use.

selected rivers.

3.3.1. Policy

- Regarding domestic solid waste management, the main aspect being considered is solid waste separation at source, including establishing legal documents to serve programs on solid waste separation at source: (1) Regulation on classification and storage at source, (2) Collection from source, (3) Transit and transport, (3) Reuse and recycle, and (4) Treatment and recycle.
- Develop policies to reduce single-use plastic products (having regulation on single-use plastics) and plastic bags.
- The governments of the three countries should promulgate policies encouraging recycling plastic waste, especially invaluable plastic waste, and support funding to improve existing recycling facilities or invest in recycling facilities with advanced technologies.
- Develop policies to limit the import, production, and supply of non-degradable plastic bags.

3.3.2. Database building and scientific research

- Strengthen monitoring and investigations of plastic waste and MPs in the canal and river systems.
- Establishing a database system on domestic solid waste, including plastic and MPs waste.
- Strengthening scientific research on recycling single-use or invaluable plastic waste (plastic bags).

3.3.3. Human resources

- Develop human resources for urban solid waste management, especially plastic waste.
- Organize a monitoring group for the classification of solid waste at source and indiscriminate disposal of waste in the local community.

- Decentralization of solid waste management, where local authorities (community level) are responsible for enforcing solid waste separation at source and controlling littering in the environment.

3.3.4. Tax and fee tools

- Increase environmental protection tax on plastic bags and bring single-use plastic products into the category subject to environmental protection tax.
- Deposit refund system: For some plastic packaging, the buyer will be refunded the deposit when returning packaging to the store after using the product.

3.3.5. Propaganda, education to raise awareness

The public plays a vital role in increasing effective plastic waste management. Thus, participation of public sectors and communities in solid waste separation at source is critical to minimizing plastic waste and MPs in the aquatic ecosystem. The following activities and campaigns are recommended to increase public participation and awareness on plastic waste and MPs problems.

- Organize activities to raise awareness amongst the population about the negative impacts caused by improper plastic waste management and leakage in the environment at all levels by propaganda programs, which should be carried out continuously and regularly in various forms to attract public participation.
- Activities to increase people's awareness of behaviour and habits of using single-use plastic products and non-degradable plastic bags and littering habits in communities.
- Communication education on the harmful effects of plastic waste and MPs should be conducted in communities and schools (at all levels).
- Strengthen training programs for staff at public and private agencies on plastic waste, MPs, and their harmful effects.
- Television and radio programs should devote time to propagate about plastic waste, MPs and their harmful effects on human health, biota and the environment.

3.3.6. Domestic wastewater treatment

The government of the selected countries should plan a roadmap to treat all domestic wastewater generated from urban zones of the rivers with advanced technologies, taking into account the pollutant component of MPs.

4. CONCLUSION

MPs were detected in all surface water samples collected from the Chao Phraya (Thailand), Citarum (Indonesia), and Saigon River (Viet Nam). Variation of MPs levels was found to depend mainly on land use around rivers. The number of MPs at urban zones was higher than that of estuary zones. This demonstrated that the abundance of MPs increases with the increase of the urbanization rate. Also, the number and size of MPs at the Chao Phraya River and Saigon River were comparable at both urban and estuary zones. However, at the Citarum River, the number of MPs was much lower and the size much larger than the two other rivers. For the morphologies of MPs, fragments and fibres were predominant types at all rivers. Polymer types of PP and PE were the most abundant in all collected samples from the three rivers. The selected rivers in this study play important roles in water supply and aquaculture activities in their countries. Thus, the occurrence of MPs in these rivers can create harmful impacts on humans, biota and ecosystems. This study also provides important background data to bridge the knowledge gap for MPs pollution in rivers from the Association of Southeast Asian Nations (ASEAN) region. Also, potential plastic management strategies to minimize MPs problems in the selected rivers are suggested in this study. Solid waste separation at the source needs to be legally implemented in all three countries. Policies to control single-use plastic and encourage plastic recycling waste are required. Awareness and education on the impacts of plastics and MPs for public sectors and communities are also essential to minimize plastic waste and MPs in the aquatic environment.

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Technical report

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Rainwater harvesting for enhancing upland agriculture: Lessons and experiences in selected upland farming communities in Albay Province, Philippines

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ABSTRACT

The upland farming communities in the Philippines are among the vulnerable sectors to climate change impacts. Their agricultural production is generally rainfed, and their farms are in marginal upland areas with steep slopes prone to soil erosion. Water scarcity is a common and perennial problem. To address the need expressed by the smallholder farmers, 11 rainwater harvesting facilities (RWHFs) were established in three upland farming communities in Albay Province, Philippines. The project team facilitated the establishment of RWHFs from two state universities, three local government units, and farming communities. Capacity development and participatory project planning and implementation were the important project approaches. This project generated several lessons. These include the essence of multisectoral collaboration, comprised of local government units, farming communities, and state colleges and universities; the value of collective action of farmers; effectiveness of cross-farm visits and on-site training; tapping locals for project monitoring; integration of sustainable land use management system to sustain RWHFs; and, the importance of resource sharing in carrying out project activities. The project experiences and lessons could be used as a reference by other development programmes in replicating this initiative in other upland farming communities in the country.

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KEYWORDS

Smallholder farmers, agroforestry, cross-farm visits, collective action, resource sharing

HIGHLIGHTS

- The lack of irrigation water limits the agricultural production of upland farmers in the three upland farming communities in Albay Province.
- Eleven (11) RWHFs, aimed at maximizing the agricultural production of small-holder farmers, were established.
- RWHF establishment served as a mechanism to expand farmer-cooperator's agricultural production areas and enabled the upland farmers to cultivate rice in two cropping seasons.
- Harnessing active engagement of local communities and tapping local experts facilitated the project implementation amid the pandemic.

1. INTRODUCTION

Smallholder farmers dominate the agriculture sector worldwide. Lowder, Skoet, and Singh (2014) reported that 85% of the 525 million farms worldwide are less than two hectares. Many of these smallholder farmers are poor, food insecure and have limited access to market and basic services (Rapsomanikis, 2015). Fortenbacher and Alave (2014) highlighted that the upland settlers are the poorest among the rural population because of low farm productivity, limited access to rural advisory services, alternative employment opportunities, and basic social services. Furthermore, most upland farmers cultivate in marginal lands, with generally steep slopes that are prone to soil erosion and are rainfed or dependent on rainfall as a source of irrigation (Landicho et al., 2015). Hence, they are also vulnerable to climate change impacts and other weather and natural disturbances.

In their research, (Landicho, Van, & Ximenes, 2018) emphasized that the low level of adaptive capacity for climate change adaptation among the upland farmers in Southeast Asia, particularly in the Philippines, Viet Nam and East Timor, is brought about by the low level of farmers' knowledge and awareness about the climate change adaptation strategies, low level of assets, and weak leadership or governance in natural resources management. These results suggest the need for capacity development programmes, particularly on climate change adaptation strategies. Specifically, the upland farming communities in Albay Province have been experiencing climate change impacts such as unavailability of water during the dry season and long dry spell, stunted crop growth, low crop productivity and yield, and increased farm inputs (Landicho et al., 2018).

The need for a water source for crop irrigation was on the top list of upland farmers for them to adapt to climate change impacts. Han (2006) argues the need for a new paradigm in rainwater management as the weather becomes more severe and unpredictable due to climate change. The new paradigm involves developing small-scale detention ponds or rainwater storage facilities instead of large remote projects. Each small-scale facility promotes multi-purpose rainwater management rather than single-purpose watershed management (Contreras, Sandoval, & Tejada, 2013). Rainwater harvesting through small water impounding projects (SWIPs) addresses the unbalanced rainfall distribution by collecting and storing direct rainfall and surface runoff for future use (Contreras et al., 2013). SWIPs which serve as rainwater harvesting and storage structures consist

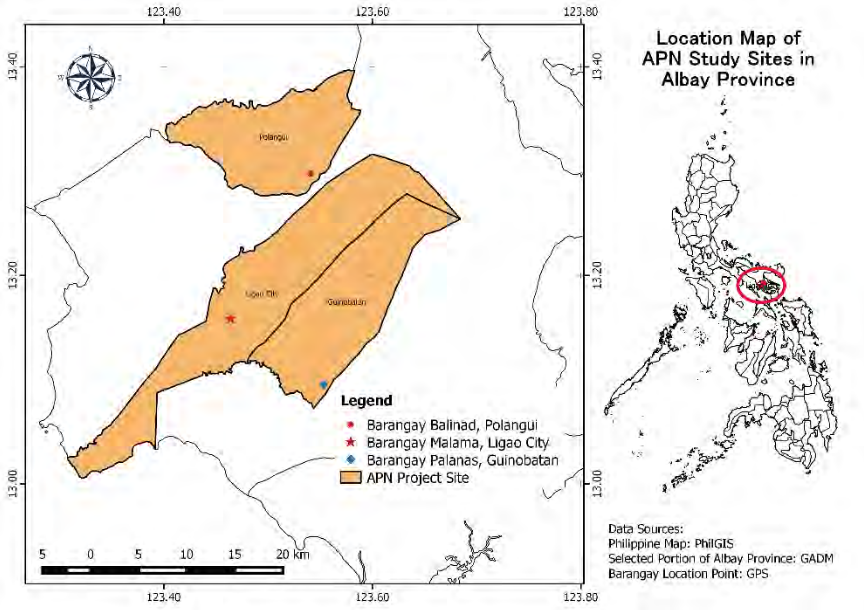

FIGURE 1. Location map of the project sites.

of an earth embankment, spillway, outlet works and canal facilities. Aside from economic benefits, SWIPs have an important role in enhancing the multi-functionality of agriculture, particularly in the uplands (Concepcion et al., 2006). Socio-economic benefits from SWIPs can be seen at the farm and community levels (Monsalud, Montesur, & Abucay, 2003; Naval, 2016) .

Given the potential of rainwater harvesting ponds and SWIPs in addressing the impacts of climate change on agricultural production of smallholder farmers, a capacity development project was implemented in Albay Province, Philippines, in 2019, which centred on the establishment of rainwater harvesting ponds, using the principles of multisectoral collaboration and engagement. Multisectoral collaboration means that multiple sectors and stakeholders collaborate in a managed process to achieve shared outcomes and common goals (Kuruvilla et al., 2018) and enhance technology promotion and adoption (Landicho, Cabahug, & De Luna, 2009; Cruz, Carandang, Galapia, Carandang, & De Luna, 2014).

This article highlights the lessons and experiences of establishing rainwater harvesting ponds in the three upland farming communities in Albay Province, Philippines, using the multisectoral collaboration as an approach.

2. METHODOLOGY

The project was implemented in three upland farming communities: Barangay Malama in Ligao City; Barangay Palanas in Guinobatan, and Barangay Balinad in Polangui (Figure 1). The project was managed by the four research collaborators representing the University of the Philippines Los Baños-Institute of Agroforestry (UPLB-IAF) and the Bicol University College of Agriculture and Forestry (BUCAF). The local government units of Ligao City, Polangui and Guinobatan, Albay Province were also tapped as local partners through their respective Offices of City/Municipal Agriculturists and are represented by the concerned agricultural technicians. The key leader of each of the three upland farming communities and the agricultural technicians of the three LGUs comprise the Local Project Facilitating Team. Technical experts from the Department of Agriculture-Regional Field Unit in Bicol were tapped to provide technical advice and assistance in establishing and maintaining the rainwater harvesting ponds. Eleven (11) farmer-cooperators were selected, and their respective farms showcased the rainwater

FIGURE 2. Sites of cross-farm visits showcasing rainwater harvesting facility, andsoil and water conservation measures.

harvesting ponds. Meanwhile, other upland farmers in each of the three project sites were also actively engaged in establishing the rainwater harvesting ponds.

Capacity-building activities were organized to enhance the knowledge and skills of farmer-cooperators and other volunteer upland farmers on rainwater harvesting, soil and water conservation measures, and agroforestry. These activities include cross-farm visits and on-site training on rainwater harvesting, soil and water conservation and management, and agroforestry. The farmer-to-farmer training approach was utilized to ensure a more effective transfer of learning.

Participatory planning and establishment of rainwater harvesting ponds were employed, utilizing the smallholder farmers' collective action (Bayanihan). The local community members (i.e. young members of the community) did periodic monitoring of rainwater harvesting ponds to assess their performance (in terms of water retention), durability, and utilization and distribution among the farmers.

3. RESULTS AND DISCUSSION

The one-year capacity development project has generated significant lessons and experiences. These are as follows:

a) The cross-farm visits and on-site training on agroforestry and soil and water conservation organized by the team served as a mechanism for the farmers in the three project sites to appreciate and recognize the importance of soil and water conservation rainwater harvesting in upland farming. A cross-farm visit to the selected model farms of the Conservation Farming Villages (CFV) programme in Barangay Oma-oma, Ligao City, enabled the 30 farmers from the three project sites to observe the agroforestry farms showcasing the integration of annual and perennial crops, and soil and water conservation measures. On the other hand, the farmer-cooperator of the Rainwater Harvesting Project in Barangay La Medalla, Polangui, Albay, talked about the community's efforts in the establishment of the rainwater harvesting pond through the assistance of the Office of the Municipal Agriculturist in Polangui and other project partners (Figure 2). This activity promoted the farmer-to-farmer training and knowledge sharing. According to Millar, Photakoun, and Connet (2005), cross-farm visits greatly impacted farmer awareness, confidence and problem-solving. It was also the farmers' preferred approach for learning new technologies. The authors added that cross-farm visits offer opportunities for farmers to see the actual field situation, talk and discuss with their fellow farmers, and share experiences and lessons directly. Moreover, farmers tend to recall the strategies and methods much better when they have seen them in the field. Building from previous capacity building projects (Landicho et al., 2009), the project collaborators believed that farmers learn

FIGURE 3. (L-R) (a) 10m x 30m pond in Barangay Palanas; (b) 8m x 10m pond in BarangayMalama; and (c) 5m x 7m pond in Barangay Balinad

from other farmers, as they share similar symbols and experiences. Farmers find it much easier to apply the technologies to their farms through cross-farm visits.

b) The establishment of rainwater harvesting facilities is site-specific. There is no standard size, type, and even process in establishing rainwater harvesting facilities in upland farming communities. The size and type of rainwater harvesting ponds depend on the existing local conditions, particularly the size of the farms being cultivated by the farmers, the type of crops being cultivated, the geographical conditions of the community and farms therein, the number of farmer-beneficiaries that would use the resource; and, the willingness and commitment of the community members to engage in the establishment and maintenance of the facility. In the case of Barangay Palanas, Guinobatan, where the dominant crop is rice—a water-demanding crop; and, where a number of adjoining farms were considered as among the farmer-beneficiaries, the size of the pond that was constructed was about three times the size of the ponds in the two other project sites (Figure 3). In this way, water collection, storage and distribution would be more effective and efficient. Other studies have also explored the use of different criteria in determining suitable rainwater harvesting facilities (Ammar, Riksen, Ouessar, & Ritsema, 2016; Martínez-Acosta, López-Lambraño, & López-Ramos, 2019) .

c) The spirit of collective action or the "Bayanihan system" is essential in a more efficient establishment of rainwater harvesting facilities. Barrameda and Barrameda (2011) define Bayanihan as any voluntary communal effort to achieve a common goal. It is a common practice in Philippine towns that community members help their neighbours move to a new place, repair homes or build communal infrastructures. As in other community-based development projects, the cooperation and spirit of "working together" played a key role in completing the RWHF establishment in the three project sites. This element is essential, particularly for development projects in the "pilot stage" and have limited funding support. The establishment of rainwater harvesting ponds is a tedious process. Through their collective action, the smallholder farmers were able to establish 11 rainwater harvesting ponds: (i) Two (2) in Barangay Palanas with a dimension of 30m x 10m x 2m; (ii) Four (4) in Barangay Malama with a dimension of 10m x 8m x 2m; and Five (5) in Barangay Balinad with a dimension of 5m x 7m x 2m (Figure 4).

d) Resource sharing is an important ingredient in any community development project and serves as a mechanism to develop a sense of project ownership among the stakeholders. Unlike the traditional projects where everything is given out by the project implementors and funding agencies, and local organizations and farming communities are merely considered as "beneficiaries", this capacity development project showed the relevance of counterparts from the local government units and the three partner communities. For instance, the LGUs provided vegetable seeds for establishing agroforestry systems/models and engaged the agricul-

FIGURE 4. Farmer-volunteers join thefarmer-cooperators in the establishment of rainwater harvesting ponds in thethree project sites through their "bayanihan" system.

tural technicians in the project without additional compensation. On the other hand, the farming communities provided labour in the establishment of RWHFs and agroforestry systems as their counterpart (Figure 5). Sharing of resources and efforts enables the local stakeholders to value the project, develop a sense of project ownership, and pave the way for the sustainability of the project initiatives.

FIGURE 5. The community members provide labour as their project counterpart.

e) Addressing the expressed/felt need of the communities guarantee their commitment and engagement in the project activities. Since agriculture is their main livelihood, the three farming communities were in dire need of water sources that would provide irrigation to sustain their agricultural production even during the dry season. This need was expressed in 2018 when a study was conducted in the three farming communities (Landicho et al., 2018) . Since the project's inception, the farmers and the local leaders have extended their support and active engagement in the project activities. Despite the pandemic and natural disasters brought about by typhoons in 2020, the farmers persisted in completing the establishment of RWHFs (Figure 6).

f) The establishment of rainwater harvesting ponds enabled the farmers to enhance their agricultural production. For instance, in Barangay Palanas, the farmers used to cultivate rice in one cropping season only. However, they started cultivating rice for two cropping seasons because of the good retention of the rainwater collected in the rainwater harvesting ponds (Figure 7). In Barangay Balinad, on the other hand, the farmers did not cultivate the sloping areas surrounding their coconut farms because of the lack of water. However, with the establishment of rainwater harvesting ponds, these farmers started cultivating these idle lands with agricultural crops. In Barangay Malama, the land area allocated for rice production was increased by the farmer-cooperators because of the availability of irrigation water.

g) The establishment of rainwater harvesting ponds gave way for adopting agroforestry systems and technologies in the sloping agricultural production areas of the upland farmers.

Given the marginal conditions of the upland farming communities, agroforestry is considered an appropriate land use management system. Agroforestry is a dynamic, ecologically-based natural resource management system that deliberately combines woody perennials with herbaceous crops and/or animals either in some

FIGURE 6. Functional ponds in the three project sites.

form of spatial arrangements or temporal sequence on the same land to diversify and sustain production for increased social, economic and environmental benefits (Leakey, Temu, Melnyk, & Vantomme, 1996). A number of studies have shown that agroforestry offers potential in enhancing the socio-economic productivity of the farmers because of the diverse crop components (Landicho et al., 2016; Tolentino, Landicho, De Luna, & Cabahug, 2010; Cunningham, Nicholson, Yaou, & Rinaudo, 2008) while at the same time addresses the ecological dimension (Baliton et al., 2020; Palma & Carandang, 2014; Casas, Marin, Toledo-Bruno, Lacandula, & Aguinsatan, 2014).

In Barangay Palanas, the upland farmers, through the technical assistance of the agricultural technician, have established an agroforestry system, integrating mulberry (*Moros alba*) as hedgerow species, and dragon fruit (*Hylocereus undatus*) as alley crops, in the alley/hedgerow cropping system (Figure 8a). Being a woody perennial, mulberry serves as the permanent crop and is planted as contour hedgerows. On the other hand, the dragon fruit, which is a medium-term crop, is planted along the alleys and annual vegetable crops. Besides their suitability to the site, mulberry and dragon fruit provides economic potentials, being high-value crops. Furthermore, mulberry wine is being produced in Bicol Region, and therefore, Barangay Palanas could be a potential supplier of raw materials to the processors. The vegetable crops would serve as a food source for the upland farmers.

FIGURE 7. Farmers in Barangay Palanas, Guinobatan can now produce rice in two cropping seasons because of water availability.

In Barangay Malama, the sloping farms around the ponds were developed into contour farms, where kakawate (*Gliricidia sepium*) serves as the hedgerow, and lemon (*Citrus limon*), cacao (*Theobroma cacao*), turmeric (*Curcuma longa*) and vegetable crops serve as the alley crops (Figure 8b). Lemon, cacao and turmeric are among the high-value crop species in Albay. Lemon is integrated into farms with open areas, as this species is light-demanding, while cacao is integrated into farm areas with coconut. Vegetable crops are a source of food for the household and other community members. *Gliricidia sepium* offers a number of potentials, including soil fertility restoration, being a nitrogen-fixing tree species, a source of fuelwood, particularly the prunings, and, as a source of feeds for the livestock, particularly the leaves. The leaves could also be used as botanical pesticides. In Barangay Balinad, the steep areas around the ponds were developed into contour farms with *Gliricidia sepium* as the hedgerow crop and corn as the alley crop (Figure 8c).

Integrating soil and water conservation measures such as the contour hedgerows is an appro-

FIGURE 8. (L-R) (a) mulberry-dragon fruit integration in Barangay Palanas; (b) integration of citrus, cacao and yellow ginger with *Gliricidia sepium* as contour hedgerows in Barangay Malama; and, c) integration of *Gliricidia sepium* as contour hedgerows in the corn production area in Barangay Balinad.

priate strategy to prevent soil erosion in the sloping areas, which are oftentimes the sites that smallholder farmers cultivate. Integrating soil and water conservation measures in upland farming does not only control soil erosion in the sloping areas and conserve soil nutrients needed by the crops but, more importantly, helps protect the ponds from being damaged by the soil and debris from the sloping areas around them.

h) Support of the local government units at various levels helps facilitate the smooth project implementation in the three project sites. The active involvement of the Office of the Municipal/City Agriculturist, through their agricultural technicians in the three project sites, helped mobilize the farmers in all stages of project implementation and closely monitored the status of project implementation (Figure 9). Furthermore, mobilizing the Local Multisectoral Team through the leadership of the agricultural technicians representing the Office of the Municipal/City Agriculturists in the three local government units. Constant communication and close coordination are being done regarding the field activities, and these are being relayed to the key leaders of the partner communities. Literature has pointed out the crucial role of the LGUs in promoting sustainable natural resource management in the Philippines (Landicho & Dizon, 2020; Cruz et al., 2016; Luna, 2018; Landicho et al., 2018).

i) Regular communication of the project collaborators via electronic mail and other forms of social media is a key to sustaining the project implementation despite the travel restrictions and face-to-face interactions brought about by the pandemic. The diverse means of communication ensured that the project implementation is on track and issues and problems arising from the project implementation are immediately being addressed (Figure 10).

j) Tapping the locals as the Local or On-Site Monitors is both capacity development and a project facilitating opportunity. These on-site monitors served as the link between the farmers and the collaborators since the agricultural technicians, whose municipalities were also on lockdown, were restricted to fieldwork. The local/on-site monitors organized the field activities, coordinated with the collaborators for logistics and technical concerns, and monitored the progress of RWHF establishment (Figure 11). These local/on-site monitors were also tapped to conduct periodic monitoring using the monitoring tool that the project collaborators developed. Engaging youth in-field monitoring did facilitate project implementation and provided an opportunity to enhance their capacities coordinating and monitoring projects and enhancing their communication skills. In Barangay Balinad, the local/on-site monitor was the President of the 4H-Youth Club, while the Barangay Secretary was tapped as the local monitor in Barangay Malama. In Barangay Palanas, the President of Sangguniang Kabataan (Youth Organization) was also engaged as the local monitor.

4. CONCLUSION

Water availability is the primary factor influencing the agricultural production of smallholder

FIGURE 9. The LGUs at the municipal and village (barangay)-level are actively engaged in facilitating project implementation.

FIGURE 10. Despite the pandemic, the project collaborators are able to maintain regular communications and updating via Zoom meetings.

farmers in the rainfed areas. This article concludes the viability of establishing rainwater harvesting facilities in the upland farming communities in Albay Province, Philippines. While the establishment of rainwater harvesting facilities is complex and multidimensional, the lessons and experiences generated by this project suggest that certain mechanisms can facilitate the establishment and sustained management of these facilities. These include the multisectoral collaboration—of the LGUs, farming communities and other assisting institutions such as the state colleges and universities; collective action of the farming communities; capacity development through cross-farm visits and training, and tapping the locals as part of the monitoring team; integration of sustainable land use management and other supporting technologies such as agroforestry and soil and water conservation and management; and resource sharing. These lessons could be used by the other development organizations and LGUs to implement similar initiatives in other upland farming communities in the country.

FIGURE 11. The locals managed to conduct regular monitoring of the rainwater harvesting ponds.

As the rainwater harvesting ponds are still in their first two years of being operational, further studies can be undertaken regarding the efficiency of the water utilization and distribution of the ponds to the cropped fields. Studies on the evapotranspiration rate and underground seepage of the 11 rainwater harvesting ponds could also be investigated to further improve water collection and storage effectiveness and efficiency. Finally, an impact assessment can be conducted after three years of the pond establishment and utilization to assess how these facilities contribute to the agricultural production of the farming communities and analyze the strengths and weaknesses of the facilities, including the mechanisms of maintenance, utilization and distribution of the rainwater to farmer-beneficiaries.

5. POLICY IMPLICATIONS

The lessons and experiences of this capacity development project proved the workability of establishing rainwater harvesting ponds in the upland farming communities in the country. Hence, the local government units, through the Office of the Municipal Agriculturists and other concerned offices, could work together towards the establishment of at least one rainwater harvesting pond in each of the clusters of the upland farming communities. This will ensure the availability of water for use in the irrigation of their crops. The establishment of rainwater harvesting ponds could be mainstreamed in their local development programmes to facilitate the allocation of a budget for the sustainable management of these ponds. This is also consistent with the Republic Act 6716, also known as the Rainwater Collector and Springs Development Act of 1989, which requires the construction of rainwater collection in every ”barangay” or village to prevent flooding and ensure the continuous provision of clean water during the dry season.

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Spatial planning-based ecosystem adaptation (SPBEA) as a method to mitigate the impact of climate change: The effectiveness of hybrid training and participatory workshops during a pandemic in Indonesia

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ABSTRACT

Climate change has a greater effect on the long-term viability of coastal environments and people's livelihoods. The idea of using ecosystems to help people deal with the effects of climate change is becoming more common at the international, national and local levels, especially when it comes to spatial planning. So, learning about spatial planning-based ecosystem adaptation (SPBEA) is important for early-career practitioners because they will be the responsible generation responding to decisions being made now. Coastal communities must also understand the steps they can take to lessen the effects of coastal disasters in their area. This study looks at how the SPBEA concept can be taught to early-career practitioners and coastal communities through training and workshops, and how effective online training is in transferring knowledge. The training implemented a hybrid style for comparison. A hierarchical approach was taken, starting from the compilation of SPBEA teaching materials, followed by SPBEA training for early-career practitioners to generate SPBEA zoning and transferring the training results to the coastal communities. While online training is not as good as offline training, it was advantageous for the participants. Indeed, the pond-farming community was excited about the implementation of SPBEA.

KEYWORDS

Spatial planning, ecosystem adaptation, training, workshop

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HIGHLIGHTS

- Spatial planning-based ecosystem adaptation (SPBEA) is a critical policy concern that all stakeholders must be aware of, from the government to the public as policy users and objects.
- This concept is important for young scientists, early-career practitioners, and the community at the village level in their efforts to form a better future of sustainable spatial planning.
- Capacity building in the form of training and workshops is one of the practical ways of implementing SPBEA.

1. INTRODUCTION

1.1. Background

Climate change has a disproportionate effect on islands and coastal countries, where storms, tidal waves, sea-level rise, abrasion, accretion, coastal floods, and shoreline retreat all occur. It is expected to have a tremendous negative effect on coastal communities, especially those that rely heavily on nearby natural resources for their livelihoods. It is likely that the impact of disruption to the coastal ecosystem is not exclusively the result of a single factor but rather the result of a number of factors combined (Sutrisno et al., 2021). Consider subsidence, for example. It can have an impact on the occurrence of flooding and coastal abrasion in a coastal area, particularly when tidal waves or other sea-related phenomena are present. Coastal populations are forced to adapt their way of life to existing developments, which is not the right solution. In this case, spatial planning is a critical component of adaptation, particularly at the local level, where coastal risks may be encountered and solutions established (Robert & Schleyer-Lindenmann, 2021). Spatial planning is commonly regarded as a public sector activity concerned with influencing the future spatial distribution of activities (Yoshida et al., 2020). Thus, spatial planning is critical for facilitating proactive, preventative adaptation of human settlements to hazards induced or exacerbated by changing climate patterns and catastrophic occurrences (Mcmillana, Birkmanna, & Tangwanichagapong, 2021).

On the other hand, local planning practices encourage climate-resilient spatial planning to be fragmented, and interventions are neither systematically implemented nor carefully reviewed (Wamsler et al., 2016). This paper encourages the operationalization of ecosystem-based adaptation by spreading the understanding of how ecosystem-based adaptation can be considered in spatial planning when confronted with the effect of climate change on the coastal zone. Spalding et al. (2014) suggest that ecosystem-based adaptation approaches provide an important framework for spatial planning. The current case conveyed a vivid impression that public understanding of Spatial Planning-Based Ecosystem Adaptation (SPBEA) information is a crucial issue for all parties.

Understanding SPBEA is also important for young and early-career scientists to increase their awareness and interest in ongoing climate change. Understanding and raising awareness of the value of disaster reduction and adaptation and the role of science and technology in solving these problems is vital. Disaster reduction and adaptation is a subject that we must explore with them as part of our dedication to ensuring coastal security for future generations. Indeed, understanding SPBEA is also necessary for coastal communities since they would be particularly influenced by spatial planning policies and attempts to prevent coastal disasters.

Training and workshops are effective methods of educating young scientists and coastal communities about the need for SPBEA. However, the COVID-19 pandemic is creating barriers for traditional classroom training and workshops. So, online training has unavoidably become the preferred solution. This circumstance brings the following issues:

1. What is the effectiveness of online training for the SPBEA method?
2. Is the proposed method appropriate?
3. Is it possible to use the same strategy in rural communities?

This study aims to assess how the SPBEA concept can be shared with the young scientists and coastal communities through training and workshops and how effective the transfer of knowledge would be.

For this purpose, the subdistrict of Sayung, Demak, Indonesia, was chosen as a study area. This area is largely affected by climate change-related effects, such as tidal waves and land subsidence. Indeed, awareness of coastal ecosystem function and services, such as mangroves, has not yet been properly acknowledged (Handayani, Adrianto, Dietriech, Nurjaya, & Wardiatno, 2020).

1.2. Study area

The Sayung subdistrict is located on the north coast of central Java (see Figure 1). This coastal region is directly adjacent to the Java Sea and Semarang, the capital of Indonesia's Central Java province. As a result, the Sayung coastal area acts as a buffer for the economic and population development of Semarang city.

Sayung's coastal area is lowlands with a flat surface area of less than 2% and an elevation of between 0 and 5 m above sea level (Utami, Subardjo, & Helmi, 2017). The climate was defined by an average annual rainfall of 2,292 mm and an average daily air temperature of 27.0°C (Climate-data.org, 2019). Shoreline retreat (Sutrisno et al., 2021; Sriyana, Niyomukiza, Sangkawat, & Parahyangsari, 2020), tidal floods (Haloho & Purnaweni, 2020), and relative sea-level rise are some of the factors that affect the coastal area's long-term viability in the Sayung subdistrict (Utami et al., 2017). According to previous research, the erosion rate of coastal regions in the Sayung subdistrict ranged from 4 to 65 meters per year, with an average of 25 meters per year (Muskananfol, Supriharyono, & Febrianto, 2020). Massive conversion of mangrove forests to aquaculture ponds contributes to the degradation of coastal areas and the decline in mangrove species' composition and physical structure (Ardhani, Murdiyarso, & Kusmana, 2020). Additionally, based on the geomorphological circumstances of Sayung's coastal region, which has a high degree of erosion insecurity and an inundation intensity of 3.5 hours per day, these difficulties encourage people to adapt to these conditions (Sarasadi, Rudiarto, & Faradila, 2021).

In this case, local residents have adapted to environmental changes over a long period of time, whether through physical adaptation to the environment, economic adaptation through shifting livelihoods, or social adaptation through time adjustments to natural phenomena. Before the village was flooded, Sayung residents were food crop farmers. Then, they transitioned to fishpond farming or capture-fishing activities as their coastal areas shifted. Indeed, the changing coastal region has compelled the citizens of Sayung to respond physically and promptly, whether by restoring their homes or planning activities around the tidal season. Figure 2 portrays how people adapted to the changing coastal climate.

Surodadi was chosen as the workshop's venue for detailed scale data because it has not yet fully embraced an ecosystem-based approach to village management.

2. METHODS

This capability building exercise employs a phased approach to disseminating SPBEA understanding to the young scientists and rural communities in the research area. The approach consisted of compiling SPBEA methods into teaching materials, then sharing the SPBEA and

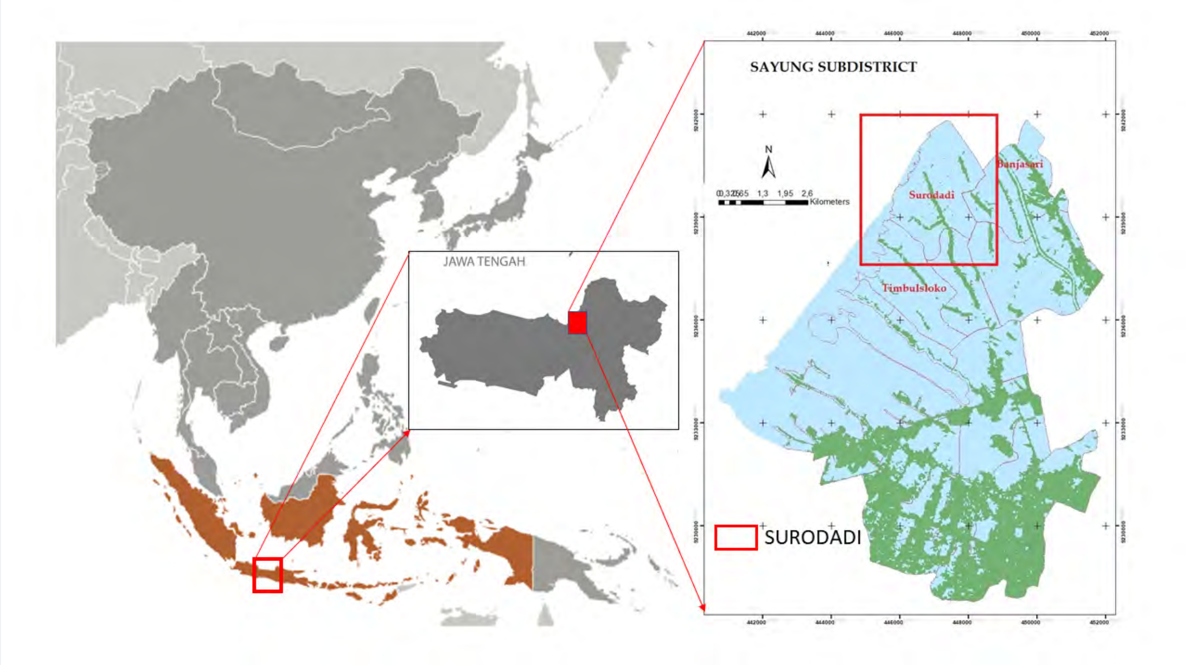

FIGURE 1. Study area, Sayung subdistrict, Central Java, and Surodadi village. Vector map from Worldometer.info (2021).

FIGURE 2. How people adapted to changing coastal areas in the study areas of Surodadi Village — Sayung subdistrict: (a) structural adjustments to housing, (b) school time adjustment, and (c) livelihood adjustment from farmers to fishermen.

related sciences with young scientists to generate SPBEA zoning, and finally, disseminating the training results to coastal communities through participatory mapping techniques (see Figure 3).

As previously stated, the training technique is online owing to the COVID-19 pandemic. Limited offline training is also conducted to compare the efficacy of the training. Similarly, because online workshops are not possible due to the constraints of village community technology, the participatory SPBEA mapping workshop is conducted offline on a limited basis. The teaching materials introduced background sciences related to SPBEA, its practical implementation by geographic information system (GIS) technology, and remote sensing.

2.1. Compiling SPBEA methods and teaching materials

Teaching materials were the core of the training program. The goal is to grow participants'

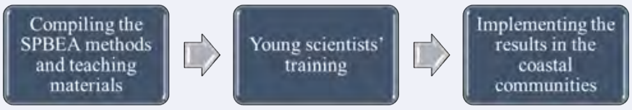

FIGURE 3. Steps of SPBEA capacity building.

awareness. Teaching materials may involve cognitive learning (knowledge) in the form of studying scientific theories and concepts, learning (skills) in the form of studying approaches to conducting and completing tasks, and effective learning (attitudes) that will manifest values or norms (Ajar, 2014). For this activity, we focused on knowledge and skills learning. The subject of the teaching materials was very specific and unique, as it pertained to SPBEA. The SPBEA material used in this training was modified from the method of Sutrisno et al. (2021) to make it easier and more feasible to implement. So, the selection of the training module and materials had to be tailored to the knowledge and skills to be acquired (Safrina, 2018), which was determined based on problem-oriented learning (see Figure 4).

Therefore, before the implementation of the training, it is crucial to (a) determine what kind of sciences and skills must be shared in the capacity building to support the SPBEA subject, (b) determine the specific method and data, and (c) determine the scientific background of the participants. The training module was discussed with the trainers through the focus group discussion (FGD). Following that, the training materials, data, and supporting science for this training were compiled.

2.2. SPBEA training

The first thing that must be determined in implementing the training is the qualifications of participants. Due to the advanced nature of the subject, trainees must possess a background knowledge of earth sciences and the ability to comprehend and operate similar software, which the lecturers would operate during the practical session.

Due to the COVID-19 pandemic, the training was performed according to a mixed model that combines offline and online classes. The materials, data, and software used in this training were shared with the participants in advance via Google Drive, ensuring that they were prepared to use the data and software for the practicum on the first day of the training. An assessment of the effectiveness of the online training was also conducted based on observation, purposive sampling, and questionnaire analysis. Then, we evaluate the findings with the offline training. The explanation is as follows:

1. The observation of the participants was employed to assess the participant's interest in the subject being taught through the activities in questions and answers (QA) and any impediments to the training's implementation. The number of participants who completed the training, including those who participated online, was used to evaluate interest in the training subjects.

2. The purposive sampling of the most active online participants was used to evaluate whether the subjects being taught were understood, based on the participants' ability to share training output in the forums and problems encountered in the training and technological obstacles.

3. The questionnaire analysis was done during the training to determine whether participants

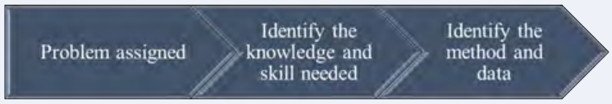

FIGURE 4. The flow of method and teaching material determination.

comprehend what they are learning, the problems, suggestions, and the usefulness of the training for their future careers.

4. To determine whether SPBEA training is more beneficial, we compare the outcomes of brief reports from online and offline training participants.

SPBEA zoning spatial data is expected to be generated due to the implementation of this training. This information will be built upon in greater depth during village-level spatial planning, implemented in a participatory format in a selected village.

Meanwhile, the target number of trainees was previously set at 40 for both online and offline training and the workshop participants were grouped into 10 people.

2.3. SPBEA workshop

Using the result of the training activities, a workshop with a group of pond farmers was implemented in two phases. The first stage involved an understanding exchange about SPBEA and a discussion and a brief demonstration of village spatial planning. The second stage was implemented on a small-scale village SPBEA, in which the SPBEA was implemented on a pond area adjacent to a river owned by the pond farmers' community leader. This stage introduced the concept of a greenbelt and associated mangrove aquaculture (AMA) and polyculture as a component of SPBEA design.

AMA or silvo-fisheries and polyculture are crucial methods for adaptation in a disaster-prone village. AMA is a system of natural resource management that incorporates a mangrove greenbelt with the adjacent aquaculture. In contrast, part of the aquaculture pond is given up to make space for riverine mangroves to restore mangrove greenbelts along inland waterways and to protect adjoining fishponds (Building With Nature, 2020). Meanwhile, polyculture is a form of agriculture that replicates the diversity of natural ecosystems by simultaneously growing multiple species and in the same area (Chrispeels & Sadava, 1994). Why is a demonstration site crucial when launching an SPBEA operation in rural areas? Pond farmers are executors who undoubtedly prefer to see results rather than hypotheses or ideas on paper.

3. RESULT AND DISCUSSION

3.1. Compiling SPBEA training materials

Coastal inundation, flooding and erosion are the most severe coastal disaster causes identified. Climate change issues, such as sea-level rise (eustatic, isostatic, or relative), storm surge, tidal waves, and high waves are being addressed. Considering the massive population growth and the number of industrial estates that are highly reliant on groundwater, the issue of land subsidence or relative sea-level rise is significant (see Figure 5). These issues were evaluated with the study area. It was concluded that tidal waves, land subsidence, and the degradation of the coastal landscape worsen issues related to coastal erosion and shoreline retreat. In addition to the groundwater discharge triggered by the rapid physical growth in the Sayung area, the decrease in the groundwater level and the building pressure on the specific type of soil all lead to an acceleration in the occurrence of land subsidence (Afif, Yuwono, & Awaluddin, 2018).

Research was conducted for evaluating the relevance of the above issues, resulting in the prototype of the SPBEA (Sutrisno et al., 2021). However, this model developed would be too complicated for the training. Thus, the SPBEA method used as training material was modified from the method of Sutrisno et al. (2021), producing a more practical and faster process. The results of the method's development are depicted in Figure 6 below.

The SPBEA modelling of Sutrisno et al. (2021) is complicated and requires the development of a more complex algorithm. However, the SPBEA approach used for training is simpler and relies on fundamental GIS techniques, such as overlay, union, updates, and intersections, as well as a simple analytic hierarchy process (AHP) assessment for a pond's aquaculture suitability area. The data for training can then be defined based on the requirement of SPBEA model development (see Table 1).

Furthermore, the material that needs to be taught has been developed by targeting the root of the problem and why the SPBEA concept is required, particularly in the study area (see Figure 5). The teaching material is defined in Table 2.

The preceding categorizations thoroughly describe the phases of the training material. The training begins by imparting a fundamental understanding of the disaster issues caused by climate change in coastal areas and an understanding of the ecological role of coastal ecosystems for disaster reduction. The training then focuses on spatial planning to deal with disasters based on the concept of adaptation to coastal ecosystems. These materials are taught with lecturers or instructors assigned to each subject depending on their expertise.

3.2. SPBEA training

Training is a critical component of building human capital capability. It not only encourages an individual to expand their awareness but also plays a role in determining how effective and successful an individual is in adapting their knowledge to their work. Thus, given that the training aims to improve young scientists' scholarly knowledge and awareness about the SPBEA concept and method as one technique for mitigating the effects of climate change on coastal areas, the effectiveness of the training is dependent on three factors. The first factor is how interesting the topic is to the young scientist; the second factor is how well the material is being taught and understood by the training participants; and the third factor is whether there are any impediments to the training's execution.

The participants' enthusiasm for the training topic, based on our observations, can be seen in the diagram below.

The diagram in Figure 7 shows a very high degree of enthusiasm on the first day of training for the topics and materials to be studied in the training; the number of attendees on the first day was 75, equal to the total number of participants. However, the number of participants declined on the second day among those who registered as online participants. From the third to fifth day, attendees remained relatively stable at 45 participants.

Only 60% of those who participated online successfully completed the training. However, measured in terms of the original target number of participants, which was about 40, the target was reached. The decreased number of participants could be due to technical issues such as time zone differences, network stability issues, network costs, distractions, time management issues involving the participants' attention being diverted to other tasks that were more urgent to complete, lack of motivation, and a lack of in-person interaction. All of these factors may have discouraged the participants from completing the training. Yustika, Subagyo, and Iswati (2019) demonstrated that online classes face several challenges, including a lack of social interaction, technological limitations, and poor participant motivation. Indeed, Herbert (2006) stated that online courses have a failure

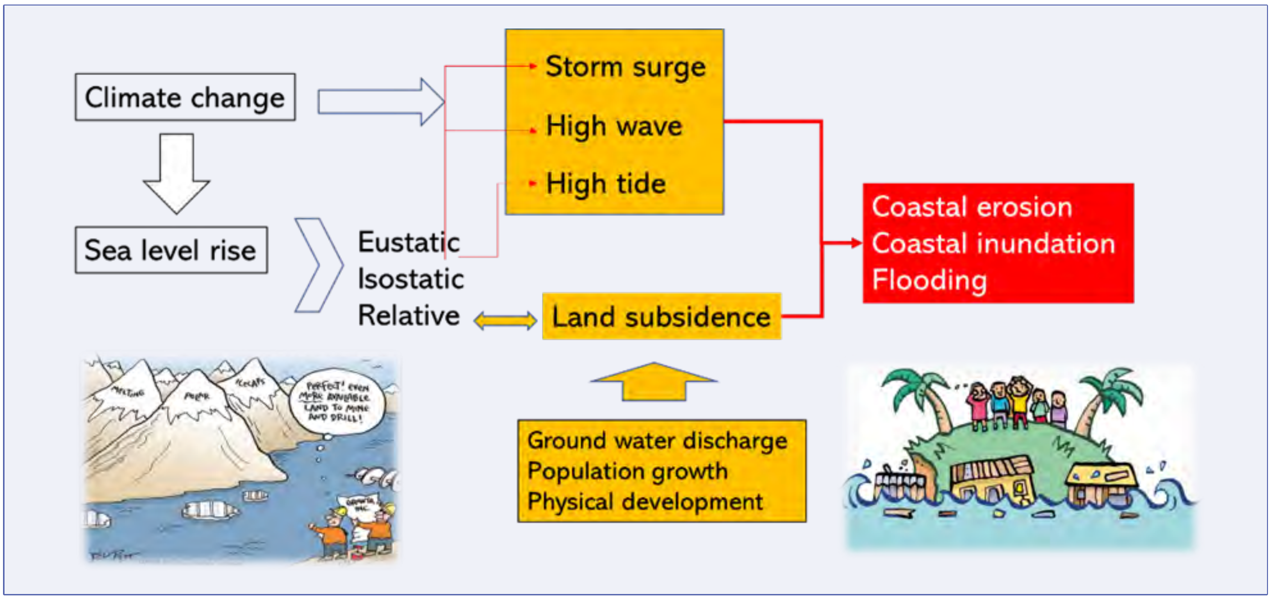

FIGURE 5. Illustration of the root of the problems in the coastal area (Sutrisno, 2019) .

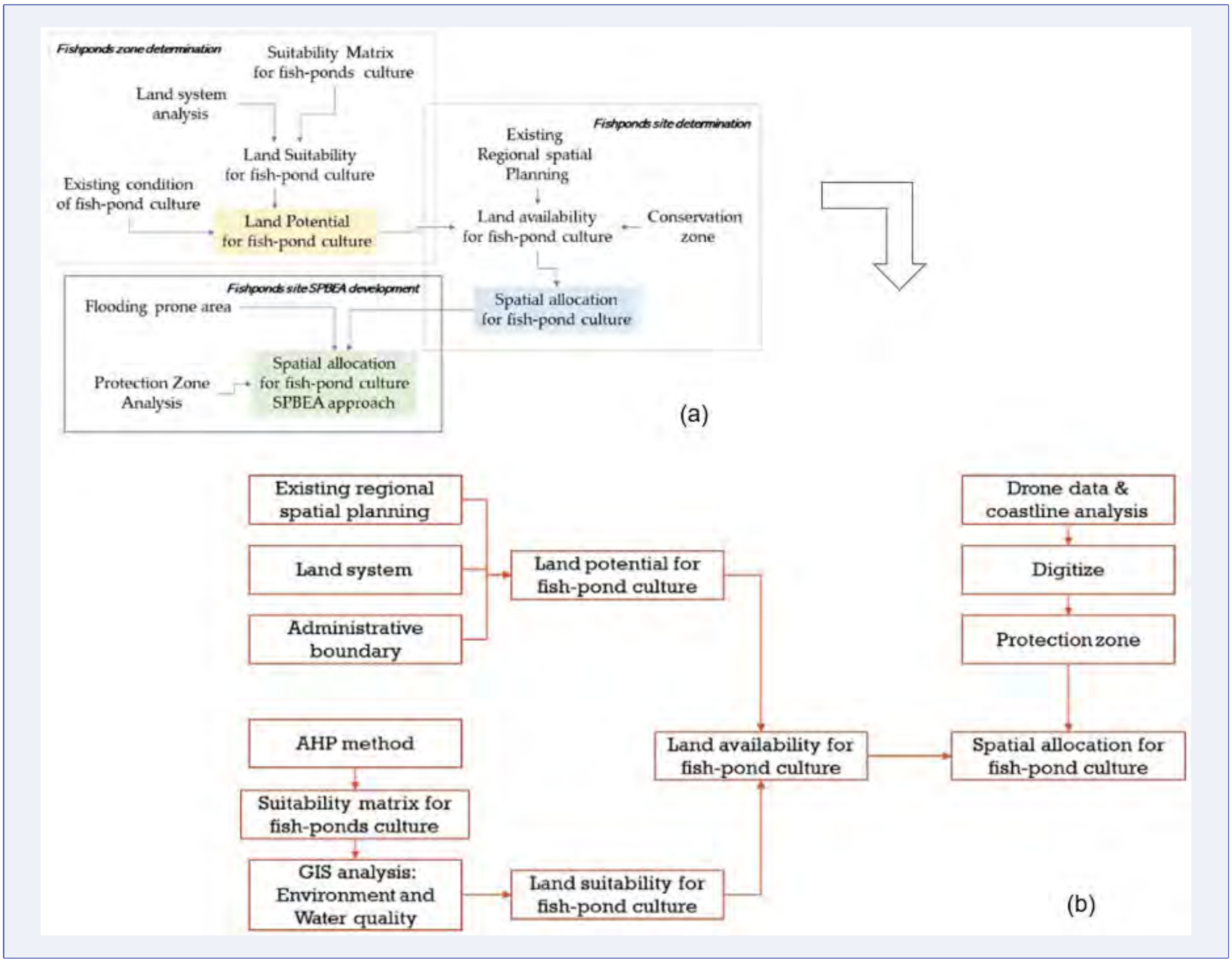

FIGURE 6. Steps of SPBEA development: (a) Sutrisno et al. (2021) and (b) SPBEA steps for training materials, Rahadiati (2021).

Data	Type	Data Output
Land system	Ancillary data	
The land-use/land Cover	Ancillary data/ RS-derived map	
Base map	Ancillary data	• Green belts • Protection zone • Coastline
Spatial plan	Ancillary data	
Slope	Ancillary data	
Flooding prone area	RS derived-map	
pH	Field data	
Salinity	Field data	
Landsat 8 Oli		• Flooding prone • Protection zone • Coastal change
Drone-based map	Field data	• Detailed land-use map • Green belt-Protection zone • Spatial planning map

TABLE 1. Data available for the training.

Issues	Lecture	Objective
Climate change that can trigger coastal disasters, such as sea-level rise, storm surge, and tidal waves	The impact of climate change on coastal area disasters, based on a hydrological approach	To explain how disasters can affect the coastal environment
	Assessing the impact of climate change on the coastal area to mitigate the impact	To create a spatial model of climate change's impact on the coastal environment
	Using the coastal vulnerability index (CVI)	To assess the vulnerability of coastal areas to climate change
Population growth and physical development has changed the nature of the ecosystem	Coastal ecosystem functions and services	Understanding the ecological role of coastal ecosystems to preserve the coastal environment's sustainability and how coastal ecosystem services can be used to enhance the wealth of coastal communities
	Social sensing	To track human behaviour and public concerns
	RS data analysis using R for disaster mitigation	To investigate spatially how mitigation can be accomplished using RS data. The result of this is coastal protection zone data
The inclusion of coastal ecosystems in spatial planning	Integration of coastal and land spatial planning	To learn about ICZM through spatial planning
	Sustainable coastal aquaculture: implementation of AMA, LEISA, and IMTA	To improve understanding of how to spatially manage sustainable aquaculture
	Spatial planning-based ecosystem adaptation theory and practice	To learn how the SPBEA method is developed
Implementation of detailed SPBEA	Spatial data acquisition using UAVs and their processing	To learn how big-scale mapping can be derived for a detailed SPBEA model
	GCPs and photogrammetry for big-scale mapping	
	Big-scale mapping	

Note: AMA = Associated mangrove aquaculture, LEISA = Low external input for sustainable aquaculture, IMTA= Integrated multi trophic aquaculture.

TABLE 2. The material of the training development.

FIGURE 7. Daily training attendees.

retention rate of 10% to 20% higher than conventional classroom training. Even though the training target was reached, it is necessary to consider the optimal number of trainees to achieve the best outcomes. Additionally, a more rigorous selection process for the trainee is required for understanding participants' interests. To increase the attractiveness, the training could provide incentives for participants, such as reimbursement of internet fees, incentives for those involved, and the ease of accessing information for those who have network delays, such as sharing the videos or YouTube recordings of training materials.

The second step in training implementation is to ascertain how well the participants retained the knowledge and skills imparted during the training, what the participants learned from the training and their experience of the training, and what overall impact the training had. To examine this question, we randomly selected 15 active participants. We used the findings to show how well they understood the training material through a presentation of the hands-on project of the training. The findings revealed that 95% of the chosen participants comprehended and enacted the material correctly. The 5% failure rate was due to a lack of ability to operate the software. Figure 8 and Figure 9 illustrate an example of the training reports and the chosen presenters.

There were no significant difficulties for the offline participants since they could complete their tasks and comprehend the content. The offline participants benefited from proximity to and direct communication with lecturers and instructors and from being more serious and focused on doing all assigned work and comprehending all training content.

From the questionnaire, 97% of participants expressed the necessity of this SPBEA concept for their jobs, while 3% could not completely comprehend it due to insufficient knowledge, technology, networks, and time. Meanwhile, 95% of participants expressed that the teaching materials were acceptable, whereas 5% desired additional in-depth knowledge and skills related to SPBEA. Most participants desired offline training due to communication issues encountered while practising the material. The following comments offer insight into what the participants experienced and what they learned from the training:

1. "Many things can be learned from this training. I've gained new knowledge here, and I hope that events like this will be held regularly."

2. "Excellent and colourful training for me, as I learned a lot about spatial planning methods and knowledge. Thank you for considering me! I'd like to see you again. I'm looking forward to hearing from you again. Have a great time!"

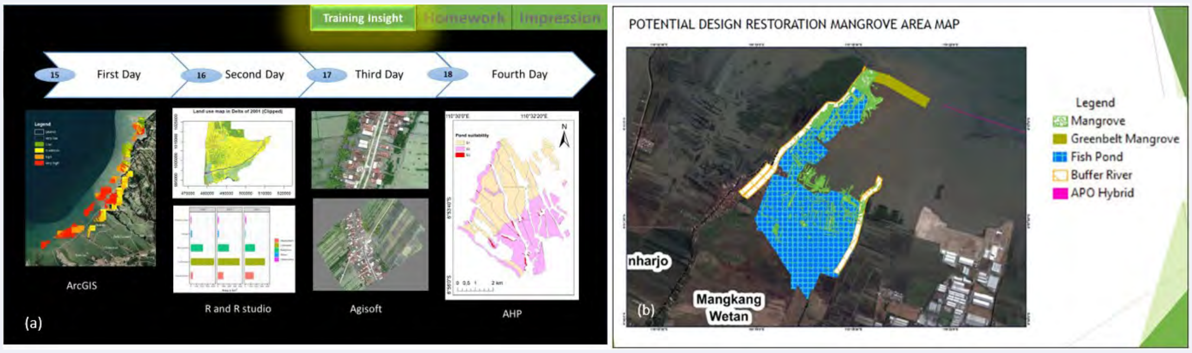

FIGURE 8. Example of training reports from the participants.

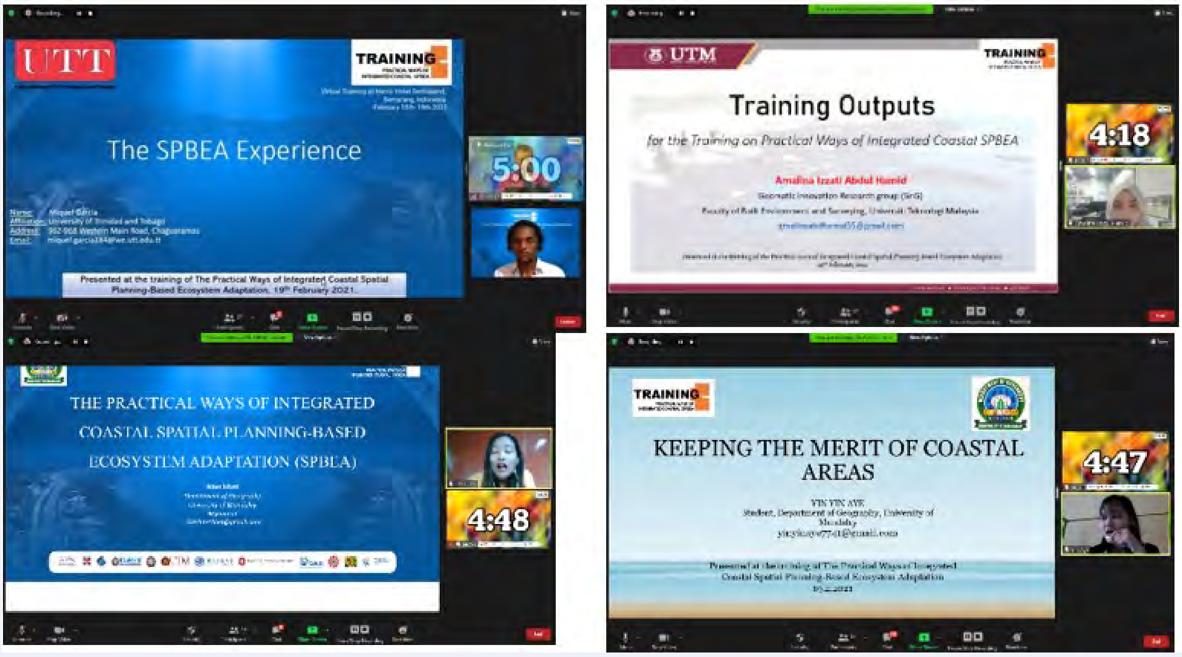

FIGURE 9. Presentation from the participants.

3. "I am very interested in this training, where I can learn new things. Hopefully, this kind of training will be continued."

4. "The most interesting topic I learn is about Big Scale Mapping because it involves data acquisition using UAV (drones) and different kinds of cameras such as Thermal Infrared Camera and Short-wave Infrared; it also involves different kind of sensors like geodetic, sonar, radar. It also involves different kinds of factors in taking photos that must be achieved, like the foreword and side overlapping, shutter speed, ISO, aperture. The drawback of this kind of mapping is the cost because it requires expensive equipment, which is not student budget-friendly. However, this topic has more to learn in the future"

5. "Thank you so much for valuable training programmes."

The training's cumulative effect is reflected in these remarks:

1. "This training course covered many informative topics that will be beneficial to my studies. I'm

hoping that the video of the lectures can be shared with us."

2. "All the topics presented in the training are very interesting. I, however, find the topic of coastal integration and land spatial planning to be the most relevant to my country's situation. SPBEA is needed for certain locations in the Solomon Islands because current adaptation projects are ineffective due to poor planning and understanding of the local geography and ecosystems. Thus, the inclusive SPBEA method could be more effective for adaptation projects."

Participants' feedback is very important to evaluate the success of the training, even though it is not always easy to ask the participants, especially those who participate online, to complete the questionnaire of evaluation.

3.3. SPBEA workshop

The participatory SPBEA workshop at the local level applied the SPBEA model developed during the SPBEA training. Via the training, information on coastal spatial zoning was obtained. The information fell into the categories of coastal and river protection zones, allocation zone classes for fishponds and settlements, large-scale-derived drone imagery, and the concept of AMA and polyculture (see Figure 10). These data were used at the village level for the SPBEA detail map. Surodadi, a coastal village adjacent to the sea, was selected as the study area for rural SPBEA implementation (see Figure 11).

The workshop was divided into two stages. The first stage was a participatory discussion about preparing for village spatial planning using drone maps and zoning maps. The second step involved introducing the SPBEA on a demonstration site of a parcel of land owned by a community of aquaculture farmers located adjacent to a river.

The participants' enthusiasm for discussing the spatial planning of their village area, where fish ponds provide revenue and production was interrupted by tidal flooding, which made this discussion extremely successful. While they were conceptually unaware of SPBEA's ecological and economic functions, the participants benefited from nearby mangroves, especially in coastal areas where mangrove conservation had been introduced. For example, a yield of mangrove crabs could be used to supplement income during the rainy season or during the low season when their ponds cannot produce an adequate yield. Thus, the participants recognized the critical role of SPBEA in ensuring the profitability and sustainability of the coastal environment.

Additionally, we promoted the Surodadi SPBEA as a rural fishing village concept. The rural fishing village maintained its culture and way of life as a coastal community reliant on aquaculture ponds. It can also serve as an ecotourism destination, thus increasing the fisheries' productivity and income for local fishermen. Gonzáles and Antelo (2020) concur that fisheries and tourism support the local population, as a fishing village can expand as a marine tourism destination. Indeed, Rudianto and Yanuhar (2018) suggest that fishing-based coastal village planning is a method of strengthening coastal communities. Pond farmers and villagers will benefit from the lucrative program offered by an SPBEA fishing village. In addition to establishing ecotourism in the mangrove protection region, they will be able to create agritourism businesses in fishpond cultivation areas. However, without the assistance of the local government, the implementation of the SPBEA rural fishing village would have been a failure. The village leaders and pond farmers were required to present the results of the SPBEA meeting to state and provincial councils following the discussion. This would be quite a challenge for them. With the help of local partners, such as the local university or other local officials, this could be easier and more effective.

We attempted to put our rural spatial planning concept into practice on a demonstration site following a workshop discussion and exercise on rural SPBEA. Spatial suitability planning was used to implement AMA or silvo-fisheries and the development of coastal and river green belts. Mangroves were planted along the riverbank, and fish seedlings were distributed using the polyculture concept in the sample ponds belonging to the pond farming

FIGURE 10. Material for discussion of rural SPBEA: (a) big-scale map-derived drone, (b) zonation maps.

FIGURE 11. Participatory discussion about preparing for village spatial planning.

communities (see Figure 12).

However, given the project's timeline and the fact that the presentation requires time to develop, it is doubtful that we will be able to measure the program's performance. The alternative seems to be that the local university's collaborators resume the initiative after the end of the project, either through updates from the farmer community or through site visits.

4. CONCLUSION

SPBEA is a key policy issue that must be addressed by all parties, from the government to the public as policy users and objects, including young scientists and farming communities. Before the training, it was shown that the training participants (young scientists) did not fully comprehend how SPBEA works or what approaches can be taken to apply SPBEA. Meanwhile, not everybody in the village was aware of the rural SPBEA or its potential impact on their way of life. After the workshop, they felt that this training would help them improve their understanding of SPBEA implementation in practical ways.

Given the limited time available, training had to be conducted in practical and simple ways, making it easier to understand and execute. Open-source software is recommended for potential implementation by a trainee. Likewise, direct practice makes it easier for participatory workshops to share awareness about SPBEA than ideas on paper. However, these participatory workshops need to have an adequate time for the performance assessment. Due to the limited timeline of the project, the assessment will likely be carried out by local partners such as the collaborating local university.

Additionally, the findings indicate that offline training is more advantageous than online train-

FIGURE 12. Demonstration site development.

ing due to the availability of technical support and better opportunities for communication. Online training is a format that could be considered in the future. Still, it must be theoretically strengthened by restricting the optimal number of participants to ensure that the training runs successfully. We suggest that 40 people is optimal for the hybrid process, with a 3:1 ratio between online and offline participants. Additionally, future training should introduce a more stringent screening procedure to recruit highly motivated individuals who possess the necessary background knowledge. The attractiveness of the training should be increased by having internet fees covered and providing benefits to those who attend and providing immediate backup tutorials to those who experience network delays.

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Author contributions

The main contributors to this research article are Dewayany Sutrisno (conceptualization, method development, analysis, and original draft preparation) and Ati Rahadiati (analysis, data curation, and review). Other contributors include Mazlan Hashim, Peter Tian-yuan Shih, Rongjun Qin, Armaiki Yusmur, and Li Zhang (review and editing). All authors have read and agreed to the published version of the manuscript.

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Energy and water footprints comparison of East Asia: A heterogeneity analysis

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ABSTRACT

Population and economic growth have posed serious challenges to meet global energy and water needs. With the formation of global value chains and regional economic models changing the location and scale of environmental pressures, East Asia deserves special attention because of its importance in world trade. This paper constructed a global multi-regional input-output table based on the Global Trade Analysis Project (GTAP) 10 database and innovatively matched the energy and water databases to analyze the issues in 2014. The results show that in East Asia, (1) China is a net exporter and presents unique embodied energy characteristics with a trade deficit of 392Mtoe. Moreover, trade is the main reason for embodied energy and water in other countries. (2) The electricity sector, petroleum and coal products sector, and the services sector are the main sectors of embodied energy use, in which the latter accounts for 25.9% - 43.9% of the total embodied energy use in major countries. (3) Paddy rice sector and processed foods sector produce lots of embodied water for production and consumption, respectively. And the embodied water of processed foods accounts for more than 40% of major countries consumption.

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KEYWORDS

East Asia, Multiregional inputoutput analysis, Embodied energy, Water footprint

HIGHLIGHTS

- A database of energy and water use at the sectoral level was created for analysis.
- The national characteristics of embodied energy and water in East Asia were captured.
- The key sectors of embodied energy and water were identified.

1. INTRODUCTION

Water and energy are essential for economic activity and are closely linked to regional development (Fan, Feng, Dong, & Zhang, 2022). As the material basis for economic and social development, water and energy have been over-consumed in the last decades. Over the last two decades, the global annual per capita availability of freshwater has decreased by more than 20% (Food and Agriculture Organization of the United Nations [FAO], 2021), and the world's total annual energy consumption has increased by 187.04 EJ (The British Petroleum Company plc [BP], 2021). In addition, on the one hand, economic and social development and population growth have exacerbated the worldwide energy and water crisis, especially in countries with energy and water shortages (Liu & Chen, 2020; McPhearson et al., 2016). On the other hand, accelerated globalization has improved the trade ties among different countries and regions (Fan, Zhang, Wang, & Wang, 2019). The global supply and production chains have not only fundamentally changed the way of production, exchange and consumption of commodities but also changed the location and scale of the environmental and social impacts they cause (Acquaye et al., 2017; Wiedmann & Lenzen, 2018).

As one of the most economically active regions, East Asia plays an important role in global supply chains. Major countries in East Asia have long maintained 8-10% GDP growth rates over time and have realized industrialization, urbanization, electrification, and motorization in 20-30 years (White, Hubacek, Feng, Sun, & Meng, 2018). East Asia's total export as a share of total world exports grew from 17.8% in 2010 to 22.9% in 2020, and total import as a share of total world imports grew from 16.2% in 2010 to 19.2% in 2020 (Asian Development Bank [ADB], 2021). East Asian countries are still facing environmental and resource sustainability challenges with rapid economic development. All East Asian countries had less renewable inland freshwater resources per capita than the world average in 2017 (14017.8 m^3 and South Korea's renewable inland freshwater resources per capita are less than 1/10 of the world average (World Bank, 2021a). In addition, economic development has led to a rapid increase in energy consumption in East Asia. For example, Chinese total energy consumption had tripled from 42.45 EJ to 145.46 EJ between 2000 and 2020 (BP, 2021). Therefore, ensuring water and energy security is crucial to achieving sustainable development goals for a country or a region.

In recent years, many studies have focused on the impact of the production and consumption of economies on environmental resources. The existing studies vary in the environmental indicators, with most focusing on single embodied energy or embodied water. For example, Rodríguez, Camacho, Almeida, and Molina (2021) identified the key sectors of embodied energy in Brazil through the MRIO method and distinguished the domestic and foreign energy use of various industries. The results showed that more and more domestic industries relied on foreign energy imports. The emission reduction responsibilities related to the end energy consumption of various departments were borne by different countries with the supply chain distribution. A few studies research the combination of the two indicators. Based on an input-output model, Fan, Chen, and Zhang (2020) investigated the impact of residents' consumption activities on embodied energy and embodied water in China from a consumer perspective. The results showed that the electricity and agriculture industries were the key sectors with high energy and water consumption in 2012. Furthermore, large economies have been the focus of studies on embodied energy or embodied water, such as China (Zhang, Qiao, Chen, & Chen, 2016) and the EU (Camacho, Almeida, Rodriguez, & Molina, 2021), while the relevant studies of East Asian countries mainly focus on a single sector or single index and mainly discusses from the consumer side. Therefore, to explore the energy and water consumption caused by end consumption in East Asia from the sector level, this paper constructs a global multi-regional input-output table for 2014 based on the latest GTAP10 database and innovatively matches the sectoral water withdrawal database and energy use data for each country. On this basis, this paper analyzes the structural heterogeneity of sectoral water and energy consumption under each end-use category from the perspective of production and consumption in East Asia to provide a policy reference for addressing energy and water issues at the national and sectoral levels.

2. METHODOLOGY

2.1. EE-MRIO Model

The environmentally extended multi-regional input-output (EE-MRIO) model can analyze multiple environmental impacts driven by production or consumption and describe the input-output relationship between sectors and regions in a specific area or multiple sectors in different areas (Boulay, Hoekstra, & Vionnet, 2013; Meng et al., 2018; Zhao & Chen, 2014). For a multi-input-output table with m regions and n sectors, there is a value balance that can be expressed as a matrix on the equation relationship:

$$X = AX + Y \tag{1}$$

where X is the total output of all regions with $mn \times 1$ dimension, A is a complete matrix composed of the direct input coefficient matrix of each region with $mn \times mn$ dimension, Y represents the final demand matrix with $mn \times 1$ dimension, each element y^{rs} is a $n \times 1$ vector, which can be further divided into household consumption $y^{rs}_{household}$, government consumption $y^{rs}_{government}$, and investment $y^{rs}_{investment}$ in the framework of the GTAP10 database, representing the three types of final demand from region r to region s.

Equation (1) can be further rearranged as:

$$X = (I - A)^{-1}Y = LY \tag{2}$$

I is an identity matrix with $mn \times mn$ dimension, L is an inverse matrix of Leontief with $mn \times mn$ dimension.

2.2. Selection of relevant sectors

To measure the environmental impact at the sectoral level, specific sectoral scopes need to be further defined. Due to research needs, we aggregated the 65 sectors in GTAP10 into 45 sectors based on sector similarity. Briefly, we have made certain modifications to the original codes in the GTAP10 database, and the corresponding sector code and sector description are shown in Table 1. The research scope of this study is the independent 45 sectors in new sector numbers and codes.

2.3. Data source and processing

The available GTAP database is balanced and has enough information to construct a multiregional input-output table. Therefore, we have combined various data to form various sub-matrices of the multiregional input-output table for 2014 by referring to Peters, Andrew, and Lennox (2011). The process was as follows: first, we used the GTAPAgg2 program, which is used to aggregate GTAP sectors, to aggregate the original 65 GTAP sectors to the 45 sectors needed for the study; then, we extracted the relevant data with the help of the ViewHAR program (a GTAP database visualization software) and Excel; finally, we distributed and adjusted the import data and the domestic data for intermediate use and final

New No.	New code	GTAP No.	GTAP code	Sector description
19	OtherMing	13	frs	Forestry
		14	fsh	Fishing
		18	oxt	Minerals nec
25	TexWapp	27	tex	Textiles
		28	wap	Wearing apparel
30	OtherLightMnfc	43	mvh	Motor vehicles and parts
		44	otn	Transport equipment nec
		45	omf	Manufactures nec
36	OtherHeavyMnfc	34	bph	Basic pharmaceutical products
		36	nmm	Mineral products nec
		40	ele	Computer, electronic and optic
		41	eeq	Electrical equipment
		42	ome	Machinery and equipment nec
45	Other Service	50	trd	Trade
		55	whs	Warehousing and support activity
		56	cmn	Communication
		57	ofi	Financial services nec
		58	ins	Insurance
		59	rsa	Real estate activities
		60	obs	Business services nec
		61	ros	Recreational and other services
		62	osg	Public Administration
		63	edu	Education
		64	hht	Human health and social work
		65	dwe	Dwellings

TABLE 1. One-to-one correspondence of sector aggregation (only aggregated sectors are shown)

consumption, obtaining a multi-regional input-output table of 141x45. In addition, since bilateral trade data from region *r* to region *s* only provide information on export product sector *i* and not on consumption sector *j*, as described in Peters et al. (2011), we allocated bilateral exports (in the prices of the producing country) proportionally to the intermediate use sector and final consumption according to the import structure of the importing region (in prices of the consuming country), which ensures output balance while constructing the non-diagonal matrix Z^{rs} and y^{rs}.

$$Z_{ij}^{rs} = \frac{(Z^m)_i^s j}{vim_j^s} e_i^{rs} \tag{3}$$

$$y_{ij}^{rs} = \frac{(y^m)_i^s j}{vim_j^s} e_i^{rs} \tag{4}$$

Z_{ij}^{rs} represents the input from sector *i* in region *r* to sector *j* in region *s*, y_i^{rs} represents the final consumption of region *s* for the products of sector *i* in region *r*, vim_i^s represents total import of *i* into region s, e_i^{rs} represents export of *i* from region *r* to region *s*, $(Z^m)_{ij}^s$ represents the use of products in sector *i* by sector *j* in region *s*,$(y^m)_i^s$ represents the final consumption of products in sector *i* by region s.

The energy consumption of each sector in the 141 countries and regions is taken from the corresponding GTAP10 database account. Since the GTAP database does not contain sector-level freshwater withdrawals for 2014, we extrapolated global sector-level withdrawals through multiple calculation methods. Based on the definition of water use (National Bureau of Statistics [NBS], 2015), we divided water withdrawals into three categories (i.e., agricultural, industrial, and residential withdrawals). The freshwater withdrawals data and the proportions of the three types of withdrawals were obtained from the World Development Indicators (WDI) database (World Bank, 2021b) . The three types of freshwater withdrawals were assigned to 45 sectors. The proportions of water use in the agricultural subsector by country in 2014 were obtained based on freshwater withdrawals in the agricultural subsector from the 2011 GTAP water accounts. Assuming that the relative water withdrawal intensity between the industrial subsectors is constant for each country and does not significantly vary across the different regions, the ratios of industrial subsectors were used to allocate the total industrial amount into subsectors and obtained from Fan, Wang, Zhang, Kong, and Song (2019). The distribution of water withdrawal in the service sector is similar to the industrial sector, while ecological water withdrawal was not considered in this study. For the regions with missing data in total water withdrawal or industrial distribution, sectoral water intensity was replaced by the global average water intensity at the sectoral level.

3. RESULTS AND DISCUSSION

3.1. The overview of energy and water footprint of East Asian countries

The total global energy use embodied in the products of production (consumption) and exports (imports) in 2014 were 9,649 and 7,573 Mtoe, respectively. There is a significant difference between the embodied use of energy for production-based accounting (PBA) and consumption-based accounting (CBA) in East Asian countries (Figure 1). CBA embodied energy use is greater than PBA embodied energy use in Japan, Mongolia, and other East Asian countries or regions. And, PBA embodied energy use is only 51 Mtoe higher than CBA embodied energy use in South Korea. In contrast, China's PBA embodied energy use (2,687 Mtoe) is significantly higher than its CBA embodied energy use (2,295 Mtoe), suggesting that China has undertaken many embodied energy exports to meet the final demands in the rest of the world. At the same time, closely related to the large population, China's production-side and consumption-side embodied energy use both have a large global share, accounting for 28% and 24%, respectively. In addition, China's embodied energy of exports and imports account for only 13% and 26% of the total on the consumption and production sides, indicating that most of the energy supply is self-sufficient in China's domestic market, while the proportions of energy imports and exports in embodied energy use for the rest East Asian countries are all at a high level.

In terms of the different end-use categories, in East Asia, household consumption is dominant in the end-use of embodied energy for all countries except China. Specifically, the share of household consumption in Japan, South Korea, Mongolia, and other East Asian countries is above 60%, while the share of household consumption in China is 45%. In addition, energy use is driven by investment consumption and accounts for a relatively large proportion of the energy use structure of various countries, whereas the embodied energy use on the production side has similar results.

In 2014, the global total water use for production (consumption) and export (import) reached 398 billion m^3 and 332 billion m^3, respectively. The embodied water of CBA/imports is greater than PBA/exports for all countries except for other regions in East Asia where there is less embodied water, indicating that East Asia is a net importer of embodied water in global trade relations (Figure 2). China's PBA embodied water and CBA embodied water are large, accounting for over 10% of the world total, with 52,671 and 59,181 million $m^3$of water used on the production and consumption side. Japan and South Korea have a relatively small world share of PBA and CBA embodied water, with CBA embodied water higher than PBA embodied water. Similar to energy use, imports and exports are still the main reason for embodied water use on the consumption and production side in all countries except China, where exports and imports account for only 26% and 17% of the consumption and production side.

The embodied water driven by household consumption in East Asia accounts for a large proportion of all embodied water. The proportion of embodied water use of residents in five countries or regions is more than 60%. Among them, the embodied water use of residents in Japan and Mongolia accounts for more than 80%, and the total

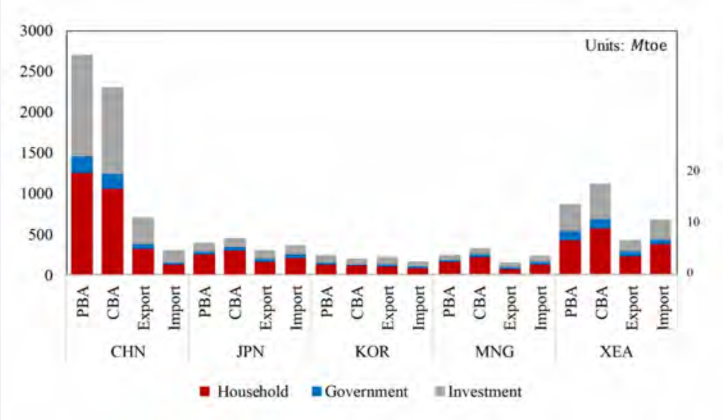

FIGURE 1. The embodied energy use by different final demands for East Asia countries in 2014. Notes: CHN, JPN, KOR, MNG, and XEA refer to China (Chinese Mainland), Japan, South Korea, Mongolia, and other countries or regions in East Asia (Korea, Democratic People's Republic of; Taiwan, China; Hong Kong, China; Macao, China), respectively. PBA is production-based accounting and CBA is consumption-based accounting. Because Mongolia and other East Asian countries have relatively small footprint values, a separate right-hand axis has been set up for them.

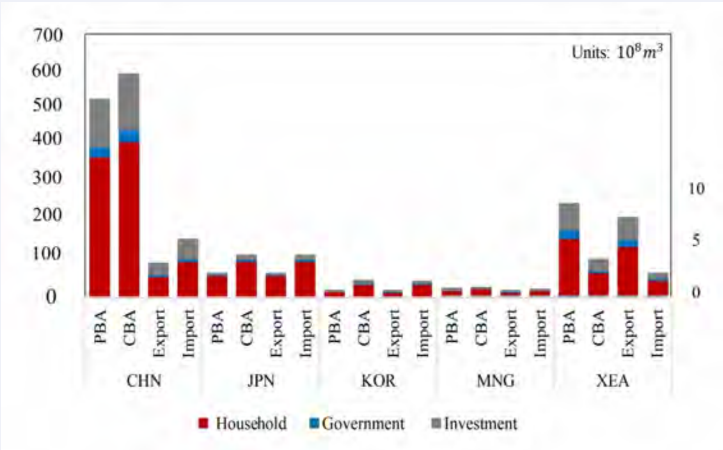

FIGURE 2. The embodied water use by different final demands for East Asia countries in 2014. Note: Please refer to the notes in Figure 1.

amount is $98.13 Gm^3$ and $0.52 Gm^3$, respectively. China has a relatively low water use share of 70% for household consumption, but due to its extremely large population, its total household water use is higher at $69.49\ Gm^3$.

3.2. The sector structure of embodied energy and embodied water in East Asia

There is significant heterogeneity in embodied energy use driven by household consumption among different sectors in both the production and consumption sides in East Asia (Figure 3). In terms of embodied energy use on the production side, industry sectors, like the electricity, petroleum and coal products sectors, are the main energy-using sectors in East Asian countries. In South Korea and Japan, PBA energy use in both sectors are over 90%, while PBA energy use in the electricity sector of Mongolia accounts for 88% of the total production-side embodied energy use. In terms of CBA embodied energy use on the consumption side. At the same time, industry sectors, dominated by the petroleum and coal products sectors are still the main sectors consuming energy in each country in East Asia. The services sectors have increased significantly in terms of their share in end-use energy, becoming the most energy-intensive sectors in East Asian countries in addition to the industry sectors. The share of embodied energy use in the service sectors of the total in South Korea, Japan, and Mongolia is

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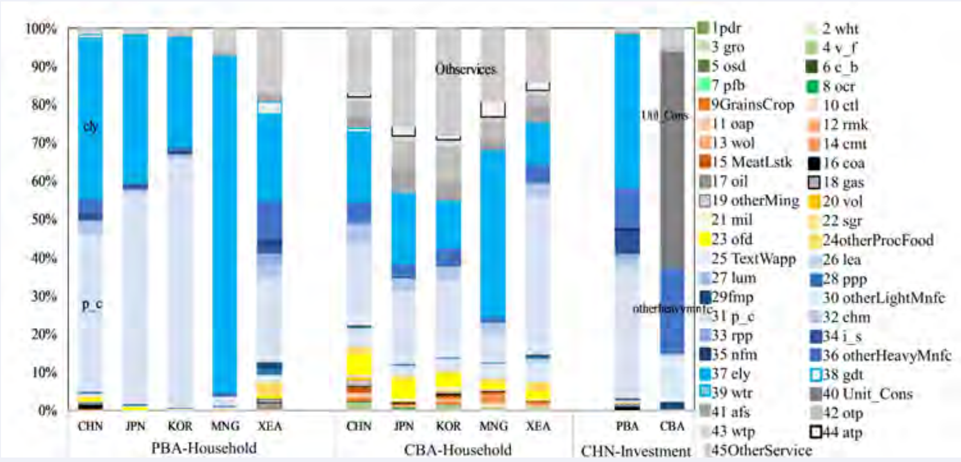

FIGURE 3. The sector structure of embodied energy used by household consumption for East Asia in 2014. Notes: Green represents agriculture sectors (1-8), orange (9-15) and yellow (20-24) represent processed foods sectors, blue-white represents industry sectors (25-39), grey represents service sectors (40-45), and black and its patterns represent coal, petroleum, natural gas, and other mineral sectors (16-19). The sector corresponding to the code is shown in the appendix.

44%, 41%, and 28%, respectively.

Since embodied energy use driven by investment consumption in China is another important energy use component, it was further analyzed. The results show that the findings of the PBA and CBA embodied energy use driven by household consumption in China are similar to those of other East Asian countries, with the electricity sector and the petroleum and coal products sector accounting for 83% of the total in the PBA perspective, and the services sectors accounting for 26 % in the CBA perspective. An analysis of investment consumption shows that the electricity sector and the petroleum and coal products sector are the main end-use sectors in the PBA perspective, with a combined share of 74% of the total. However, in the CBA perspective, the construction sector and heavy manufacturing sector are the main energy-use sectors, with a share of 56% and 23%, respectively, indicating that these sectors not only attract a large amount of fixed capital inflows but also drive a large amount of energy use.

Figure 4 illustrates the sectoral structure of embodied water use driven by household consumption in East Asian countries. The agriculture and processed foods sectors are the most important water-use sectors on the production and consumption side. The sectoral distribution of embodied water use in East Asia from the CBA perspective shows diversity and complexity compared to those from the PBA perspective. On the production side, the agricultural sectors, especially the paddy rice sector, are the key water-use sector in the major East Asian countries, except for the rest of East Asia, which is associated with high irrigation water demand for cultivation. For example, the agricultural sector embodied water accounts for 89.4% of Japan's total water. In comparison, the paddy rice sector alone accounts for 84.1% of the total water footprint. The share of agricultural sectors' water use in South Korea and China is 89% and 83%, respectively, with the paddy rice sector embodied water accounting for 78% and 35% of the total, respectively. Mongolia's share of embodied water in agriculture sectors is 65%, and unlike the other countries, the vegetable, fruit and nut sector accounts for the largest share of embodied water at 63%. Moreover, there is significant heterogeneity in the sectoral distribution of embodied water use between the consumption and production sides. Specifically, processed foods, industry, and services sectors are key water-use sectors in most countries. The share of embodied water in processed food sectors is over 40% in China, Japan, and South Korea, and the proportion of the processed foods sectors' embodied water accounts for nearly 60%

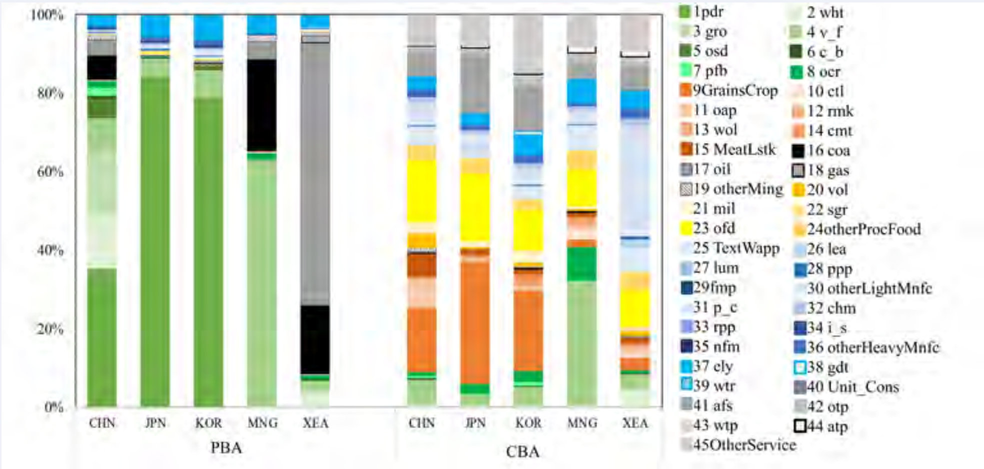

FIGURE 4. The sector structure of embodied water used by household consumption for East Asia in 2014. Note: Please refer to the notes in Figure 3.

of the total in China and Japan. The processed rice sector in the processed foods sector is also the main contributor to the total amount of embodied water, accounting for 31% and 21% of total embodied water in Japan and South Korea. The share of embodied water in the industry sectors and service sectors ranges from 10% to 20% in China, Japan and South Korea. Related to its dietary preferences, the sectoral structure of Mongolia's embodied water differs significantly from that of China, Japan, and South Korea, mainly in its higher water use of primary agricultural products on the consumption side.

4. CONCLUSION

Based on the constructed 2014 Environmentally Expanded Global Multi-Regional Input-Output Table, we quantitatively assessed and analyzed the heterogeneity of energy consumption and water withdrawals driven by different categories of end-use in the major countries of the East Asian region, with the following main findings:

East Asia is one of the major regions of embodied energy use in the world, with the total embodied energy of production and consumption side of China, Japan, and South Korea accounting for 33% of the total (99.50% and 99.25% of the total energy use in East Asia respectively). China has the largest energy use on the production and consumption side, which is related to its large population. China and South Korea are net exporters of embodied energy; Japan, Mongolia, and the rest of East Asia are net importers. Moreover, imports and exports are the main sources for embodied energy use in the rest of East Asia except China. In contrast, China's energy use embodied in the trade accounts for a relatively low proportion of the total on the consumption side (13%) and production side (26%). Except for China, where the share of embodied energy driven by household and investment consumption is large, household consumption is the most important final demand for embodied energy in other East Asian countries. The industry sectors are the main household consumption of energy in East Asian countries, dominated by the electricity sector and petroleum and coal products sector, with Mongolia accounting for 88% of its energy use in the electricity sector alone. The proportion of embodied energy use in the service sectors on the consumption side increases, but the industry sectors are still the main sectors causing energy use on the consumption side in all countries. In addition, from the perspective of energy use driven by investment consumption in China, the electricity sector and petroleum and coal products sector require a large amount of energy input on the production side, while the construction sector and other heavy manufacturing pull in a large amount downstream energy use.

Water use in East Asia is still dominated by China, Japan, and South Korea, with the total production and consumption side water consumption of these three countries reaching 98.6% and 99.5% of the total in East Asia, respectively. China is the leading consumer of water in East Asia, with a total of 53 and 59 billion cubic meters of water used on the production and the consumption side, respectively. China, Japan, South Korea, and Mongolia are all net importers of embodied water. Except for China and the rest of East Asia, imports and exports are the main reason for embodied water use on the consumption and production side in all other countries. China's imports and exports are only 26% and 17% of the consumption and production side, respectively, indicating that China uses more water in its domestic production and consumption processes than other East Asian regions. Household consumption is still the most important final use for embodied water in all countries. The agricultural sectors are the dominant sectors of embodied water use by residents in this region. The paddy rice sector is the sector that uses the most water in China, Japan, and South Korea due to irrigation needs. On the consumption side, the main sectors of water use by residents in the region are more complex than the production side, with the processed foods sector being the main sector of water use in China, Japan and South Korea. Embodied water use is significantly higher in the industry and service sectors than in the production side. On the other hand, Mongolia consumes the largest amount of embodied water for primary agricultural products (41%), followed by processed foods sectors, industry sectors and services sectors.

Based on the above findings, the following policy insights have been gained. Firstly, household consumption has become an important part of end-use consumption within East Asian countries. Sustainable consumption contributes to the achievement of several national-level Sustainable Development Goals (SDGs) (SDG 6 Clean water and sanitation, SDG 7 Ensure access to affordable, reliable, sustainable and modern energy for all, SDG 12 Responsible consumption and production, SDG 14 Life below water). However, as technology accelerates and incomes increase, people are more inclined to buy energy-intensive products (Tian, Wu, Geng, Bleischwitz, & Chen, 2017) and product waste, especially food products, is high (Vanham, Bouraoui, Leip, Grizzetti, & Bidoglio, 2015), which leads to an increased energy and water footprint. Therefore, there is a need to promote sustainable consumption in the East Asian region by raising public awareness of energy and water conservation through the use of various means of advocacy such as advertising in the media, publishing environmental pamphlets, and holding lectures on environmental topics. Secondly, sustainable resource management is essential for the development of the East Asian region. To begin with, there is a need to establish a dynamically updated international resource database at the sectoral level, distinguishing national use from international use, to monitor resource use embedded in domestic consumption and trade. Next, as East Asia's key energy and water consuming sectors are similar, technical cooperation and technology sharing can be enhanced to jointly promote sustainable development goals. Thirdly, economic instruments such as resource use taxes can be used to improve resource use efficiency, reduce resource use in net importing countries such as Japan and South Korea, and assist in technology development and environmental management in net exporting countries (e.g. China's energy use).

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A. APPENDIX

Supplementary table: One-to-one correspondence of sector.

	No.	Sector code	Sector description
Agriculture	1	pdr	Paddy rice
	2	wht	Wheat
	3	gro	Cereal grains nec
	4	v_f	Vegetables, fruit, nuts
	5	osd	Oilseeds
	6	c_b	Sugar cane, sugar beet
	7	pfb	Plant-based fibres
	8	ocr	Crops nec
Processed Foods	9	GrainsCrops	Processed rice
	10	ctl	Bovine cattle, sheep and goats
	11	oap	Animal products nec
	12	rmk	Raw milk
	13	wol	Wool, silk-worm cocoons
	14	cmt	Bovine meat products
	15	MeatLstk	Meat products nec
Minerals and others	16	coa	Coal
	17	oil	Oil
	18	gas	Gas
	19	OtherMining	Other industries
Processed Foods	20	vol	Vegetable oils and fats
	21	mil	Dairy products
	22	sgr	Sugar
	23	ofd	Food product nec
	24	otherProcFood	Beverages and tobacco products
Industry	25	TexWapp	Textiles and clothes
	26	lea	Leather products
	27	lum	Wood products
	28	ppp	Paper products, publishing
	29	fmp	Metal products
	30	LightMnfc	Light Manufacturing
	31	p_c	Petroleum, coal products
	32	chm	Chemical products
	33	rpp	Rubber and plastic products
	34	i_s	Ferrous metals
	35	nfm	Metals nec
	36	otherHeavyMnfc	Other Heavy Manufacturing
	37	ely	Electricity
	38	gdt	Gas manufacture, distribution
	39	wtr	Water
Service	40	Util_Cons	Construction
	41	afs	Accommodation, Food and service
	42	otp	Transport nec
	43	wtp	Water transport
	44	atp	Air transport
	45	OtherService	OtherService

TABLE 2. One-to-one correspondence of sector.

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Impact of biomass burning sources during the high season on $PM_{2.5}$ pollution observed at sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand

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ABSTRACT

This study aimed to assess $PM_{2.5}$ concentration and the potential impacts of biomass burning sources on $PM_{2.5}$ measured at the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand during the high season (from January to April) in 2021 in which intensive biomass burning activities occur in Southeast Asia (SEA) region. For this purpose, an integrated approach of $PM_{2.5}$ in-situ measurement, receptor and trajectory modelling techniques and satellite remote sensing was employed. Results showed that the average value of $PM_{2.5}$ daily concentrations measured at the sampling site in Hanoi was higher than that at the sampling site in Chiang Rai during January–February (winter) periods. In contrast, the average value of $PM_{2.5}$ daily concentrations measured at the sampling site in Hanoi was slightly lower than the counterpart at the sampling site in Chiang Rai during March–April (spring) periods. Elevated concentrations of $PM_{2.5}$ measured in Chiang Rai during March–April periods were largely associated with intensive biomass burning activities in the SEA region. Positive Matrix Factorisation (PMF) receptor model-based source apportionment results indicated a larger contribution of biomass burning sources to the $PM_{2.5}$ measured at the sampling site in Chiang Rai compared to that at the sampling site in Hanoi. Analysis of MODIS cumulative fire radiative power maps in the SEA region and three-day air masses backward trajectories arrived at the sampling sites in Hanoi and Chiang Rai further suggested the potential impacts of biomass burning sources on the $PM_{2.5}$ measured at the sampling sites in Hanoi during the winter periods and in Chiang Rai during the spring periods.

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KEYWORDS

PM2.5 pollution, PMF receptor model, MODIS fire map, biomass burning sources, Southeast Asia

HIGHLIGHTS

- A contrasting pattern of $PM_{2.5}$ concentrations was measured in Hanoi and Chiang Rai for the winter and spring periods
- The contribution of biomass burning sources to the measured $PM_{2.5}$ in Chiang Rai was larger than that in Hanoi
- Potential impacts of both local and regional biomass burning sources on the measured $PM_{2.5}$ in Hanoi and Chiang Rai during the high season were found

1. INTRODUCTION

Southeast Asia (SEA) has been reported as one of the world's largest biomass burning source regions. The regional haze known as 'Asian Brown Cloud' resulting from biomass burning sources occurs almost every year in SEA, which strongly impacts human health, the environment, and global climate variations (Chen et al., 2017). In most SEA countries where the economic development is based largely on the agricultural sector, actions to slow the adverse impact of poor air quality caused by biomass burning are stalling in the face of intense economic imperatives and the pace of development.

To date, several studies have been conducted to assess the impacts of biomass burning sources on air quality in SEA countries. For example, See, Balasubramanian, Rianawati, Karthikeyan, and Streets (2007) reported that biomass burning sources, particularly those within peat soil areas in Sumatra and Kalimantan, Indonesia, contributed to the high emissions of fine particles and gases into the atmosphere. Engling, He, Betha, and Balasubramanian (2014) measured total suspended particles (TSP) in Singapore during a haze episode and showed that large-scale forest and peat fires in Sumatra and Kalimantan were the sources of smoke aerosol in downwind areas in Singapore. Pengchai et al. (2009) reported that vegetative burning was one of the major contributors to PM_{10} concentration in Thailand's Chiang Mai-Lamphun basin. In the study carried out by Quah (2002), biomass burning sources in Indonesia were found to influence the air quality in neighbouring countries such as Singapore, Malaysia, Brunei and Thailand. In the upper part of SEA (Myanmar, Thailand and Laos), forest fires and the burning of agricultural residues in the transition period from the winter to dry season were reported as the causes of haze and PM_{10} pollution in Chiangmai, Thailand (Kim Oanh & Leelasakultum, 2011). Sillapapiromsuk, Chantara, Tengjaroenkul, Prasitwattanaseree, and Prapamontol (2013) estimated the emission of PM_{10} over Chiang Mai and found that the highest PM_{10} emission in 2010 was due to the burning of forest, while that in 2011 was from the burning of agricultural residue. More recently, Punsompong and Chantara (2018) used the potential source contribution function to identify potential sources of PM_{10} pollution from biomass burning in northern Thailand. They reported that most high-potential sources and emissions were transboundary from Myanmar (73.2%) and within Thailand (26.8%). Hansen et al. (2019) showed that five regions were identified as the dominating sources of PM10 pollution during haze seasons in Singapore, including Riau, Peninsular Malaysia, South Sumatra, and Central and West Kalimantan. Vongruang and Pimonsree (2020) used the WRF-CMAQ modelling system to investigate the contributions of biomass burning sources to PM_{10} concentrations over countries in mainland SEA. Their results showed that biomass burning contributed to 73%, 69%, 59%, 45%, 33%, and 31% of PM_{10} concentration in Laos, Myanmar, Cambodia, Thailand, China, and Vietnam, respectively.

Despite several studies that have been carried out for assessing the impacts of biomass burning sources on coarse particles (mainly TSP and/or PM_{10}) in SEA countries, there have been limited studies concerning the impacts of biomass burning sources on the fine particle ($PM_{2.5}$) pollution in the SEA region. In order to contribute to the evidence on the impact of biomass burning sources on $PM_{2.5}$ pollution in SEA, this study aimed to assess the $PM_{2.5}$ concentration and the potential impacts of biomass burning sources on the $PM_{2.5}$ measured at the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand during the high season (from January to April) in 2021 with intensive biomass burning periods.

2. METHODOLOGY

2.1. Study areas and sampling sites

Hanoi is the capital and the second-largest city of Vietnam, with a total area of about 3,328 km^2 and a population of about 8.1 million people. Hanoi features a subtropical climate that is influenced by the northeast monsoon in winter and the southeast monsoon in summer with four distinct seasons including spring (from March to May), summer (from June to August), fall (from September to November) and winter (from December to February). During the last decade, there has been rapid economic development, urbanization, urban population growth and motorization in Hanoi. The city is characterized by a large number of private vehicles (mainly motorcycles and cars). Traffic emission has been considered one of the most important sources of air pollution in Hanoi (Nguyen & Nowarat, 2011). This study considers the sampling site (Lat 21.003N, Lon 105.842E) in Hanoi located on the roof of a two-storey building in the Hanoi University of Civil Engineering, Hai Ba Trung District, Hanoi (Figure 1). The sampling site could be considered mixed site influenced by diverse emission sources such as traffic, domestic, construction, and industrial activities (Luong et al., 2021).

Chiang Rai is the northernmost province of Thailand that shares borders with Laos and Myanmar. The atmospheric circulation of Thailand is characterized by the monsoon system. Cool, dry continental air masses prevail during the northeast monsoon season (October–February) that could transport air pollutants from distant areas. Whereas, the maritime and clean air masses mainly dominate during the southwest monsoon season (May–September). The biomass burning season in northern Thailand generally occurs during the dry months (February–April). Biomass (i.e. agricultural waste, sugarcane, rice straw and other crops) is usually burnt before the harvest season to quickly clear the land and prepare the fields for the next crop cycle (Kayee et al., 2020). In this study, the sampling site (Lat 19.943N, Lon 99.846E) in Chiang Rai was located about 2.5 m above ground at the Office of Hydrology, Muang District, Chiang Rai (Figure 1).

2.2. $PM_{2.5}$ sampling and chemical analysis

24-h integrated $PM_{2.5}$ measurement campaigns were conducted concurrently at both sampling sites in Hanoi and Chiang Rai from January to April 2021. $PM_{2.5}$ samples were collected on quartz-fibre filters (Whatman, QM-H pure quartz, size 47 mm, USA) using low-volume air samplers that operated at a flow rate of 16.7 L/min. The quartz-fibre filters were weighed twice before and after sampling. Before weighing, the filters were equilibrated for 24 hours in a desiccator at a temperature of 25°C ± 5°C and a relative humidity of 50% ± 5 %. Before sampling, the quartz-fibre filters were preheated in an electric furnace at 900°C for 3 hours to remove possible carbonaceous contaminants. After sampling, these samples were sealed in an aluminium foil and kept in a clean plastic bag. They were transported to the laboratory and stored with silica gel particles in a desiccator. The collected quartz-fibre samples were stored in a refrigerator at about 4°C to prevent the evaporation of volatile components before chemical analysis. The collected samples were then determined gravimetrically for the $PM_{2.5}$ total mass. Field blanks were collected using the same procedures applied for the $PM_{2.5}$ samples but without running the sampling system.

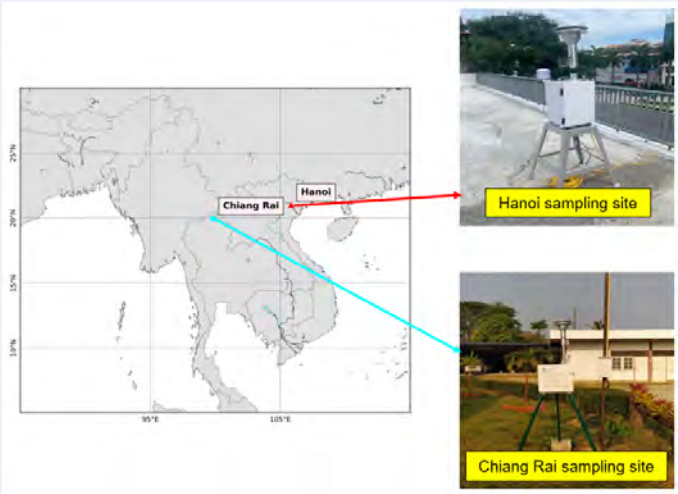

FIGURE 1. Study areas and PM2.5 sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand.

Concentrations of water-soluble inorganic ions (NH_4^+, Na^+, Mg^{2+}, K^+, Ca^{2+}, NO_3^-, SO_4^{2-}, F^-, and Cl^-) in $PM_{2.5}$ were analyzed by ion chromatography (IC). A quarter of the filter was put in an Erlenmeyer flask with 10 ml of ultrapure water (Millipore Direct Q, resistivity 18.2 MΩ) and treated in an ultrasonic bath for 30 min. For analysis of anions and cations, the extract was filtrated through 0.45 μm nylon syringe filters and injected into IC Dionex 600. The AS4A-SC (4 mm x 250 mm) column was used to determine anions, with an eluent mixture of 1.7 mM $NaHCO_3$ and 1.8 mM Na_2CO_3 was used, and its flow rate was 2 ml/min during the analysis. The CS12A (2 mm x 250 mm) column was used to determine cations with an eluent of 22 mM H_2SO_4 solution, and its flow rate was 0.25 ml/min during the analysis. For analysis of both anions and cations, the IC injection volume was 25 μl, the run time was 30 min, and the column temperature was 35°C. The method detection limits (MDLs) for Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+} were 0.01, 0.02, 0.03, 0.05, 0.05, 0.06, 0.03, and 0.08 $\mu g/m^3$, respectively. Field blanks were routinely analyzed and the results were subtracted from the sample values.

Meanwhile, a quarter of the sample filter was treated to analyse trace elements by the digestion method according to EPA method IO-3.1. The piece of filter sample was digested in 5 ml of mixed acid solution (HNO_3: HCl with a ratio of 1:3) and kept on a hot plate at high temperature until a transparent solution was boiled. After complete digestion, the digested sample was heated at low temperature until nearly dry to remove excess acid. Then, a solution was diluted in a 25 ml volumetric flask with distilled water. Samples were analyzed using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS, ELAN 900, Perkin Elmer, USA) for 18 elements, including aluminium (Al), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), Coban (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), strontium (Sr), molybdenum (Mo), cadmium (Cd), antimony (Sb), barium (Ba), and lead (Pb). A blank sample, a duplicated sample, and a spiked sample were measured for quality control in the analysis. The relative standard deviation of each element was within 10% and the analytical errors were <10%. The detection limit for all trace elements was 0.01 ng/m^3, except for Cd (0.002 ng/m^3).

Aerosol carbonaceous contents (OC and EC) in $PM_{2.5}$ were analyzed using the Organic Carbon - Elemental Carbon (OC-EC) Analyzer (Model 5L, Sunset Laboratory Inc., USA). The NIOSH 870 thermal optical transmittance protocol was used in this study to determine OC and EC content in $PM_{2.5}$ collected on the quartz-fibre filters. An area of 1.5 cm^2 was punched from each $PM_{2.5}$ filter sample and placed in the quartz oven for analysis. The quartz filter paper was heated in the oven according to the different temperatures of 310°C, 475°C, 615°C, and 870°C in an oxygen-free environment of pure helium to produce four OC fractions (OC1, OC2, OC3 and OC4). Then, the temperature of the sample oven was reduced to around 550°C, and EC was analyzed by subsequent heating at 550°C (EC1), 625°C (EC2), 700°C (EC3), 775°C (EC4), 850°C (EC5), and 870°C (EC6) in an environment of 98% He and 2% O_2. Carbon vapour in the heating processes was oxidized to CO_2 in the oxidizing oven. The CO_2 was quantitatively reduced to CH_4 in nickel catalyst and then quantitatively measured with a flame ionization detector (FID). The instrument's detection limit was 0.2 μg C/cm^2 and the analytical uncertainty was equal to $\pm$ (OC/EC concentration $\times$ 0.05) + instrument blank concentration.

Analysis results of $PM_{2.5}$ chemical composition (ions, trace elements, and carbonaceous species) were used as the input for the receptor model as described below.

2.3. Receptor modelling for source apportionment analysis

Source apportionment (including the contribution of biomass burning sources to the measured $PM_{2.5}$) was conducted using the USEPA Positive Matrix Factorisation (PMF) receptor model. The PMF receptor model aims to reconstruct the contribution of emissions from different sources to the measured $PM_{2.5}$ based on the $PM_{2.5}$ chemical composition data obtained at the sampling sites. PMF is a multivariate factor analysis tool that decomposes a matrix of $PM_{2.5}$ speciated sample data into two matrices: factor contributions and factor profiles. These factor profiles need to be interpreted by the user to identify the source types that may be contributing to the $PM_{2.5}$ sample using measured source profile information and emissions or discharge inventories (US EPA, 2014). PMF introduces a weighting scheme taking into account errors of data points that are used as point-by-point weights. The adjustment of corresponding error estimates allows it to handle missing and below detection limit data. Moreover, non-negative constraints are implemented to obtain more physically meaningful factors. This study employs the PMF v.5.0.

2.4. MODIS fire radiative power data

This study uses the cumulative fire radiative power (FRP) data product derived from the collection 6 MODIS active fire detection algorithm (Giglio, Schroeder, & Justice, 2016) for exploring biomass burning activities occurring in the SEA region during the study periods and their possible impacts on the measured $PM_{2.5}$ at the sampling sites in Hanoi and Chiang Rai. The cumulative FRP data was obtained from the Fire Information for Resource Management System website (https://firms.modaps.eosdis.nasa.gov), which was provided by both MODIS Aqua and Terra. This study used the FRP averaged from MODIS Terra and Aqua data with a high-confidence level.

2.5. Air mass backward trajectories

This study analyses the three-day isentropic backward trajectories of air masses to identify the most likely biomass burning source regions influencing the measured $PM_{2.5}$ at the sampling sites in Hanoi and Chiang Rai. Three days were expected to be enough time for most trajectories to pass through the possible source regions in SEA. Backward trajectories were generated using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model (Rolph, 2003; Draxler & Rolph, 2003) that was accessed and run through the NOAA website (https://www.ready.noaa.gov/HYSPLIT.php). Calculations were made interactively using the National Centers for Environmental Prediction's Global Data Assimilation System data set. Trajectories were computed every hour with a starting height of 1,500 m above the ground level.

3. RESULTS AND DISCUSSION

3.1. $PM_{2.5}$ mass concentration in Hanoi, Vietnam and Chiang Rai, Thailand

Figure 2 shows the daily mean concentration of the measured $PM_{2.5}$ during the January–February periods at the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand. The daily mean $PM_{2.5}$ concentrations (65.41–129.29 μg/m^3) measured at the sampling site in Hanoi exceeded the 24h-average national ambient air quality standard for Vietnam (50 μg/m^3) for all sampling dates. The increased concentration levels of $PM_{2.5}$ at the sampling site in Hanoi could be due to the impact of the stagnant condition caused by the low mixing height during the winter period that could largely enhance the accumulation of air pollutants near the surface. In addition, the highly elevated concentration of $PM_{2.5}$ at the sampling site in Hanoi could also be influenced by the long-range transported air pollutants from regional sources during the winter period. For the measurement conducted at the sampling site in Chiang Rai, the daily mean $PM_{2.5}$ concentrations (range 27.11–53.68 μg/m^3) exceeded the 24h-average national ambient air quality standard for Thailand (50 μg/m^3) for several sampling dates. The average value of $PM_{2.5}$ daily concentrations for the whole measurement period in January–February at the sampling site in Chiang Rai was 39.93 μg/m^3, which was about 2.39 times lower than the counterpart estimated for the sampling site in Hanoi.

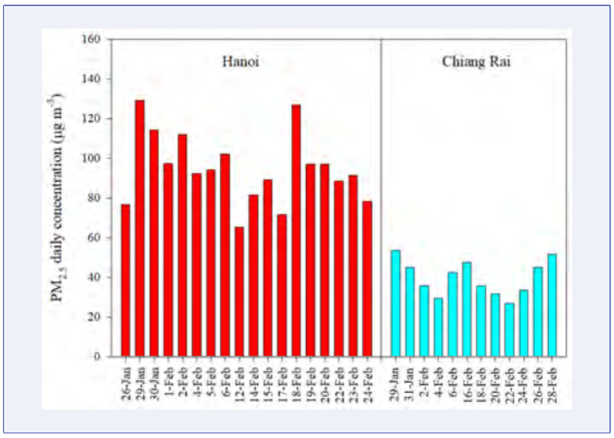

FIGURE 2. Daily mean PM2.5 mass concentration measured during January-February periods at sampling sites in Hanoi and Chiang Rai.

Figure 3 displays the daily mean concentration of PM2.5 measured during the March–April periods at the sampling sites in Hanoi and Chiang Rai. The daily mean PM2.5 concentrations (21.34–113.13 μg/m^3) measured at the sampling site in Hanoi were higher than the 24h-average national ambient air quality standard PM2.5 in several sampling dates. However, the average value of 45.96 μg/m^3 for the whole measurement period was still lower than the national standard value for PM2.5. The daily mean PM2.5 concentrations (23.75–111.61 μg/m^3) at the sampling site in Chiang Rai also exceeded the 24h-average national ambient air quality standard for PM2.5 in several sampling dates. Interestingly, the average value of 47.39 μg/m^3 for the whole measurement period at the sampling site in Chiang Rai was slightly higher than the counterpart in Hanoi, which is different from those observed for the January–February measurement periods. This suggested that the PM2.5 measurement at the sampling site in Chiang Rai during the spring period could be largely influenced by local and/or regional biomass burning sources that will be discussed later in the article.

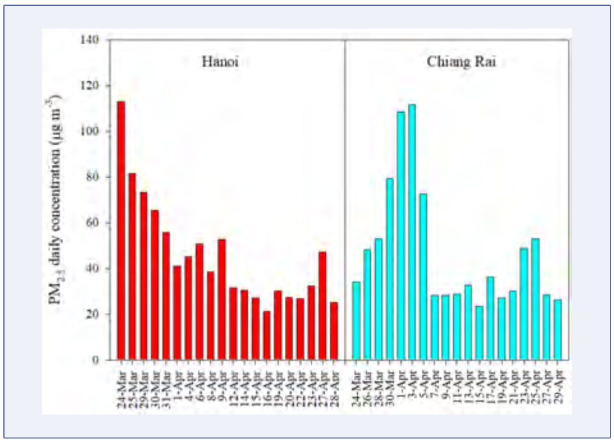

FIGURE 3. Daily mean PM2.5 mass concentration measured during March-April periods at sampling sites in Hanoi and Chiang Rai.

3.2. Source apportionment for $PM_{2.5}$ measured in Hanoi and Chiang Rai

Figures 4 and 5, respectively, show the PMF receptor model-based $PM_{2.5}$ source apportionment results for the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand for the high season in 2021. At the sampling site in Hanoi (Figure 4), secondary aerosols and long-range transport were the largest source contributing to the measured $PM_{2.5}$. This result is consistent with the previous study in Hanoi carried out by Hien et al. (2021). The second-largest source was coal combustion and followed by biomass burning. The contribution of biomass burning to the measured $PM_{2.5}$ for the high season (10.6%) was remarkable.

At the sampling site in Chiang Rai (Figure 5), the related biomass combustion and garbage burning were reported as the largest sources contributing to the measured $PM_{2.5}$, followed by fine soil and secondary aerosols. This result confirmed the significant impact of biomass burning sources on the measured $PM_{2.5}$ at the sampling site in Chiang Rai during the high season.

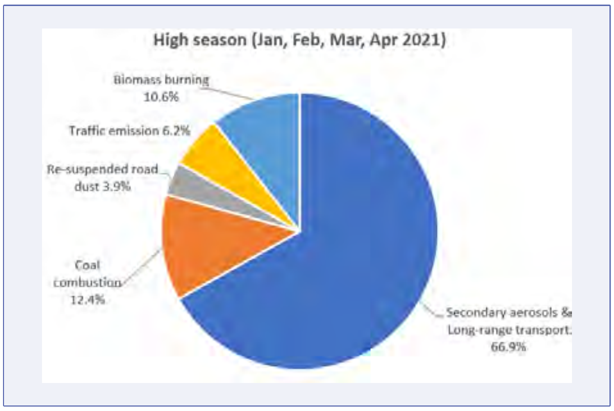

FIGURE 4. PMF receptor model-based source apportionment for $PM_{2.5}$ measured at sampling site in Hanoi.

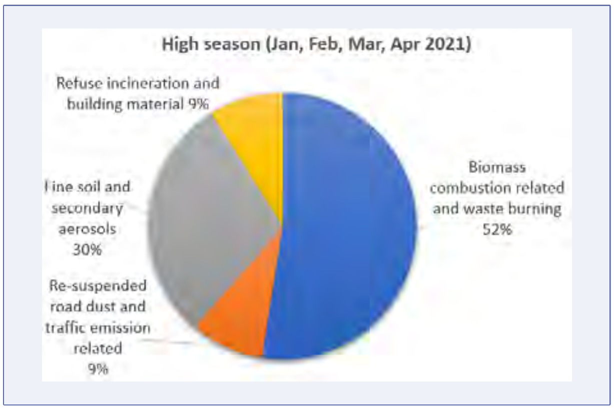

FIGURE 5. PMF receptor model-based source apportionment for $PM_{2.5}$ measured at sampling site in Chiang Rai.

3.3. Impacts of biomass burning sources on the measured PM2.5 at sampling sites in Hanoi and Chiang Rai

The integrated maps of cumulative FRP derived from the collection 6 MODIS active fire product and three-day air masses backward trajectories generated using the HYSPLIT model were constructed to further investigate the impacts of biomass burning sources on the measured $PM_{2.5}$ at the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand. Figures 6, 7, 8 and 9 show the regional maps of MODIS cumulative FRP and three-day air masses backward trajectories that arrived at the sampling sites in Hanoi and Chiang Rai during different measurement periods. Fire activities occurring in the SEA region and the southern part of China during the measurement periods in January, February, March and April of 2021 were numerous.

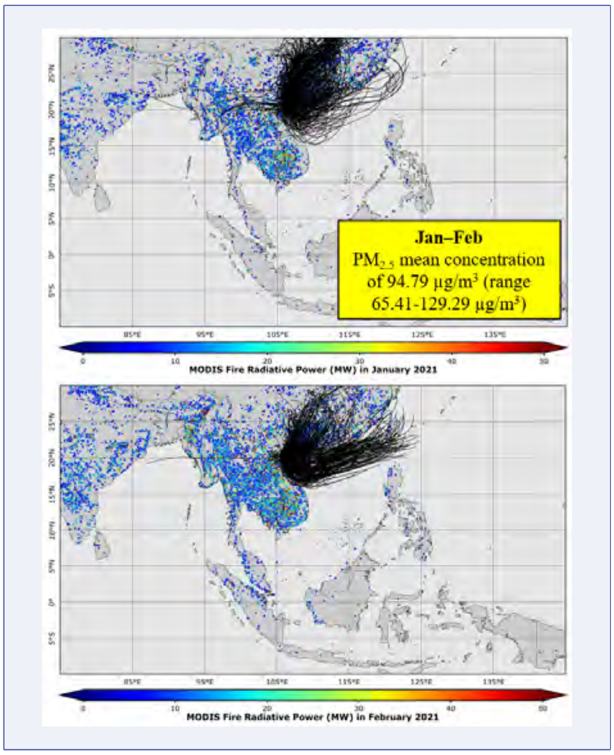

FIGURE 6. Maps of MODIS cumulative FRP in SEA during Jan-Feb 2021 and three-day air mass backward trajectories arrived at the sampling site in Hanoi.

Air masses that arrived at the sampling site in Hanoi during the measurement periods in January and February were observed mainly from the north and northeast directions and passed over the dense fire regions in the southern part of China (Figure 6). Regionally transported air masses could bring many air pollutants from these fire regions to the sampling site in Hanoi and contribute to the highly increased concentrations of $PM_{2.5}$ in the winter period. The mean concentration of $PM_{2.5}$ measured at the sampling site in Hanoi for the winter period was 94.79 $\mu g/m^3$ (range 65.41-129.29 $\mu g/m^3$). Meanwhile, during the measurement periods in March and April, air masses mainly originated from the East Sea before arriving at the sampling site in Hanoi (Figure 7). The predominant occurrence of maritime air masses could be the reason for the lower concentrations of $PM_{2.5}$ (mean 45.96 $\mu g/m^3$, range 21.34-113.13 $\mu g/m^3$) in the spring period compared to those observed for the winter period at the sampling site in Hanoi. However, there were several days (i.e. 24, 25, 29, 30 March and 6, 9 April) in which air masses travelled over the dense fire regions in the central and northern parts of Vietnam as well as in the neighbouring SEA countries such as Laos and Thailand before arriving at the sampling site. Since air masses pass over both local and regional biomass burning sources, they might also contribute to the increased concentration of $PM_{2.5}$ measured at the sampling site in Hanoi on those days (Figure 3).

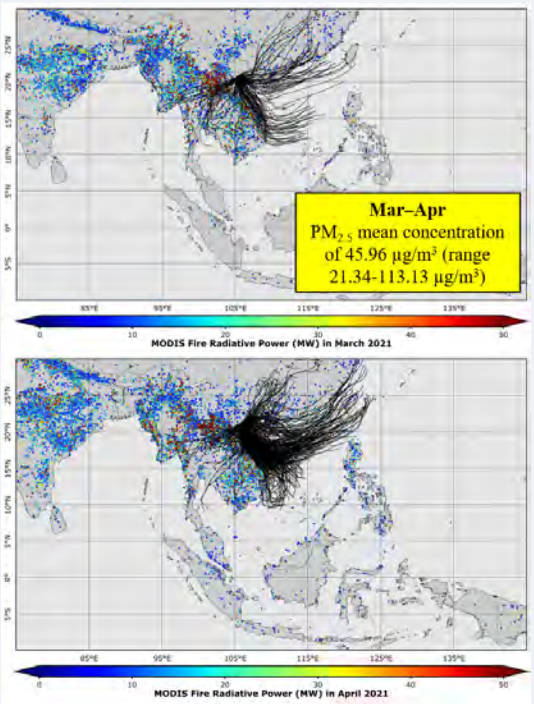

FIGURE 7. Maps of MODIS cumulative FRP in SEA during Mar-Apr 2021 and three-day air mass backward trajectories arrived at the sampling site in Hanoi.

During the measurement periods in January, February, March and April in Chiang Rai, air masses arrived at the sampling site were from the west and northwest directions and mainly originated from the Andaman Sea and the Bay of Bengal, which were then passed over the dense fire regions in the southern part of Myanmar and the northwestern part of Thailand (Figures 8 and 9). The influence of air masses, especially the slow-moving air masses in March and April (Figure 9), which travelled over both locally and regionally intensive biomass burning source regions, was recognized as the main reason for the high concentrations of the measured $PM_{2.5}$ (mean 47.39 $\mu g/m^3$, range 23.75-111.61 $\mu g/m^3$) during these periods at the sampling site in Chiang Rai. In comparison, the mean concentration of $PM_{2.5}$ measured for the period Jan–Feb was 39.93 $\mu g/m^3$ (range 27.11-53.68 $\mu g/m^3$), which is lower than that for the period March–April.

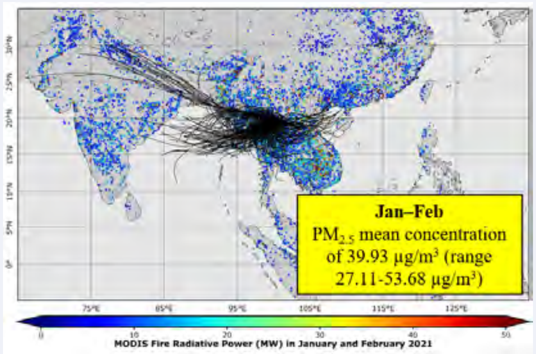

FIGURE 8. Map of MODIS cumulative FRP in SEA during Jan-Feb 2021 and three-day air mass backward trajectories arrived at sampling site in Chiang Rai.

4. CONCLUSION

In this study, the $PM_{2.5}$ measurement campaigns were conducted concurrently at the sampling sites in Hanoi, Vietnam and Chiang Rai, Thailand during the high season from January to April in 2021. Results showed that the average value of $PM_{2.5}$ daily concentrations measured at the sampling site in Hanoi was higher than that measured at the sampling site in Chiang Rai during the January–February periods. In contrast, the average value of $PM_{2.5}$ daily concentrations measured at the sampling site in Hanoi was slightly lower than the counterpart at the sampling site in Chiang Rai during the March–April periods. The elevated concentrations of the $PM_{2.5}$ measured in Chiang Rai during the spring periods were largely associated

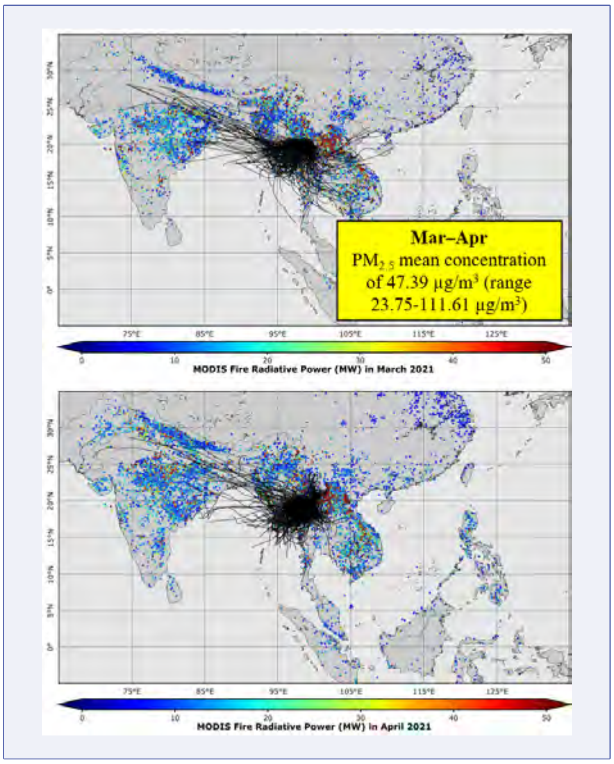

FIGURE 9. Maps of MODIS cumulative FRP in SEA during Mar-Apr 2021 and three-day air mass backward trajectories arrived at the sampling site in Chiang Rai.

with the intensive biomass burning activities in the SEA region. Results for the PMF receptor model-based source apportionment indicated a larger contribution of biomass burning sources to the $PM_{2.5}$ measured at the sampling site in Chiang Rai compared to that at the sampling site in Hanoi. The analysis of integrated maps of MODIS cumulative FRP in the SEA region and three-day air masses backward trajectories arrived at the sampling sites in Hanoi and Chiang Rai during the measurement periods further suggested the potential impacts of biomass burning sources on the measured $PM_{2.5}$. It was observed that the long-range transported air masses passing through the fire regions in the southern part of China could contribute to the elevated $PM_{2.5}$ concentrations at the sampling site in Hanoi during the January–February periods. Meanwhile, the air masses that travelled over the dense fire regions in the northwestern part of Thailand and the southern part of Myanmar were likely the main cause for the high $PM_{2.5}$ concentration at the sampling site in Chiang Rai during the March–April period.

5. ACKNOWLEDGEMENT

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Spatial variability of nutrient sources determining phytoplankton Chlorophyll-*a* concentrations in the Bay of Bengal

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ABSTRACT

Primary production is a key marine ecosystem driver in the Bay of Bengal and is important for the societies and economies of the surrounding countries. Although the availability of inorganic nutrients is known to control primary production in this region, the specific nutrient sources that affect primary production in different parts of the bay have not been identified. In this study, we assess the importance of nutrients from different sources in determining chlorophyll-*a* concentration, an indicator of primary production, in the Bay of Bengal by conducting multiple linear regression of satellite-derived chlorophyll-*a* concentration, sea surface height anomaly, and sea surface temperature; modelled dust deposition; and in situ river discharge from 1997 to 2016. River-borne nutrients were important up to approximately 200 km from the coast. Deep-ocean nutrients influenced chlorophyll-*a* concentrations mainly in the south-western and western bay, whereas wind-borne nutrients were more important in the central and eastern bay. Any attempt to understand the impact of nutrients from a certain source should also consider the potential impacts of other nutrient sources. Although climate impacts on chlorophyll-*a* concentrations through river discharge were observed in our study, future studies should investigate climate-change impacts through atmospheric aerosols and mesoscale eddies.

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KEYWORDS

Chlorophyll-a, remote sensing, atmospheric deposition, nutrient entrainment, upwelling

HIGHLIGHTS

- We mapped the nutrient sources that determine chlorophyll-*a* in the Bay of Bengal.
- River-borne nutrients are important for phytoplankton in coastal waters.
- Deep-ocean nutrients are important for phytoplankton in the south-west and west bay.
- Atmospheric nutrients are important for phytoplankton in the central/eastern bay.

1. INTRODUCTION

The Bay of Bengal, located in the northeastern Indian Ocean, is one of the world's biggest large marine ecosystems (LMEs). Eight national governments in the region (those of India, Bangladesh, Sri Lanka, Myanmar, the Maldives, Thailand, Malaysia, and Indonesia) have agreed to build a consensus on a strategic action program to solve existing socio-economic issues in the bay (Elayaperumal, Hermes, & Brown, 2019). Geographically, the Bay of Bengal is bounded by the Asian continent to the north, the eastern coast of India to the west, and the Andaman Sea to the east. In the south, the bay is open to the South Indian Ocean.

One of the key factors influencing socio-economic issues in the Bay of Bengal LME is primary production, which refers to the production of organic matter by phytoplankton through photosynthesis. Primary producers are the base of the marine food web, and their production supports the biomass and secondary production of higher trophic levels. Previous reports have identified a strong relationship between phytoplankton biomass or primary production and fisheries production in various coastal and pelagic ecosystems (Nixon & Thomas, 2001; Nixon & Buckley, 2002). Particularly in the Bay of Bengal, the production of the tropical hilsa fishery, which contributes to the economies of India, Bangladesh, and Myanmar, is controlled by primary production (Hossain, Sarker, Sharifuzzaman, & Chowdhury, 2020).

Besides inorganic nutrients, light is also an important factor for primary production (Kumar et al., 2010), especially in the northern Bay of Bengal, because of the high turbidity associated with large sediment inputs from the Ganges and Brahmaputra rivers (GBR). Furthermore, because of the large flux of freshwater from the GBR in this region, the water column is strongly stratified, inhibiting inorganic nutrient input from the deep ocean to the euphotic zone, especially in the central bay and during summer (Kumar et al., 2002). However, in regions of the bay where light is not a limiting factor, inorganic nutrient input is thought to be the main determining factor for primary production.

At least three main sources of inorganic nutrients are thought to determine primary production in the Bay of Bengal: riverine inputs, upwelling or vertical mixing from the deep ocean, and atmospheric dust deposition (DD). In this study, we used phytoplankton chlorophyll-*a* (CHL) concentration as an indicator of ocean primary production. Freshwater discharge from the GBR and nutrient inputs from ocean upwelling and mixing change seasonally due to reversing monsoon winds, resulting in seasonal changes in marine productivity patterns in different areas of the bay (e.g., Gomes, Goes, and Saino, 2000; Martin and Shaji, 2015).

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Previous studies have identified how inputs of inorganic nutrients from rivers and the deep ocean determine seasonal CHL concentrations in the Bay of Bengal (e.g., Gomes et al., 2000; Levy et al., 2007; Vinayachandran, 2009). The supply of riverine nutrients from river discharge elevates CHL concentrations mainly in coastal areas during the boreal summer (e.g., Vinayachandran, 2009; Kay, Caesar, and Janes, 2018), especially in the northern bay, where the Ganges–Brahmaputra–Meghna river system ranks fourth globally in freshwater outflow to the sea (average: 1032 km^3 $year^{-1}$; Dai and Trenberth, 2002). By contrast, inputs of deep-ocean nutrients due to upwelling and vertical mixing elevate CHL concentration mainly in the southwestern bay during the boreal winter (e.g., Martin & Shaji, 2015; Vinayachandran and Mathew, 2003).

Besides nutrient inputs from rivers and the deep ocean, atmospheric DD can also be a potent source of inorganic nutrients to the bay. Grand et al. (2015) have reported that the concentration of nutrients in the surface water of the Bay of Bengal is highly consistent with the distribution of mineral atmospheric DD, except in the northern bay, where the GBR largely supplies nutrients. Yadav, Sarma, Rao, and Kumar (2016) have recently confirmed that atmospheric DD increases CHL concentrations in September even in coastal areas, where the input of riverine nutrients is quite high.

To date, however, the impact of various nutrient sources on CHL has not been mapped in detail across the entire Bay of Bengal. Identifying the main sources of nutrients that determine CHL concentrations is a prerequisite to fully understanding the impacts of climate change on primary production in the Bay of Bengal and hence on the Bay of Bengal LME overall. This is because climate patterns such as the El Niño/Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) do not drive ocean primary production directly. Instead, they affect productivity indirectly through nutrient inputs by modifying river discharge, ocean upwelling and downwelling, and atmospheric circulation. Understanding the impacts of climate change on primary production in the Bay of Bengal is particularly important given the strong relationship between phytoplankton primary productivity and fisheries production, meaning that this knowledge is needed to take action toward climate change adaptation in fisheries. In this study, we used multi-year satellite-derived CHL concentrations, in situ GBR discharge, and modelled DD to assess the spatial extent of the influence of nutrients from various sources (i.e., rivers, deep ocean layers, and the atmosphere) on CHL concentrations in the Bay of Bengal.

2. METHODS

2.1. Region of study

The study region selected for this study (Figure 1a) is characterized by relatively low offshore satellite-derived CHL concentrations (< 0.5 mg m^{-3}) but high coastal CHL concentrations (> 2 mg m^{-3}) associated with terrigenous inputs from adjacent river systems. A large area of high CHL concentration is apparent along the northern coast and is attributable to discharge from large river systems such as the GBR (e.g., Gomes et al., 2000).

On average, freshwater discharge from the GBR peaks in mid-to-late summer (August to September, Figure 1b). These high freshwater discharges are associated with peaks in precipitation that occur 1–2 months prior (in June or July). The discharged freshwater contains high suspended sediment loads, increasing turbidity along the northern coast. Additionally, large freshwater inputs strengthen water-column stratification, which can restrict nutrient input from the deep ocean (Kumar et al., 2002; Madhupratap et al., 2003).

2.2. Data sources and analysis

We downloaded satellite-derived, blended monthly CHL concentration at 4-km resolution from the ESA Ocean Colour Climate Change Initiative (https://esa-oceancolour-cci.org), monthly sea surface height anomaly (SSHA) at 25-km resolution from the AVISO+ Satellite Altimetry Database (https://www.aviso.altimet

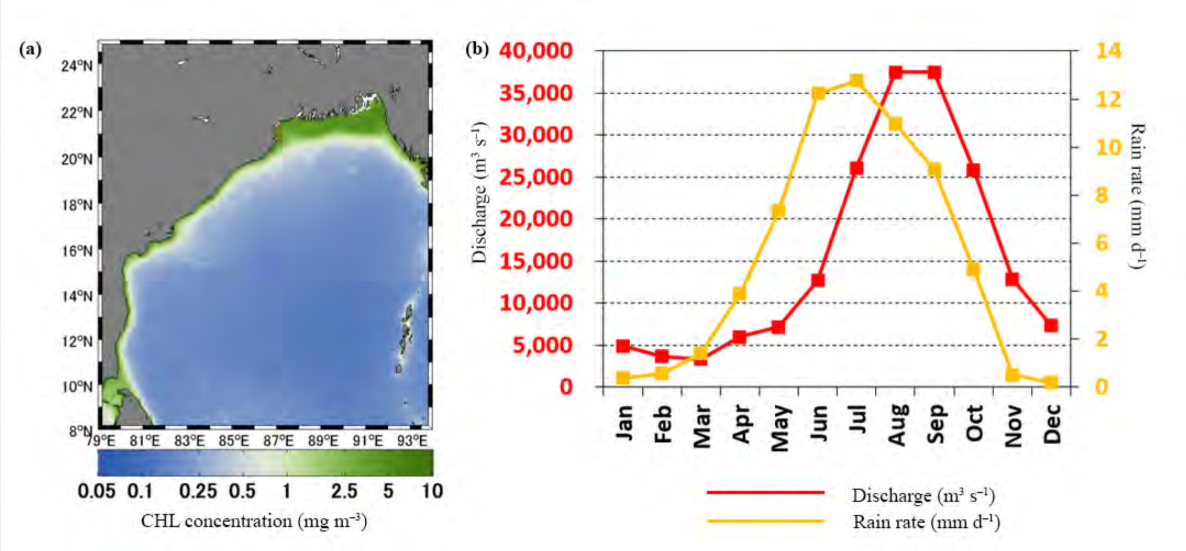

FIGURE 1. (a) Map of the study region showing mean chlorophyll-*a* (CHL) concentrations (1997–2016) in the Bay of Bengal. (b) Monthly climatological means of rain rate (yellow line) in the region (defined as the catchment area) and freshwater discharge (red line) from the Ganges and Brahmaputra rivers.

ry.fr), monthly rain rate from the Asia-Pacific Data-Research Center (http://apdrc.soest.hawaii.edu), and daily sea surface temperature (SST) at 4-km resolution from NOAA (https://www.nodc.noaa.gov). Daily SST data were then averaged to produce monthly mean SSTs. Changes in SST and SSHA are widely used to assess nutrient inputs from the deep ocean associated with physical oceanographic processes such as upwelling and vertical mixing (e.g., Rao, Smitha, and Ali, 2000; Latha et al., 2015; Singh, Gandhi, Ramesh, and Prakash, 2015 ; Siswanto, 2015; Honda et al., 2018). In this study, we used satellite data from 1997 to 2016. Detailed descriptions of the algorithms used to calculate CHL concentration, SSHA, and SST can be found on the websites for each data source.

As a proxy for riverine nutrient input, we used in situ GBR discharge data from the Bangladesh Water Development Board (https://www.bwdb.gov.bd). Atmospheric DD data were derived from the Spectral Radiation-Transport Model for Aerosol Species (Takemura et al., 2000; Takemura, Nozawa, Emori, Nakajima, & Nakajima, 2005; Takemura, Nakajima, Dubovik, Holben, & Kinne, 2002), a numerical model developed by the Research Institute for Applied Mechanics at Kyushu University (http://sprintars.riam.kyushu-u.ac.jp). To represent ENSO variability, we used the index Nino3.4 from the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov). To ensure consistency with satellite data, particularly for spatiotemporal and linear regression analysis, we analyzed river discharge, DD, and climate indices from 1997 to 2016.

Multiple linear regression analysis (MLRA) based on the methods described in Siswanto (2015) and Nathans, Oswald, and Nimon (2012) was used to relate CHL concentration to other environmental variables and determine where inorganic nutrients from the deep ocean or atmosphere were more important. The analytical procedure included removing seasonal variations and trends and standardizing variables to a mean of zero and standard deviation of one. Standardization allowed each variable's effect on CHL concentrations to be compared against that of other variables.

To carry out the MLRA, it was first necessary to fill any spatiotemporal gaps in the data. Unlike the SSHA and DD data, CHL and SST data were observed by satellite-borne optical and infrared sensors and contained data gaps caused by clouds and rain belts. Thus, interpolation and data reconstruction were needed to fill the missing data pixels. We used the data interpolating empirical orthogonal functions (DINEOF) method (e.g., Alvera-Azcarate, Barth, Rixen, and Beckers, 2005) to do so. The binary code used to run the DINEOF method can be found on the DINEOF website (https://github.com/aida-alvera/DINEOF).

Another requirement of MLRA is that the spatial dimensions (in latitude and longitude) of the dependent variable (CHL concentration) and independent variables (SST, SSHA, and DD) be the same. Therefore, prior to MLRA, re-gridding with linear interpolation was applied to the SST, SSHA, and DD data to resize their spatial dimensions. A p-value of 0.05 was used as the threshold for significance in all statistical comparisons.

3. RESULTS AND DISCUSSION

To assess the maximum distance offshore that riverine nutrients from the GBR affect primary production, we calculated a time series of CHL concentration (Figure 2a) across a north-south transect (Figure 2c). Offshore dispersions of high CHL concentration were particularly obvious during summer and fall (Figure 2a and b) and were related to GBR discharge. Particularly during the summer and fall of 1998, 2007 and 2011, we observed extremely high rain rates over the catchment area and high discharge from the GBR (Figure 2b) associated with La Niña conditions (Figure 2b). However, even during these extreme high-rainfall, high-discharge events, the southernmost latitude where elevated CHL concentrations could be observed was about 20°N. This implies that river-borne nutrients are only important in determining CHL concentrations in coastal areas (approximately 200 km from the coastline). This conclusion is consistent with the results reported by Madhupratap et al. (2003).

Thus, other nutrient sources (i.e., the deep ocean and atmosphere) might be more important in determining CHL concentrations offshore and in the open ocean. We used MLRA to assess the dependencies of CHL concentration on DD (i.e., atmosphere-borne nutrients) and SSHA and SST (proxies for nutrient input from the deep ocean). SST co-varies with nutrient supply from the deep ocean because upwelling and/or vertical mixing of nutrient-rich deep waters transfers the low water temperatures at depth to the surface. Upwelling also tends to decrease SSHA. Therefore, falling SSTs or low SSHA is usually associated with high nutrient supply to the surface from depth.

We estimated partial regression coefficients of SSHA (β_{SSHA}) and DD (β_{DD}) by relating CHL concentrations to SSHA and DD in an MLRA (Figure 3a and b). Similarly, we estimated partial regression coefficients for SST (β_{SST}) and DD (β_{DD}) by relating CHL to SST and DD (Figure 3d and e). Based on the coefficient of determination of these partial regressions (Figure 3c and f), it appears that nutrients from both the deep ocean and atmosphere are important for phytoplankton growth in offshore waters.

β_{SSHA} and β_{SST} were significantly negative, especially in the south-western and western parts of the bay (Figure 3a and d). This indicates that CHL concentrations increased with proxies of stronger upwelling and vertical mixing, such as low SSHA and low SST. The implication is that nutrients from deep waters seemed to be more important than DD in determining CHL variation in these areas. By contrast, the fact that β_{DD} was significantly positive over the central and eastern parts of the bay (Figure 3b and e) indicated that CHL concentrations tended to increase with higher DD. This suggests that atmospheric dust-borne nutrient deposition is more important than nutrient supply from deep water (by upwelling and mixing) in determining CHL variation in these areas.

As previously reported, the upwelling and vertical mixing that pumps nutrients from deep to surface waters (thereby triggering phytoplankton blooms) in the south-western and western Bay of Bengal can be driven by mesoscale cyclonic eddies and the passage of cyclones (Chen et al., 2013; Sarma et al., 2016). Although increases in CHL concentration can also be observed in the central bay after the passage of cyclones, mesoscale eddy formation is rare in this area (in comparison to the western bay), and the presence of a barrier layer

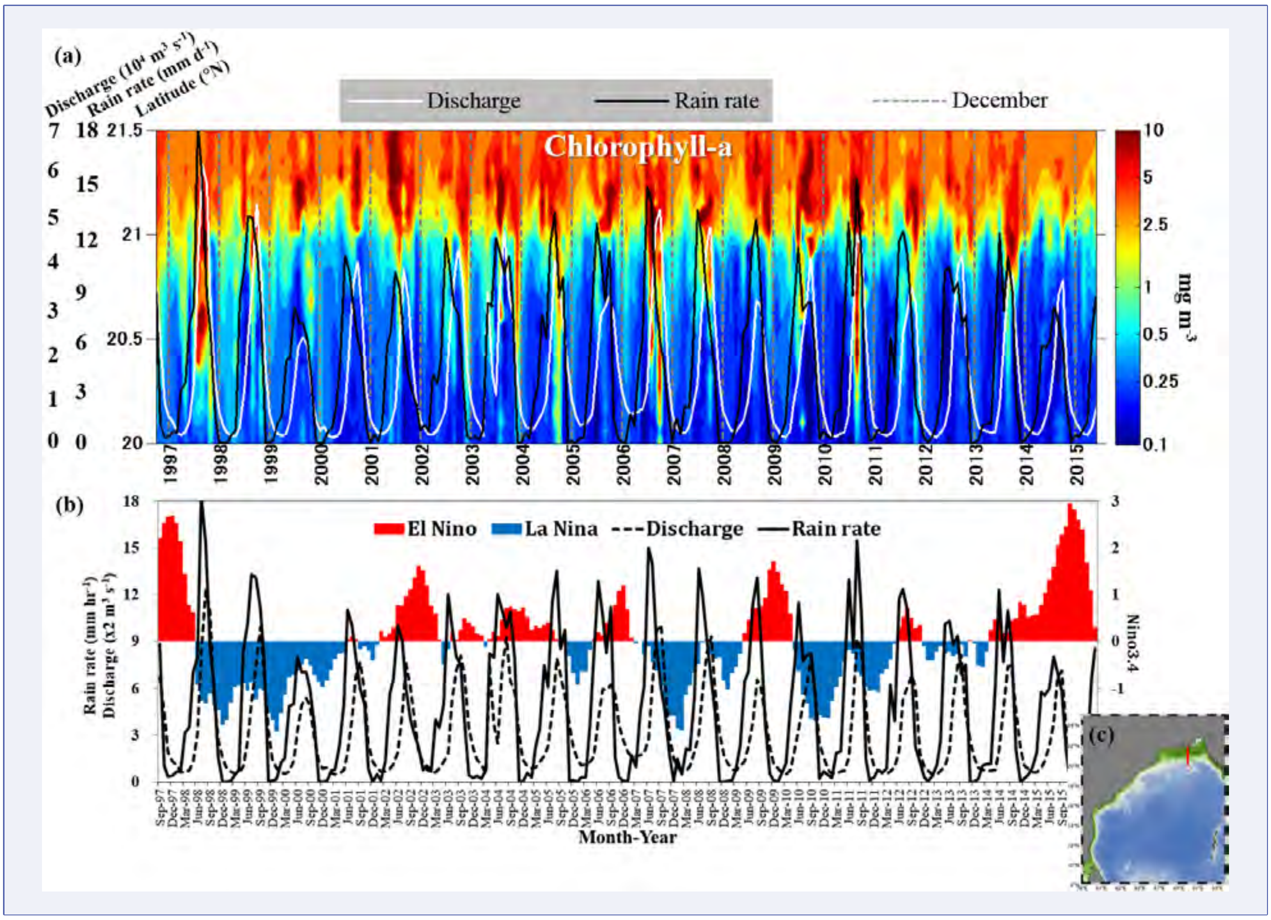

FIGURE 2. Time series of (a) chlorophyll-a (CHL) concentrations (colours), rain rate (black line), and freshwater discharge (white line) from the Ganges and Brahmaputra rivers (GBR). CHL concentrations were extracted from a north-south transect (shown by the red line in panel [c]) located near the mouth of the GBR. (b) Time series of the ENSO index Nino3.4 indicating the strength of the El Niño (red columns) and La Niña (blue columns). Solid and dashed lines in (b) show time series of rain rate and GBR discharge, respectively.

formed by freshwater influx from the GBR means that the central bay is less sensitive to upwelled nutrients than the south-western and western areas of the bay. The barrier layer extends to depths of 25–30 m from the surface and restricts the entrainment of nutrients from depth (Vinayachandran, Murty, & Babu, 2002). Based on these results, we suggest that any attempt to understand the impact of nutrients from a certain source (e.g., atmospheric DD) should also consider the possible impacts of nutrients from other sources (e.g., upwelling).

Although the influence of ENSO on river discharge rates and hence on CHL concentrations was detected in coastal waters in our study (Figure 2), climate is also expected to affect nutrient inputs to the Bay of Bengal in other ways. For example, climate variations are expected to affect the dryness of terrestrial environments and hence the intensity of atmospheric DD. Also, seasonal surface currents from the Arabian Sea to the western Bay of Bengal have been affected by anomalous wind patterns and changes in ocean surface circulation in the equatorial Indian Ocean (especially related to the IOD). Because these ocean surface currents are important drivers of mesoscale eddy generation, these changes in surface currents are also expected to influence CHL concentrations. More work is needed to identify how ENSO and IOD will influence CHL concentrations in the Bay of Bengal through these mechanisms.

4. CONCLUSION

Nutrients supplied from river discharge, deep ocean waters, and atmospheric deposition affected CHL concentrations in different regions of the Bay of Bengal. Nutrients supplied by river discharge appear to be important only in waters within approximately 200 km of the coast, whereas nutrients supplied

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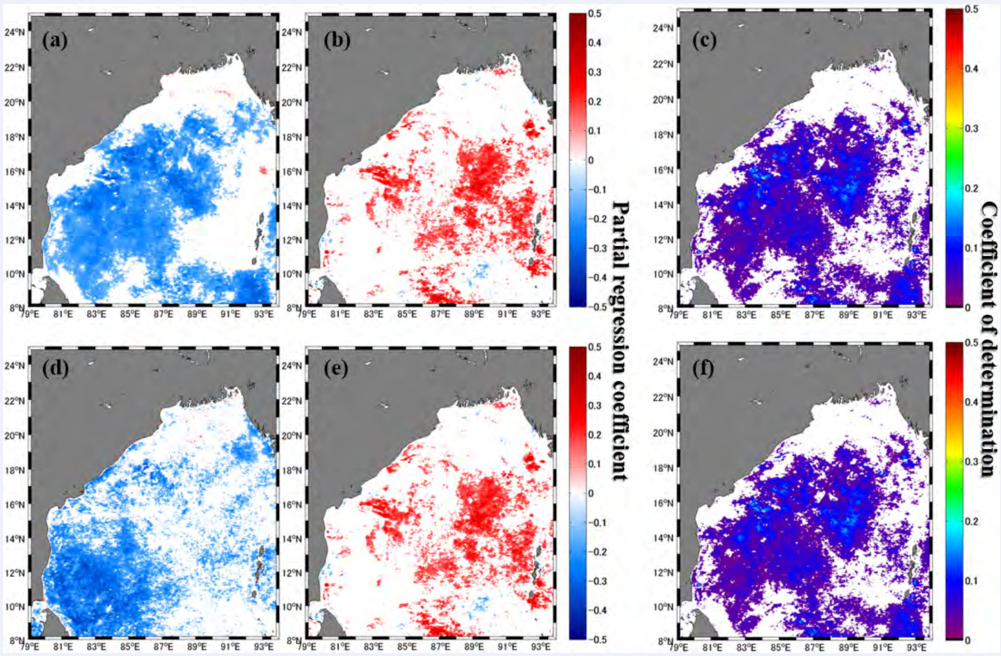

FIGURE 3. Maps showing estimated partial regression coefficients of (a) sea-surface height anomaly (SSHA) and (b) dust deposition (DD) and (c) the coefficients of determination of the relationship between the two independent factors and chlorophyll-*a* concentration. Areas shown in white indicate locations where the partial regression coefficients or coefficients of determination were insignificant. Panels (d–f) are the same as panels (a–c), except that the independent factors shown are (d) sea-surface temperature (SST) and (e) DD.

from the deep ocean influenced CHL concentrations in the south-western and western areas of the bay, and atmospheric nutrient input was most important in the central and eastern bay. Because of the large number of factors that can determine CHL concentrations in this region, any attempt to understand the impact of nutrients from a certain source should consider the potential impacts of other sources. Although we were able to identify the impact of climate on CHL through river discharge, future studies should investigate how climate change might affect CHL concentrations by modifying atmospheric aerosols and mesoscale eddy generation.

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Smart city indicators: Towards exploring potential linkages to disaster resilience abilities

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ABSTRACT

Recent advances in Information and Communication Technologies (ICTs) have transformed all aspects of human life. Enabled by these advances, over the past few decades, many smart city initiatives have been developed across the world. Subsequently, various efforts have been made to develop indicators and frameworks for the assessment of smart cities. Generally, smart cities are expected to enhance the quality of life and provide solutions to deal with societal challenges. One major societal challenge is the increase in the frequency and intensity of disasters and adverse events. Therefore, smart cities are expected to contribute to enhancing disaster resilience. Integrating resilience thinking into smart city indicators and assessment frameworks is likely to promote better attention to the resilience contributions of smart cities. Against this background, through reviewing the literature, I first introduce a comprehensive list of indicators for assessing city smartness. Multiple indicators related to economy, people, governance, environment, mobility, living and data dimensions of a smart city are listed. Next, I explore if these indicators are aligned with the four resilience abilities: planning, absorption, recovery, and adaptation. Results show that smart city indicators are particularly linked to planning and absorption abilities. More attention to the recovery and adaptation abilities is, therefore, needed.

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KEYWORDS

Smart city, disaster resilience, indicators, urban, disasters, assessment tools, index

HIGHLIGHTS

- Smart cities have increasingly become ubiquitous.
- Smart cities should contribute to enhancing community resilience.
- A comprehensive list of indicators for smart city assessment is introduced.
- Resilience thinking is not fully integrated into smart city indicators.
- A framework to integrate resilience thinking into smart city assessment is proposed.

1. INTRODUCTION

We now live in the age of digital revolution, and digital technologies have transformed almost every aspect of our lives. As cities have historically been centres of innovation, it is no surprise that they are now at the forefront of developing and implementing digital technologies. In fact, many cities around the globe are increasingly relying on digital technologies, enabled by Information and Communication Technologies (ICTs), to overcome societal challenges, enhance the quality of life, and improve the efficiency and efficacy of urban operations (Ahvenniemi, Huovila, Pinto-Seppa, & Airaksinen, 2017; Clarke, 2013; Kourtit & Nijkamp, 2018; Woods, Labastida, Citron, Chow, & Leuschner, 2017). The ICT-enabled efforts and activities are often referred to as smart city movements.

The smart city concept emerged in the early 2000s and has gradually evolved over the past two decades. During this period, many smart city projects and initiatives have been developed, and this trend is expected to continue further in the coming decades (Angelidou, 2015; Caragliu, Del Bo, & Nijkamp, 2011; Marsal-Llacuna, Colomer-Llinas, & Melendez-Frigola, 2015). This increasing interest in smart cities is not surprising given their multiple utilities. For instance, it is now widely believed that becoming smart is critical to maintaining a competitive advantage in an increasingly connected world (Giffinger et al., 2007; Giffinger, Haindlmaier, & Kramar, 2010). Related to this, smarter cities are likely to be in a better position to attract talented and creative citizens capable of contributing to local economy and growth through promoting innovative and efficient approaches (Angelidou, 2015; BSI, 2014). Furthermore, ICT-enabled smart solutions are expected to contribute to enhancing the urban quality of life, enhance the transparency of urban management, and help overcome some long-standing challenges related to urban inequalities, ageing society, and safety and security (BSI, 2014; Manville et. al., 2014).

Related to the focus of this paper, smart cities are also expected to provide solutions for dealing with a major societal challenge: the increase in the frequency and intensity of disastrous events. These include events related to climate change, as well as natural disasters such as earthquakes and man-made events such as nuclear events (Huovila, Airaksinen, Pinto-Seppä, Piira, & Penttinen, 2016). This is motivated by the fact that an increasing trend in the annual frequency of climate-induced, natural, and human-made disasters can be observed from the analysis of loss events in the past few decades (Hoeppe, 2016; Smith & Katz, 2013). For instance, as a clear sign of global warming, the last six years have been the warmest on record since 1850 and last year was the warmest (World Meteorological Organization, 2020). Extreme heat and multiple other adverse events, cumulatively, result in billions of dollars of economic loss in cities that are often more vulnerable due to their higher concentration of humans and resources.

According to some estimates, every year, about USD 300 billion is lost to disasters in cities and, unless cities build on their resilience, economic losses to disasters in cities may cross USD 400 billion by 2030 (Word Bank, 2016). Given these threats and challenges, it is clear that one major contribution of smart city solutions, technologies, and projects should be enhancing disaster resilience. Here, resilience refers to the "ability to plan and prepare for, absorb, recover from, and more successfully adapt to adverse events" (Cutter et al., 2013). Resilience is also characterized by multiple attributes such as robustness, stability, diversity, redundancy, resourcefulness, creativity, agility, flexibility, efficiency, self-organization, inclusiveness, and foresight capacity (Sharifi & Yamagata, 2016).

In planning and policymaking circles, assessment is widely recognized as an effective method for improving the performance of projects, and policies and smart city projects and policies are no exception (Sharifi, 2020). Indeed, assessment can provide useful insights to municipal authorities, smart city developers and investors, and the public (Caird & Hallett, 2018; Mohan, Dubey, Ahmed, & Sidhu, 2017). For instance, it can facilitate regular performance monitoring, highlight strengths and weaknesses, track progress towards targets and goals, identify technical requirements and economic feasibility issues, showcase best practice cases, encourage constructive competition through benchmarking, enhance governance transparency, raise general awareness, and provide engagement motivations (Caird & Hallett, 2018; Mohan et al., 2017). Given these multiple utilities of assessment frameworks, it is essential to ensure that they are well-designed and capable of addressing the capacity to deal with societal challenges.

Against this backdrop, the main objectives of this study are to provide a list of indicators that have been used for smart city assessment and to explore their potential contributions to the four resilience abilities, namely, planning/preparation, absorption, recovery, and adaptation. In other words, it aims to examine if smart city indicators are aligned with resilience abilities. Planning refers to the ability to take preparatory measures before the occurrence of a shock to better deal with possible disasters. Absorption indicates the ability to minimize functionality loss and associated socio-economic damages. Recovery refers to the ability to return to pre-shock conditions in a timely manner. Finally, adaptation indicates the ability to learn from the adverse event to not only bounce back but also bounce forward. The paper is structured as follows. The methods are described in the next section. Section 3 provides the list of indicators and discusses how resilience thinking can be integrated into smart city indicators. Finally, section 4 concludes the study by summarizing the results and providing recommendations.

2. METHODOLOGY

Content analysis of smart cities literature is the main method used for developing a comprehensive list of smart city indicators and classifying them into several categories. First, I searched for relevant documents in the Web of Science using combinations of terms related to smart cities and assessment. For this purpose, the following broad-based search string was used:

TS=((("certificat*" NEAR/1 ("tool*" OR " toolkit*" OR "system*" OR "indicator*" OR "framework*" OR "index" OR "scorecard*" OR "scheme*")) OR ("evaluat*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "indicator*" OR "framework*" OR "index" OR "scorecard*" OR "scheme*")) OR ("assess*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "framework*" OR "indicator*" OR "index" OR "scorecard*" OR "scheme*")) OR ("measur*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "framework*" OR "indicator*" OR "index" OR "scorecard*" OR "scheme*"))) AND ("smart") AND (("city" OR "cities" OR "communities" OR "community" OR "neighbo*rhood*" OR "district*"))) (Sharifi, 2020). Documents retrieved using this string were screened, and 58 articles were selected for final analysis (Sharifi, 2019). In addition, I did a Google search to find potentially relevant grey literature that can be used for extracting indicators. After downloading the documents, the inductive content analysis method was used to extract the list of indicators (Mayring, 2014). An inductive content analysis data collection and analysis are conducted simultaneously (Mayring, 2014). In this case, this means that as the first document was reviewed, relevant indicators were added to the list. When reading the next document, it was checked whether the mentioned indicators fall under the previously listed indicators or should be added as new ones. This process was continued for all the documents, and, based on the results, a complete list of indicators was developed that will be presented in the next section. While doing the content analysis, I also noted major smartness dimensions mentioned in the literature. These were economy, people, governance, environment, mobility, living, and data (Sharifi, 2020). In the end, the extracted indicators were assigned to the smartness dimensions. This was done based on the author's discretion and, therefore, involves some form of subjective judgment. To explore links between the indicators and resilience, each indicator's relevance to different resilience abilities was examined, and a synthesis table was developed. More specifically, based on the literature and the author's opinion, it was determined if each indicator contributes to the four resilience abilities (planning, absorption, recovery, and adaptation). This was determined based on yes/no questions. For each theme, depending on the percentage of indicators linked to each resilience ability, its extent of alignment with the resilience abilities was determined.

3. RESULTS AND DISCUSSION

In this section, I first present the list of indicators related to economy, people, governance, environment, mobility, living and data. Next, I discuss an approach for integrating resilience thinking into smart city assessment.

3.1 Smart city indicators

In each of the following subsections, indicators related to the seven major smart city dimensions will be presented.

3.1.1 Economy

Many indicators related to the economy were identified, which is not surprising considering that, as mentioned earlier, one of the major objectives of smart city initiatives is to strengthen the position of cities in an increasingly competitive global economy. These indicators are divided into major themes: innovation, knowledge economy, entrepreneurship, finance, tourism, employment, local & global interconnectedness, productivity, the flexibility of the labour market, and impacts (Table 1).

Theme	Indicator
Innovation	R&D expenditure (% of GDP)
	Policies, programs, and plans for promoting creativity/innovation
	Patent applications/registration per inhabitant
	The competitive position of the city in terms of science and engineering centres
	ICT-enabled innovation leading to new businesses and market opportunities
Knowledge economy	Green economy
	Share of public/private investment in smart industries
	Rate of import-export related to smart industry and knowledge-intensive economy
	Industry-academia-government cooperation
	Contribution of knowledge economy and ICT initiatives to GDP (%)
	Space for knowledge exchange and business promotion
	Share of e-business and e-commerce transactions
Entrepreneurship	Policies, programs, and plans for promoting entrepreneurship
	Self-employment rate
	Small and Medium Enterprises trends

TABLE 1. Economic indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi, Kawakubo, & Milovidova, 2020.

Theme	Indicator
Finance	Number of start-ups
	Promotion of start-up companies
	Number of businesses and new businesses registered annually
	Funding for smart city projects (public/private finance, crowdsourced, etc.)
	Consideration of market demands and needs in smart city planning
	Total market value of commercial and industrial properties
	Financial stability (e.g., city and per capita reserves, city's debt service ratio)
	Global/regional competitiveness in attracting companies with low sales taxes
	Tax collected as a percentage of tax billed
Tourism	Importance as a tourist hub
	Affordability and accessibility as a tourist destination
	Tourism impact management
	Online and ICT-enabled tourism promotion
Employment	City's employment/unemployment rate, measures to combat unemployment
	Availability of labour force, working-age population
	Local employment opportunities
	Employment rate improved by smart solutions
	Rate of employment in tourism industry
	Rate of employment in knowledge-intensive sectors/ creative industry
Local & Global Interconnectedness	Gross regional product per capita (GRP)
	Procurement style
	Presence of major international and domestic enterprises and entities in the city
	City internationalization activities
	Cross-city smart city initiatives and collaboration
	Importance on the national and regional scale
	Adoption of International Organization for Standardization
	Using ICT measures for improving domestic and international communication and cooperation
Productivity	GDP per employed person
	Primary, secondary, and tertiary industry's share of GDP
	ICT measures to improve industry/economic/employee productivity
	Plans and strategies for economic development
	Foreign direct investment and inward investment
	Cost-benefit analysis
Flexibility of the labour market	Measures to improve accessibility to labour market
	ICT-enabled flexibility and improvement of traditional industry and job market
	Home-based work and workspace flexibilization
	Timetable flexibilization
	Perception of getting a new job; flexibility of the workforce
Impacts	Costs of development, operation, and maintenance of smart city projects
	Economic impacts of smart city initiatives
	Plans for management of risks

TABLE 1 continued. Economic indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

3.1.2 People

People are the main users of smart city solutions and technologies. In addition, as major stakeholders, they can contribute to the enhanced design and development of smart cities. Indicators related to people and their capacities are related to education, ICT skills and open-mindedness (Table 2).

3.1.3 Governance

Integrated governance mechanisms are critical to ensure the efficacy and efficiency of smart city solutions and technologies. As Table 3 shows, governance indicators are related to themes such as visioning and leadership, legal frameworks, participation, transparency, public services, and integrated management.

Theme	Indicator
Education	Importance as a knowledge hub
	Percentage of the population working in higher education and R&D sector
	Update and adjustment of educational facilities, curricula, and material to improve digital skills
	Measures to improve quality of educational infrastructure
	Adult literacy trends
	Availability and penetration of e-learning and distance education systems
	Application of ICT technology, analytics platforms, and e-learning
	IT training and raising awareness about smart city benefits
	Student/teacher ratio
Level of qualification/ ICT skills	Percentage of population with secondary-level education
	Percentage of population with tertiary-level education
	Foreign language skills of the citizens
	Individual-level of computer skills
	Internet penetration (netizen ratio)
	Social networking penetration
	Level of digital and ICT literacy and technical capability
Open-mindedness	Inhabitants' attitude towards international treaties
	Share of foreigners and nationals born abroad
	Use of ICT measures to create an immigrant-friendly environment

TABLE 2. People indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
Visioning and leadership	Clear and inclusive digital strategy and smart city vision
	Smart city roadmap
	Historical experience of technology development
	A broad-based leadership team that features appropriate mix of skills
	Sustained leadership commitment to long-term smart city programs
	Strong Leadership
	Plans and strategies for mainstreaming smart city planning
	Plans and strategies for performance monitoring and assessment
	Availability of risk governance plans and strategies and using smart solutions

TABLE 3. Governance indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
Legal frameworks	Laws and regulations for smart city planning
	Strategies to overcome organizational, legal and regulatory barriers
	Legal and regulatory frameworks to protect consumer privacy
Participation	Democracy, individual freedom, freedom of media, speech, etc.
	Extent of involvement of local authority/city administration in smart solution programs
	Public participation and stakeholder engagement in decision making
	Political activity of inhabitants
	ICT-enabled participation in bottom-up voluntary work/service
	Online civic engagement and feedback system
	Dynamic interconnection with citizens, communities, and businesses
	Collaborative service production and delivery
Transparency	Governmental transparency
	Leadership accountability
	Mapping skills and transparent division of responsibilities between different actors
	Bureaucracy status
	Corruption index and measures to fight corruption
Public services	Digitalization of governance and public expenditure on ICT and smart city transition
	One-stop platform for data integration and for online accessibility and coordination of city services
	Presence of people and public entities in social networks/media
	Penetration rate of online government service
	Presence of electronic and mobile payment platforms
Integrated management	Interoperability between urban systems and subsystems
	The state of data/information sharing among various institutions
	Shared architecture for multi-level governance and inter-agency collaboration
	Cross-agency coordination for integrated infrastructure management
	Public-private partnership
	Efficiency in the provision of services
	Appropriate balance of top-down and bottom-up governance processes
	Cross-city engagements and collaborations for knowledge exchange

TABLE 3 continued. Governance indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

3.1.4 Environment

Smart cities can provide solutions to promote environmentally friendly cities. However, it is also essential to take measures to minimize their own environmental footprint. This dimension focuses on issues such as environmental monitoring, infrastructure, built environment, materials, energy, water, waste and environmental quality (Table 4).

3.1.5 Living

One of the major goals of smart cities is to enhance the quality of life of citizens. This dimension focusses on issues such as social cohesion, justice, culture, housing quality, healthcare, safety and security and subjective well-being (Table 5).

3.1.6 Mobility and communication

Mobility and communication are major sectors that have adopted smart technologies. Indicators used to assess the smartness of mobility are related to transport infrastructure and management, ICT infrastructure and management, and ICT accessibility (Table 6).

Theme	Indicator
Environmental monitoring	Sustainable natural resource management
	(ICT-enabled) environmental monitoring infrastructure
	Environmental/ecosystem protection activities
	(ICT-enabled) activities to disseminate environmental quality information
	Life cycle impacts of ICT infrastructure and smart cities
	Citizen involvement in resource management
	Availability and implementation of climate resilience plans/strategies
General infrastructure	Availability of basic critical infrastructure
	Decentralized and modular (autonomous) infrastructure systems
	Green infrastructure and green city initiatives
	Penetration level of energy-saving technologies
	Use of integrated smart management, operation, and monitoring systems
	Local food production
Built environment	Urban sprawl containment
	Mixed-use development
	Area of green/blue space
	Preservation of historic buildings
	Ambitiousness of building energy efficiency standards
	Building Information System
	ICT-enabled urban planning
Materials	Efficiency of material consumption
	Share of recycled and renewable materials used in projects
Energy resources	Energy management plans and policies
	Total energy consumption
	Penetration of clean and renewable energy sources
	Efficient management and use of energy
	Greenhouse gas emission intensity of energy consumption
	Smart grids
	Using ICT measures for management, monitoring and saving of energy
	Reliability and quality of electricity supply
Water resources	Water management plans and policies
	Quality of water resources and water bodies, quality monitoring
	Efficient generation, distribution, and use of water
	Total annual water consumption
	Water loss monitoring and reduction
	Water energy consumption
	Use of smart water meters
	Using ICT measures for management, monitoring, and saving of water
	Reliability
Waste	Waste management plans and policies
	Efficient and smart solid waste collection
	Total per capita municipal waste
	Proportion of recycled waste

TABLE 4. Environment indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
	Energy production from waste and wastewater
	Sewage and wastewater management and treatment/recycling
	Drainage system management, stormwater management
	Using ICT measures such as smart sensors for management of solid waste
Environmental quality	Air quality index/ pollution concentration levels
	Per capita GHG emissions
	Water pollution index; reduce water contamination
	Soil pollution
	Noise pollution

TABLE 4 continued. Environment indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
Social cohesion	Community cohesion
	Demographic structure
	Trust and norms of reciprocity
	Diversity and measures for promoting diversity
	Volunteer activities and civic engagement in social networks
	Universal design of the physical environment and ICT services
	Using ICT for promoting community connectivity and mutual support
Justice	Income level
	Ethnic, cultural, and gender equality
	Protection of human rights
	Physical access to amenities
	Affordable, authorized and sustainable access to services and utilities
	Enhancement in affordability and accessibility to services
Culture	Percentage of municipal/individual budget allocated to culture
	Cultural infrastructure
	Size and quality of community centres
	Use of ICT for promotion of culture
	Protection and management of cultural heritage
Housing quality	Cost of living
	Housing quality
	Housing expenditure
Healthcare	Healthcare expenditure
	Health insurance coverage
	Healthcare services and infrastructure per capita
	General well-being
	Childcare system, daycare services for children
	Healthcare for elderly; well-being of seniors
	Use of ICT and smart technologies for promoting well-being
	Use of ICT for trace-back monitoring of food and drugs
	Percentage of citizens archiving electronic health records

TABLE 5. Living indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
	Sharing rate of records, information, and resources among clinics
	Adoption of telemedicine
Safety and security	Disaster risk planning, monitoring, and management
	Response time for police and emergency departments
	Use of ICT for disaster prevention and prediction
	Disaster-related economic losses
	Individual safety and security
	Community safety and crime rate
	Using technology and ICT for crime prediction, prevention and control
	Crime reduction rate attributable to ICT usage
Subjective well-being	Satisfaction (perception of) with quality of life
	ICT-enabled increase in employee satisfaction

TABLE 5 continued. Living indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
Transport infrastructure	Green transportation modes
	Number of EV charging stations in the city
	Autonomous Vehicle (AV) testing and deployment
	Public transport system and its quality, diversity, and multi-modality
	Private car ownership rate
	Car and bike-sharing services
	Cycling infrastructure options and facilities
	Pedestrian environment and walking options
	Street/pedestrian area smart/automatic lighting management system
Transportation management	Strategic transportation network management
	Travel distance
	Share of total trips made by active /public transport modes
	Performance, safety, and efficiency of public transportation
	Real-time information about transit services and parking
	Road traffic efficiency
	Road safety, rate of traffic accidents
	ICT-enabled transportation damage and fatalities reduction
	Private car traffic restriction
	Sensing and monitoring for real-time, smart and automated traffic management
	Trackability and traceability of goods and vehicles
	Smart pricing, smart price policies, demand-based pricing
ICT infrastructure	Availability of IT and digital infrastructure
	Broadband internet
	Maintenance and regular revision of the ICT infrastructure
	Integrated platform for real-time smart city operation and management
	Fixed phone (landline) and mobile phone network coverage

TABLE 6. Mobility indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
	Rate of coverage by mobile broadband (3G, 4G, 5G)
	Availability of apps
	Availability of smart computing technologies and platforms
ICT management	Quality of internet service
	Information privacy and security management
	Existence of systems and regulations to ensure child online protection
	Application of cloud computing services
	Diversity of booking/payment options
	Integrated fare/payment system for inter-service digital fare collection capability
ICT accessibility	Physical accessibility of IT infrastructure
	Socio-economic accessibility to digital technologies
	Per-capita public/private ICT expenditure
	Fixed and wireless broadband subscriptions
	Personal computer/laptop/tablet ownership rate
	Smartphone penetration
	Free Wi-Fi coverage in public spaces

TABLE 6 continued. Mobility indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

Theme	Indicator
Data openness	Availability and publication of data in an open format
	Open data platforms for making information open to the public
	The user-friendliness of the open data platform/portal
	Data platforms that are linked to each other
Sensing and collecting	Infrastructure, systems, and strategies for data collection
	Strategies and infrastructure for autonomous real-time sensing of data
	Citizen participation in collecting real-time data and using them
	Infrastructure for storing and structuring data
	Systems, strategies, protocols, and infrastructure for timely data communication
Judging (analytics)	Data quality management
	Strategies, tools, and infrastructure for data filtering and classification
	Systems, strategies, protocols, tools and infrastructure for data analytics
	Strategies, tools, and infrastructure to evaluate data and use it for making predictions
Reacting	Government decision-making based on data and evidence
	Enterprise decision making
	Citizen decision making
Learning	Mode upgrading
	Process upgrading
	Experience upgrading

TABLE 7. Data indicators. Adapted from Sharifi, 2019; Sharifi, 2020; and Sharifi et al., 2020.

3.1.7 *Data*

Data is the cornerstone of smart city projects. Indicators belonging to this dimension cover issues such as data openness, data collection, data analytics, data use, and learning (Table 7).

3.2 Links between the indicators and disaster resilience

As mentioned earlier, in this study, resilience is defined as the ability to plan and prepare for, absorb, recover from, and adapt to adverse events (four abilities). To determine if the smart city indicators can contribute to resilience, their potential to contribute to each of the four abilities was examined. The synthesis results are shown in Table 8. More elaboration on how each theme is linked to resilience abilities is beyond the scope of this study. Interested readers are referred to Sharifi and Allam (2022) for more information. This table shows the extent of relevance of indicators related to each theme to resilience abilities (in %). As can be seen, the highest linkages to resilience abilities are to planning and absorption with 63% and 58%, respectively.

In contrast, only 34% and 25% are related to adaptation and recovery, respectively. Overall, these results show that smartness assessment indicators can, to some extent, also be used to evaluate the resilience abilities of cities and projects. There is clearly limited attention to recovery and adaptation abilities. Further research is needed to understand better why those abilities have not been well accounted for. One possible reason could be that the concepts of smart city and resilience city are relatively new and have often been undertaken in isolation from one another. More integrated approaches towards them are likely to help solve this issue.

Theme	Planning (%)	Absorption (%)	Recovery (%)	Adaptation (%)
Innovation	100	0	20	80
Knowledge economy	71	29	14	57
Entrepreneurship	50	67	33	67
Finance	50	50	33	33
Tourism	50	100	25	25
Employment	67	100	50	0
Local & Global Interconnectedness	14	86	86	0
Productivity and efficiency	43	71	57	14
Flexibility of the labor market	20	100	0	80
Impacts	100	33	0	0
Education/ lifelong learning	100	22	0	44
Level of qualification	100	43	29	0
Cosmopolitanism	33	33	0	100
Visioning and leadership	100	0	22	44
Legal and regulatory frameworks	100	0	0	100
Participation	100	0	86	29
Transparency	100	0	100	0
Public and social services	60	80	0	60
Efficient and integrated management	75	50	63	13
Environmental monitoring	71	71	14	43
General infrastructure	50	83	17	33

TABLE 8. Links between the themes and resilience abilities.

Theme	Planning (%)	Absorption (%)	Recovery (%)	Adaptation (%)
Built environment/	29	57	57	57
Materials	0	100	0	100
Energy	50	88	13	50
Water	33	78	11	67
Waste	25	100	0	75
Environmental quality	100	20	0	0
Social cohesion	43	71	86	0
Justice	33	67	83	0
Culture	60	80	40	0
Housing quality	33	100	67	0
Healthcare	18	91	55	36
Safety and security	38	100	0	0
Convenience and satisfaction	100	0	0	0
Transport infrastructure	33	78	0	89
Transportation management	58	92	0	100
ICT infrastructure	75	75	25	0
ICT management	83	67	0	17
ICT accessibility	100	100	0	0
Data openness	100	50	0	0
Sensing and collecting	100	80	20	0
Analytics	100	25	0	0
Reacting	100	0	0	0
Learning	0	0	0	100
Average	63	58	25	34

TABLE 8 continued. Links between the themes and resilience abilities.

4. CONCLUSION

Smart city initiatives, enabled by ICTs, have become ubiquitous in the past few years. By developing smart cities, planners and policymakers hope to, among other things, enhance the quality of life, improve the efficacy and efficiency of urban management, and provide solutions for complex societal challenges, such as the increase in the frequency and intensity of disasters. Assessment is argued to be an effective method to mainstream smart city principles into decision- and policy-making processes and to ensure achievement of the smart city objectives.

The main objectives of this study were to provide a comprehensive list of indicators that can be used for smart city assessment and to examine their potential linkages to four resilience abilities: planning/preparation, absorption, recovery and adaptation. The results show that smartness is a multi-dimensional concept and is beyond just technological development. Multiple indicators were introduced that are divided into seven major dimensions: economy, people, governance, environment, living, mobility and data. Obviously, achieving smartness is a challenging ambition and requires concerted efforts across multiple sectors and dimensions. As for operationalizing the introduced assessment framework, it should be noted that using a large list of indicators would not be realistic in most cases due to resource limitations. Therefore, it is suggested that interested stakeholders would consider the suggested list as a pool of indicators and select those that are relevant and context-specific. Some statistical methods, such as principal component analysis, can also be used to establish a more concise and manageable list of indicators.

As for connections to resilience, it was found that smart city indicators are linked to resilience abilities, particularly abilities to plan/prepare for and absorb shocks. This is not surprising as, for instance, early warning capacities facilitated by real-time monitoring and big data analytics can allow cities to better respond to shocks. However, results show that recovery and adaptation abilities are not well accounted for. It was suggested that this could be due to, often, isolated approaches to smartness and resilience. Adopting more integrated approaches is needed to achieve better alignment between smartness indicators and resilience abilities. Further dimension-specific research is needed to better understand through what specific mechanisms smart city indicators can inform resilience-oriented urban planning and management. As resilience is also characterized by multiple attributes such as robustness, stability, diversity, redundancy, resourcefulness, creativity, agility, flexibility, efficiency, self-organization, inclusiveness and foresight capacity, future research should also explore potential connections of smart city indicators to these attributes.

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Measuring forest ecosystem services in Aceh Province for inclusion to local forest resource management plans

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ABSTRACT

The project trained forest managers from Kesatuan Pengelolaan Hutan (KPH) and Social Forestry units in Aceh Province in forest resource data collection and the use of three tools that report important forest ecosystem services. Data were collected in systematic forest plots by local KPH staff and social forestry community members for measuring forest carbon, tree biodiversity and forest ecosystem health. Teams represented nine different forest ecosystems in Aceh Province, Indonesia. Average forest carbon estimates range from a low of 27.14 Mg C ha^{-1} in a coffee agroforestry system to a high of 446.93 Mg C ha^{-1} in a tropical forest area managed under social forestry. Tree biodiversity ranged from a low of one species as expected in a coastal mangrove forest to a high of 35 species in the tropical forest area managed under social forestry. Forest health conditions on average for the nine areas were mostly healthy, with a few noted in fair condition and one considered to be in poor condition. Resources provided at the local level would enable mainstreaming of field data collection for measuring these forest ecosystem services, and continued and expanded training should be considered to meet national demand.

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KEYWORDS

Ecosystem services, forest carbon, tree biodiversity, social forestry, sustainable forest management, forest management unit

HIGHLIGHTS

- Forest ecosystem services can be measured by local forestry staff and communities.
- Ecosystem services measurement tools enable improved forest management practices.
- Co-benefit of 18 students trained in ecosystem services tools and data collection.

1. INTRODUCTION

Indonesia has experienced the devolution of forest management through government policy and regulation in the past 20 years. Two mechanisms, in particular, are noteworthy. First, the creation of Forest Management Units (FMU or in Bahasa Indonesia, KPH, *Kesatuan Pengelolaan Hutan*) for watershed-scale sustainable forest management. Second, the promotion of Social Forestry under the Indonesian Ministry of Environment and Forestry (MoEF). KPH units were introduced to enhance state forest management goals and the units act as "intermediaries between local stakeholders and local and national government agencies [sic], which retain responsibilities for forest administration" (Lestari, 2020). According to the MoEF official KPH online database (http://kph.menlhk.go.id/ accessed Dec 1, 2021), there are a total of 688 KPH units in Indonesia, though some of these are planned only and not currently under active management. In addition to KPH local forest management system is a Social Forestry program in Indonesia, which include five different management schemes: village forests (*hutan desa*), community forests (*hutan kemasyarakatan*), community plantation forests (*hutan tanaman rakyat*), forestry partnerships (*kemitraan kehutanan*), and customary forests (*hutan adat*) (MoEF, 2016). According to Rakatama and Pandit (2020), social forestry schemes cover 1.8 million ha of forest land in Indonesia, with plans by the government to increase the area to 12.7 million ha by 2021 (MoEF, 2018).

Along with an emphasis on decentralized forest management, the Indonesian government identified the importance of environmental services in forest ecosystems as early as 2007. Government Regulation No. 6/2007 references the "utilization of environmental services" for KPHL (protection) and KPHP (production) forest units and identifies specifically biodiversity protection and carbon sequestration and storage (Government of Indonesia [GoI], 2007). KPHL and KPHP units are also required to develop 10-year long-term and 1-year short-term forest management plans that include management of environmental services. Social Forestry schemes in Indonesia are also required to develop similar forest management plans. The MoEF Directorate General of Social Forestry (PSKL) regulations give guidelines for preparing village forest management plans (GoI, 2016). Activities specified in the regulations include utilizing Non-Timber Forest Products (NTFPs) such as medicinal plants, the utilization of environmental services through ecotourism activities, and carbon storage and sequestration.

Challenges exist for KPH staff and Social Forestry community members in accurately collecting and reporting information specific to forest ecosystem services such as forest carbon, biodiversity, and the various forest resources that provide provisioning and cultural benefits to local people. Thung (2019) notes that while progress has been made by the Ministry of National Development Planning (BAPPANAS *Badan Perencanaan Pembangunan Nasional*),

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the agency responsible for developing KPHs in Indonesia, progress is slow due to several factors, including "lack of technical expertise and experienced staff". Wulandari, Budiono, and Ekayani (2019), in an assessment of the Impacts of the Decentralization Law 23/2014 on implementing community-based forest management in Lampung Province, Indonesia, analyzed qualitative data for several community forests (*hutan kemasyarakatan*) areas in four districts. One of the study's conclusions regarding a decrease in community accountability and participation prior to and after the changes in regulations was an "inadequate number of trained and professional staff". In a literature meta-analysis of social forestry opportunities and challenges in social forestry implementation in Indonesia, Rakatama and Pandit (2020) note several studies that recognize social forestry creates "environmental opportunities and positive impacts on the environment, as well as contribute to sustainable development", "improves community awareness of opportunities to protect forest areas from illegal logging and forest encroachment", help in "educing deforestation, maintaining biodiversity and conservation values, aiding biodiversity conservation and conserving and sustaining forests". They also found, however, that technical assistance provided by the government for managing forests "is limited and insufficient".

To support overcoming the deficiencies in training and skills required to measure forest ecosystem services and utilize this information in sustainable forest management plans, our team from Michigan State University, Universitas Syiah Kuala and Instiper (*Institut Pertanian STIPER*) developed a training program in three phases for KPH staff and local Social Forestry community members. The training program was implemented in Aceh Province, Indonesia (February to September 2021). This paper presents the results from field data collected in nine forest areas in Aceh. The data were analyzed using three Excel-based forest ecosystem services tools to compute forest carbon, tree biodiversity, forest integrity and health, and forest resources used as cultural and provisioning benefits by local people.

2. METHODOLOGY

2.1. Three Excel-based forest ecosystem services (ES measuring and monitoring tools)

Three Excel-based tools were developed under the USAID LESTARI project (2015–2020) by Michigan State University: a Forest Carbon (FC) tool, a Tree Biodiversity (TB) tool and a Forest Integrity Assessment (FIA+) tool that includes functions for assessing forest resources used for cultural and provisioning benefits by local people. The tools store and manage field-based measurement and observation data. The tools also automatically compute data based on the field data inputs.

2.1.1. FC tool

The FC tool consists of several tabs and includes tabs with user guidance, example data, a user-defined tree species inventory list of local and scientific names, plot data tabs and a synthesis reporting tab. Tree diameter-at-breast-height (dbh; 1.3 m above the ground) measurement data from nested fixed-area plots are input to the tool and are used to compute plot-level biomass carbon using allometric equations specific to the forest type and region (Table 1a). The FC tool includes seven different allometric equations that represent most of the forest types in Aceh Province. Tree height data are computed from three measurements recorded in the field: distance of the observer from the tree, height of the observer's eyes from the ground, and the protractor angle from the clinometer tool as the observer identifies the top of the tree. Tree height and dbh data are used to estimate the biomass volume (m^3) of trees in the plot (Table 1b). The number of trees recorded is used to compute the stem density (number of trees ha^{-1}) of the plot (Table 1c). The tool computes the average tons of carbon per hectare (Mg C ha^{-1}) for all plots where data are collected and estimates the total carbon stock of the forest area (Table 1d). The tool also reports error and confidence accuracies based on the variation of carbon in the plots, the size of the forest

a): *allometric equations for estimating tree biomass (kg) in different Aceh forest types for all trees greater than or equal to 5cm dbh*			
	Forest ecosystem	**Allometric equation**	**Biomass component**
	Tropical Dipterocarp (primary)[1]	AGB = 0.125*D^2.533	Above-ground live biomass
	Tropical Dipterocarp (secondary)[2]	AGB = -2.75 + 2.591 *lnD	Above-ground live biomass
	Peat Forest (primary)[2]	AGB = 0.0145*D^3 - 0.47*D^2 + 30.64*D - 263.32	Above-ground live biomass
	Peat Forest (secondary)[2]	AGB = 0.153108*D^2.40	Above-ground live biomass
	Mangrove (*Rhriz. apiculata*)[2]	AGB-BGB = 0.75*D^2.23	Above- and below-ground live biomass
	Mangove *(Rhriz. mucronata*)[2]	AGB-BGB = 0.5*D^2.32	Above- and below-ground live biomass
	Pinus[2]	AGB-BGB = 0.103*D^2.459	Above- and below-ground live biomass
Where	D = diameter-at-breast-height, 1.3 m above the ground (cm)		
	AGB = above-ground live biomass (kg)		
	AGB-BGB = above- and below-ground live biomass or total tree (kg)		
Citations	[1] (Manuri et al., 2016)		
	[2] (Krisnawati et al., 2014)		
b): biomass volume (m^3) equations for all trees greater than or equal to 5cm dbh			
	Biomass volume$_{tree}$	V_{tree} = ((1/4)*((PI*((D/100)^2))*H)*0.6)	
Where	V_{tree} = biomass volume (m^3)		
	D = diameter-at-breast-height, 1.3 m above the ground (cm)		
	H = Height of tree (m)		
	Biomass volume$_{plot}$	$V_{plot} = \Sigma V_{tree} / P_{ha}$	
Where	V_{plot} = biomass of the plot (m^3 ha^{-1})		
	P_{ha} = Size of the plot in terms of hectares		
c): stem density (number of trees ha^{-1}) for all trees greater than or equal to 5cm dbh			
	Stem density (trees ha^{-1})	$S = \Sigma_{treecount} / P_{ha}$	
Where	Tree count = total number of trees (stems) above 5cm dbh within the plot		
	P_{ha} = Size of the plot in terms of hectares		
d): biomass carbon (tC ha^{-1}) and (tC) for all trees greater than or equal to 5cm dbh			
	Biomass carbon (Mg C)	C_{tree} = (Biomass$_{tree}$ * CF) / 1000	
Where	Biomass$_{tree}$ = the tree dry-weight biomass in kg as estimated from an allometric equation (see part a of this table)		
	CF = equals the carbon fraction estimated at 0.50 * Biomass$_{tree}$ (IPCC default value in Penman et al., 2003)		
	Biomass carbon (Mg C ha^{-1})	tCha-1 = $\Sigma C_{tree} / P_{ha}$	
Where	C_{tree} = the carbon (Mg C) value of trees within the plot		
	P_{ha} = Size of the plot in terms of hectares		

TABLE 1. FC Tool computation equations.

area, and the sample size.

2.1.2. TB tool

The TB tool has a similar set of tabs as the FC tool. Plot inventory data are recorded for the number of each tree species greater than 5 cm dbh present in the largest of the nested fixed-area plots and seedlings species (less than 5 cm dbh) in the 2 x 2m subplots. Biodiversity indices are then computed that include species richness, Shannon index of species diversity, Simpson index of diversity, evenness, and abundance (Table 2). The same plot area used for the carbon tool data collection is also used for the biodiversity tool.

2.1.3. FIA+ tool

The FIA+ tool is a modified and adapted version of The Forest Integrity Assessment Tool (FIAT) developed by the High Conservation Value Resource Network (HCVRN). FIAT is a checklist and scoring tool used for assessing and monitoring biodiversity conditions in forests and forest remnants (Lindhe & Drakenberg, 2019). The modified encoded FIA+ data sheets in Excel include automatic computations and reporting. This tool is an essential complement to the TB tool, which tends toward a more scientific assessment. The FIA+ tool includes four sections for data observations: (1) forest structure and composition, (2) impacts and threats to the forest, (3)

Indices	Equation
Species richness	S = total number of species observed
Menhinick's Richness Index	D = S/(SQRT N)
Margalef's Richness Index	(S-1)/ln(N)
Shannon Index of Species Diversity	$H' = \sum[(pi) * \log(pi)]$
Simpson Index of Diversity	1 - D
Evenness Index	E = H'/lnS
Where	
S = total number of species observed	
N = the total number of individual organisms in the sample	
pi = Proportion of individuals of i-th species in a whole community	

TABLE 2. TB Tool Computation Equations.

the forest's focal habitats, and (4) the forest's focal species. We also include data collection tabs in the tool to document the forest resources used by local communities and households that are provisioning cultural services.

The FIA+ tool scores the presence or absence of 20 forest structure characteristics and evidence or absence of 20 observed impacts or threats to the forest ecosystem. The observations are recorded in each of the same plots where data are collected for the FC and TB tools. An average score is computed from the multiple plot FIA+ scores. Scores between 0–10 indicate the forest ecosystem is in poor condition; between 11–20, it is in fair health; between 21–30, it is mostly healthy; and between 31–40, it is very healthy. Focal habitats and species are also identified when present in a plot. Also noted is the presence of any forest resource species (flora or fauna) identified by local people as being utilized for provisioning or cultural needs.

2.2. Phased training program for KPH staff and Social Forestry community members

A three-phase training program was implemented to build the capacity of KPH staff and Social Forestry community members. Phase 1 training focused on: introducing participants to the fundamental concepts of ecosystems and ecosystem services, review of several scientific phenomena (carbon cycle, greenhouse effect, climate change), explanation of the five pools of measurable forest carbon, the use of allometric equations for measuring biomass, field measurements and sample plot designs for forest inventory, and a preview of the three ES tools.

Phase 2 was a field-based practicum where participants were given hands-on training in demarking fixed-area nested plots and collecting plot-level data for use in the three tools. Data collected included: tree dbh, measurements to compute tree height (distance from tree, angle of clinometer, height above ground to observer's eye level), tree species counts, seedling counts in 2x2 m plots, and FIA+ checklist observations.

After participant teams collected field inventory data, a Phase 3 training was convened and focused on understanding the results of the Tool analyses and how best to use each of the ES Tool's information for developing improved forest management plans.

2.3. Field data collection protocol

KPH and Social Forestry community teams collected field data for use in each of the three ES tools using a systematic protocol for plot sample locations, plot design and data collection procedures. Data collection teams ranged from 3 to 10 members.

Field plot locations were established on a regular grid pattern. Each plot was located at a minimum distance of 100 m from any forest edge and 50 m from rivers or streams. The plots were located at a minimum distance of 50m from each other. No plots were located in non-tree areas.

Field plots for the FC tool were three square nested plots in which specific diameter class trees were measured: 20 x 20 m plot for trees greater than

20 cm dbh, 10 x 10 m plot for trees less than 20cm and greater than or equal to 10 cm dbh, and 5 x 5 m plot for trees less than 10cm and greater than or equal to 5cm dbh. Seedling counts by species were recorded from two 2 x 2m plots located outside the 20 x 20 m plot. Within the three nested plots, tree species, dbh, and data for calculating tree height were recorded for all trees ≥ 5 cm dbh.

The same plot was used to also record data for use in the TB and FIA+ tools. Total tree species counts for all trees ≥ 5 cm dbh within the 20 x 20 m plot were recorded for the TB tool. Observations of forest structure, impacts, focal habitats, focal species as well as forest resources noted as used by local people for provisioning and cultural uses were recorded while standing inside the 20 x 20 m plot. All noted observances of these indicators and species within the plot or seen outside the plot while observing from inside the plot were noted.

Field data were recorded on paper field sheets and then input to the appropriate ES tool following data collection.

3. RESULTS AND DISCUSSION

KPH staff and Social Forestry community members collected data in nine forest areas in Aceh Province. The locations and extents of the nine forest areas are specific forest areas each training group manages as part of a KPH or social forest area. Table 3 is a summary table of the nine forest areas and Figure 1 shows their location with a centre point pin. The teams established a total of 83 field plots. The number of plots ranged from four in one of the mangrove areas to twelve in each of the two urban forest areas. The sampling area percent ranged from 0.10% in the largest forest area, Desa Agusen LPHD Gembuluh berkah, to 20.17% in the smallest forest area, Mangrove Telaga Tujuh.

3.1. Forest carbon and tree biodiversity in nine forest areas in Aceh Province

We summarize the forest carbon average (Mg C ha^{-1}) and total carbon stock (Mg C) listing the allometric equation used and the tree biodiversity species richness, evenness and dominant species for the nine forest areas in Table 4. The results from the FC and TB tools are what we would expect. Higher average carbon per hectare values in the tropical evergreen and mangrove forest types than in the coffee agroforestry or pine forest types. The range is from a high of 446.93 Mg C ha^{-1} in the tropical evergreen social forestry of HKm Rumah Rungkoh to a low of only 27.14 Mg C ha^{-1} in the young coffee agroforestry area. Also, low biodiversity in the mangrove and pine forests than what is measured in the tropical evergreen forests. HKm Rumah Rungkoh and the two urban forest areas, Kota Langsa and Kota Nagan Raya, are considered secondary tropical evergreen forest (35, 33 and 33 species richness, respectively, with evenness values close to 1: 0.86, 0.79 and 0.84). The evenness values close to 1 indicate that the forest is not dominated by just one or two species. The two mangrove areas and the pine forest area have very low species richness values, 1, 2 and 3 species only, and their evenness values are closer to zero, with the pine forest evenness the lowest at 0.06.

The overall forest carbon stock and tree diversity are important in general for a forest area, but perhaps equally important is the spatial variation of the forest carbon and tree diversity which is information that can be useful for forest resource management activities. Understanding the variation of carbon and tree biodiversity across the plots can assist in developing management plans and actions not just in general for the forest area as a whole but to specific areas within the forest itself.

Table 5 shows the range of carbon and species diversity for the nine forest areas. Again, as expected, the mangrove forest areas and also the pine forest areas have low species richness values and, therefore, the maximum-minimum range between plots is small (mangrove 1–3 species and pine 1 species). Noteworthy from these plot level species richness data in comparison to species richness of the forest areas as a whole are the tropical evergreen forests. While HKm Rumah Rungkoh and the two urban forests have species richness values greater than 30, none of the plots in

No	KPH / Social Forest / National Park	Forest Type	Area (ha)	Plots	Sample area %
1	HKm. Rumah Rungkoh	Primary tropical	105	10	0.38%
2	Desa Agusen LPHD Gembuluh berkah	Coffee agroforestry	382	10	0.10%
3	Hutan Kota Langsa	Trop. evergreen (Urban)	2.38	12	20.17%
4	Mangrove Telaga Tujuh	Mangrove	40	10	1.00%
5	Swamp Group	Swamp	1	5	20.00%
6	Pinus Group Reje Pudung/Terangun Gayo Lues	Pine	10	10	4.00%
7	Mangrove Group	Mangrove	72	4	0.22%
8	Coffee group KPH II	Coffee agroforestry	10	10	4.00%
9	Hutan Kota Nagan Raya	Secondary Trop. (Urban)	5	12	9.60%

TABLE 3. Nine forest areas in Aceh Province for Initial ES Assessment.

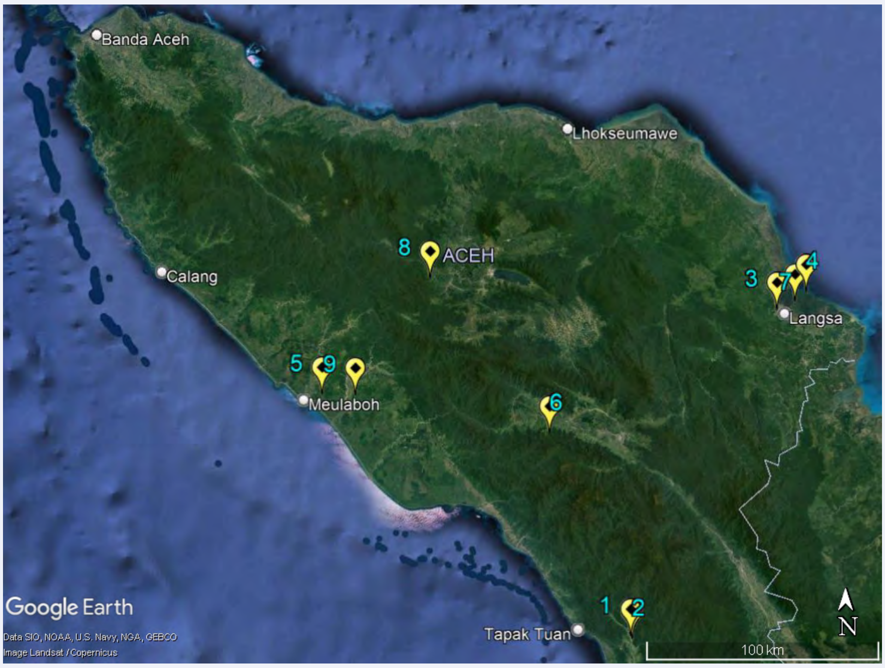

FIGURE 1. Location of Project Forest Areas. 1 = HKm. Rumah Rungkoh – Tropical Evergreen; 2 = Desa Agusen LPHD Gembuluh Berkah - Coffee Agroforestry; 3 = Hutan Kota Langsa – Secondary Tropical Evergreen Urban Forest; 4 = Telaga Tujuh KPH III – Mangrove; 5 = KPH IV – Swamp Forest; 6 = KPH V and PSDKU Gayo Lues – Pine; 7 = KPH III – Mangrove; 8 = KPH II – Coffee Agroforestry; 9 = Hutan Kota Nagan Raya – Secondary Tropical Evergreen Urban Forest.

any of these forest areas include 20 or more species. Some of the tree species, therefore, are present only in some of the plots. Furthermore, in the two urban forest areas, there is at least one plot in each forest area with only three species present and in HKm Rumah Rungkoh, only eleven species present. These forest areas, while overall having a high evenness value, are not uniform in their diversity across the landscape. This is true also for forest carbon. The range in plot-level carbon is greatest in one of the mangrove forest areas with a maximum-minimum value of 667.00 Mg C ha^{-1}. The forest area with the smallest range is the coffee agroforestry area, with a maximum-minimum range of only 36.78 Mg C ha^{-1} between plots.

3.2. Forest integrity and health in nine forest areas in Aceh Province

The FIA+ tool provides a more qualitative assessment of the health and integrity of the forest ecosystem scoring a forest by the presence or absence of specific attributes. These include attributes such as the presence of large trees or the absence of stumps which indicate impacts from logging. Teams from seven of the nine forest areas were able to collect field data for the FIA+ tool. The presence or absence of focal species in the forest

Forest Area & Allometric Equation Used	Mg C ha^{-1}	Total Carbon (Mg C)	Species Richness	Evenness	Dominant Species
HKm. Rumah Rungkoh / Tropical Dipterocarp (primary)	446.93	46,928	35	0.86	Sangkotan (*Buchanania auriculata*)
Desa Agusen LPHD Gembuluh berkah / Tropical Dipterocarp (secondary)	99.52	38,095	10	0.63	Kopi (*Coffee arabica*)
Hutan Kota Langsa / Tropical Dipterocarp (secondary)	119.07	238.39	33	0.79	Meranti seraya (*Shorea platyclados*)
Mangrove Telaga Tujuh / Mangrove (*Rhriz. apiculata*)	269.86	10,794	2	0.14	Bangka minyak (*Rhizophora apiculata*)
Swamp Group / Peat Forest (secondary)	121.53	121	10	0.59	Simpur (*Dillenia spp*)
Pinus Group Reje Pudung/Terangun Gayo Lues / Pinus	76.65	767	1	0.06	Pine (*Pinus merkusil*)
Mangrove Group / Mangrove (*Rhriz. apiculata*)[1]	240.91	17,345	3	0.43	Lindur (*Bruguiera gymnorrhiza*)
Coffee group KPH II / Tropical Dipterocarp (secondary)	27.14	271	12	0.78	Gamal (*Gliricidia sepium*)
Hutan Kota Nagan Raya / Tropical Dipterocarp (secondary)	70.74	353	33	0.84	Mane (*Vitex pubescens*)

[1] *Bruguiera gymnorrhiza* and *Rhriz. apiculate* are of the same botanical order and family.

TABLE 4. Forest carbon and tree biodiversity in nine forest areas, Aceh Province.

Forest Area	Forest Carbon (Mg C ha^{-1})		Tree Diversity (species richness)	
	Min	Max	Min	Max
HKm. Rumah Rungkoh	275.11	702.86	11	19
Desa Agusen LPHD Gembuluh berkah	45.66	82.44	2	7
Hutan Kota Langsa	28.69	340.37	3	9
Mangrove Telaga Tujuh	156.20	418.60	1	1
Swamp Group	81.59	188.41	3	4
Pinus Group Reje Pudung/Terangun Gayo Lues	22.22	210.27	1	1
Mangrove Group	15.94	682.94	1	3
Coffee group KPH II	5.00	93.02	1	4
Hutan Kota Nagan Raya	18.59	120.85	3	11

TABLE 5. Range of carbon and species richness in forest area plots.

area is also an indicator of a forest ecosystem's health. It is presumed that in highly degraded, poor forest ecosystems, there are few focal species. Since many faunae focal species can be difficult to observe directly, data collectors record the presence of a focal species through other means as well, such as a species nest, their call or song in the case of a bird, their marks as in the case of a sun bear, or their faeces. Table 6 includes the average, minimum and maximum FIA+scores at the plot level, the number of focal species observed and the number of observations for the focal species list.

The mangrove forest in Telaga Tujah has the highest average FIA+ score, followed closely by HKm Rumah Rungkoh, 32.7 and 30.8, respectively, out of a total of 40 points possible. Desa Agusen LPHD Gembuluh Berkah, a coffee agroforestry area, had the lowest score of 8.2, indicating a highly degraded forest, which is supported by the low number of focal species and observations of focal species, four and nine, respectively. HKm Rumah Rungkoh has 11 focal species present with 42 observations and the mangrove forest in Telaga Tujah has seven species with 62 observations. Hutan Kota Langsa also has 11 focal species present with 27 observations; however, this urban forest is also a zoo. Table 7 lists the focal species observed for each forest area.

Forest Area	FIA+ Score	Min	Max	Focal Species	Total Observances
HKm. Rumah Rungkoh	30.8	28	33	11	42
Desa Agusen LPHD Gembuluh berkah	8.2	5	10	4	9
Hutan Kota Langsa	25.5	20	32	11	27
Mangrove Telaga Tujuh	32.7	31	35	7	62
Mangrove Group	20.25	19	22	6	24
Coffee group KPH II	18.5	13	25	4	16
Hutan Kota Nagan Raya	24.92	18	29	4	10

TABLE 6. FIA+ data for seven forest areas in Aceh Province.

3.3. Carbon stock estimate accuracy and error

The limited number of plots in some of the forest areas and the wide variation in carbon values among these plots do impact the statistical accuracy for reporting carbon stock in the full forest area. The FC tool includes several metrics to understand the accuracy of the forest carbon stock estimates. Both the standard error and sample error are reported in the FC tool for the field plot inventory data. The FC tool also reports the lower and upper bound average Mg C ha^{-1} at the 95% confidence interval. These values are used to compute a lower and upper total carbon (Mg C) stock value along with the estimate computed from the average Mg C ha^{-1} for all plots. The tool also reports, based on the plot data input (given the standard and sampling errors, the mean, and standard deviation of the plot carbon (Mg C ha^{-1})), an estimated total number of plots to meet an accuracy of 95% confidence interval (CI) at 10%, 15%, and 20% error. Table 8 shows the two error values, mean plot carbon, upper and lower bound plot carbon, and the number of field plots together with the estimated number needed to meet an accuracy of 95% CI at 10%, 15% and 20% error for each of the nine forest areas.

The range of carbon values at the plot level is an obviously important factor. For any set of plots where the standard deviation is close to the mean carbon value, this, too, is an important factor. Only two forest area carbon estimates have a sufficient number of plots with low enough sampling and standard errors for accuracy at 95% CI and better than 15% error. These are Desa Agusen LPHD Gembuluh berkah and Pinus Group Reje Pudung/Terangun Gayo Lues. Two areas have an accuracy right at 95% CI and 20% error: HKm. Rumah Rungkoh and Mangrove Telaga Tujuh. The rest of the forest areas estimate carbon stock values with an accuracy of greater than 20% error at 95% CI. In the case of the mangrove forest with only four plots, there is such high variation in the plot carbon values that another 144 plots would be needed for an accuracy at 20% error, 95% CI (assuming no change to the mean carbon and standard deviation with the inclusion of the additional plots).

In the forest areas with fewer plots than required for significant accuracy, the lower bound estimate of carbon stock should be reported. It may also be prudent to stratify the forest area to help lower the variation of carbon at the plot level when estimating the forest carbon.

4. CONCLUSION

The results of data collection by KPH staff and Social Forestry community members and their training on the use of the three ecosystem services tools is a proof of concept that several aspects of locally managed forest ecosystems can be measured. Forest carbon, tree biodiversity, forest integrity and health can develop forest management plans and actions that sustain and protect these services. Repeat measurements every two to five years can be used to monitor the effectiveness of forest resource management activities and provide necessary data for updating management plans and actions. This utilization of forest ecosystem services information is beneficial to forest managers responsible for balancing resource preservation, ecosystem health and resource use and in developing management

Forest Area	Local Name	English Name	Scientific Name
HKm. Rumah Rungkoh	Cuca hijau	Bornean leaf bird	*Chloropsis kinabaluensis*
	Serindit	Blue crowned hanging parrot	*Loriculus galgulus*
	Dolar Bet	White chested babbler	*Trichastoma rostratum*
	Takur tohtor	Red crowned barbet	*Psilopogon rafflesii*
	Merbah Cerucuk	Yellow vented bulbul	*Pynonotus goiavier*
	Orangutan	Orang utan	*Pongo abelli*
	Kambing hutan	Wild goat	*Capra aegagrus hircus*
	Siamang	Sumatra lar Gibbon	*Hylobates lar vestitus*
	Cinenen	Ashy tailorbird	*Orthotomus ruficeps*
	Julang Emas	Wrinkled Hornbill	*Aceros corrugatus*
	Olva Sumatera	Sumatra lar Gibbon type 2	*Hylobates lar vestitus*
Desa Agusen LPHD Gembuluh Berkah	Elang	Eagle	*Haliastur indus*
	Burung kedi	Great knot bird	*Calidris tenuirostris*
	Monyet ekor panjang	Crab eating macaque	*Macaca fascicularis*
	Burung Elang	Eagle type 2	*Haliastur indus*
Hutan Kota Langsa (Includes a zoo)	Damar	Resin tree	*Agathis borneensis Warb*
	Burung bujuk/jalak	Starling	*Sturnus contra*
	Burung raja udang	Alcedo meninting	*Blue eared kingfisher*
	Burung perkutut	Western Spotted dove	*Spilopelia suratensis*
	Meranti Merah	Red meranti	*Shorea leprosula*
	Beringin	Fig tree	*Ficus benyamina*
	Biawak	Monitor lizard, Goanna	*Varanus salvator*
	Rusa	Deer	*Cervus unicolor*
	Kuda	Horse	*Equus ferus caballus*
	Kura-Kura	Freshwater tortoises / terrapins	*Batagur baska*
	Buaya	Saltwater Crocodile	*Crocodylus porosus*
Mangrove Telaga Tujuh	Monyet ekor panjang	Crab eating macaque	*Macaca fascicularis*
	Kelelawar	Bat	*Craseonycteris thonglonglay*
	Kepiting	Crab	*Ocypode quadrata*
	Kerang	Shellfish	*Anadara granosa*
	Siput	Snail	*Cornu aspersum*
	Cicak terbang	Flying lizards, flying dragons or gliding lizards	*Draco volans*
	Bangka minyak	Mangrove tree A	*Rhizopora apiculata*
	Bangka kurap	Mangrove tree B	*Rhizopora mucronata*
Mangrove Group	Monyet ekor panjang	Crab eating macaque	*Macaca fascicularis*
	Elang	Eagle	*Haliastur indus*
	Burung raja udang	Alcedo meninting	*Blue eared kingfisher*
	Kepiting	Crab	*Ocypode quadrata*
	Kerang	Shellfish	*Anadara granosa*
	Siput	Snail	*Cornu aspersum*
	Belangkas	Horseshoe Crab	*Carcinuscorpius rotundicauda*
Coffee group KPH II	Burung kuning	Hairy backed bulbul	*Tricholestes criniger*
	Tupai	Squirrel/treeshrew	*Tupaia glis*
	Burung ekor putih/kutilang	Sooty headed bulbul	*Pycnonotus aurigaster*
	Luwak	Mongoose/Asian palm civet	*Paradoxurus hermaphroditus*
Hutan Kota Nagan Raya	Burung prenjak	Bar winged prinia	*Prinia familiaris*
	Burung duit	White chested babbler	*Trichastoma rostratum*
	Burung tekukur	Spotted dove	*Spilopelia chinensis*
	Burung gereja	Sparrow	*Passer montanus*

TABLE 7. FIA+ focal species observed in the forest areas.

Forest Area	Standard Error	Sampling Error	Mg C ha^{-1} Mean	95% CI Lower Bound	95% CI Upper Bound
HKm. Rumah Rungkoh	43.88	3.35	446.93	431.95	461.92
Desa Agusen LPHD Gembuluh berkah	5.51	5.34	99.52	94.21	104.83
Hutan Kota Langsa	16.86	7.59	119.07	110.03	128.11
Mangrove Telaga Tujuh	26.54	4.32	269.86	258.2	281.51
Swamp Group	16.56	9.3	121.53	110.23	132.83
Pinus Group Reje Pudung/Terangun Gayo Lues	3.52	5.54	76.65	72.41	80.89
Mangrove Group	153.1	16.35	240.91	201.53	280.29
Coffee group KPH II	8.75	24.65	27.14	20.45	33.84
Hutan Kota Nagan Raya	8.38	9.01	70.74	64.37	77.12

Forest Area	No. of Plots	Plots for 95% CI at #% Error 10%	15%	20%
HKm. Rumah Rungkoh	10	38	17	10
Desa Agusen LPHD Gembuluh berkah	10	12	5	3
Hutan Kota Langsa	12	40	28	20
Mangrove Telaga Tujuh	10	38	17	10
Swamp Group	5	16	11	7
Pinus Group Reje Pudung/Terangun Gayo Lues	10	8	3	2
Mangrove Group	4	476	248	148
Coffee group KPH II	10	158	108	75
Hutan Kota Nagan Raya	12	46	26	16

TABLE 8. Confidence and error of carbon estimates.

plans that consider explicitly ecosystem services.

Two key factors impact the utility of measuring forest ecosystem services at the local level by KPH staff and Social Forestry community members. The first factor is allocating resources required to support field data collection. Data collection in forest ecosystems does not require expensive equipment, but it does take time and requires some specialized skilled labour for laying out nested plots, collecting tree biometric data, knowledge of local tree species and expert forest resource observation abilities. Teams of trained data collectors in certain forest conditions may only be able to complete data collection for one or two plots in a single day. Data allocation within large forest tracts may also require teams to hike several kilometres in adverse conditions (thick vegetation, heat, rain, steep topography, etc.). Funding data collection is a necessity to ensure enough plots are established to compute ecosystem services with some level of accuracy.

The second factor important for measuring forest ecosystem services is continued and expanded training for KPH staff and local people. This APN project was able to train 40 individuals from several KPH units and Social Forestry areas in Aceh Province. However, the need for these skills is national in Indonesia, with more than 600 KPH units planned and a goal of 12.7 million ha of lands under Social Forestry permits. Skills exist at several universities in Indonesia and through collaboration with non-national researchers and scientists outside of Indonesia that is sufficient to develop and implement a national training program for local forest managers at the KPH and community level. A training program scaled to the national level, however, will also require resources.

One final note of the value for this APN project beyond the forest ecosystem services results detailed in this technical report is one important and unexpected co-benefit. The implementation of the project through project collaborators at Universitas Syiah Kuala (USK) meant the opportunity also to train students at the undergraduate and graduate levels. Eighteen students from USK participated in data collection and training to use the tools and have included this in their academic education and research.

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Climate change scenarios over Southeast Asia

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ABSTRACT

Southeast Asia is one of the world's regions most vulnerable to climate change impacts with low-lying land, more severe floods and droughts, larger populations, higher dependency on agriculture for the economic sector, and low resilience of communities. Therefore, a study on how future climate change will affect this region has been conducted, and the results are provided in this paper. Projected surface temperatures and total precipitation from the baseline period of 2013 up to 2100 for Southeast Asia were investigated using the Global Climate Model (GCM) and the Weather Research Forecast (WRF) v3.9.1.1 modelling systems under RCP4.5 and RCP8.5 future climate scenarios. The results showed that future temperatures were projected to increase under both climate scenarios RCP4.5 and RCP8.5; however, precipitation was projected to decrease. The temperature was projected to increase by 0.93°C and 2.50°C under RCP4.5 and 8.5. Meanwhile, precipitation greatly varied under the RCP4.5 and RCP8.5 climate scenarios in both monsoonal seasons. We conclude that the change in climate variables, particularly the temperature and precipitation, could potentially increase the vulnerability of this region.

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KEYWORDS

Climate change, Southeast Asia, global climate model (GCM), weather research forecast (WRF), surface temperature, precipitation

HIGHLIGHTS

- Southeast Asia is at risk from climate change in the next 20 years due to the region's long coastlines, growing economic activities and population, abundant low-lying areas, and reliance on the agricultural sector, making the area under threat of climate change.
- Climate model simulations indicate that average annual temperatures are likely to increase across the Southeast Asia region by approximately 1°C through 2030 and will keep increasing throughout the century.
- The trends of future precipitation changes showed decrement patterns and varied geographically and temporally across the region in the next 20 years.

1. INTRODUCTION

Surface temperature in climate research has shown the most observable indications of variations arising from climate change. This is due to the availability of long observational records, a significant response to anthropogenic forcing, and a strong theoretical understanding of the key thermodynamic driving of its changes (IPCC, 2021). As strongly suggested in the synthesis report of Article 5 of IPCC (2018), it is highly likely that the observed increase in global mean surface temperature from early 1950 to 2010 has been caused by human activities (Flato et al., 2013; Shepherd, 2014; IPCC, 2021). Despite that, the rate of warming reduced from 1998 to 2012 due to strong aerosol cooling (Palmer & Stevens, 2019) and an overestimated warming rate (Golaz et al., 2019; Flynn & Mauritsen, 2020). In the Asian region, there is compelling evidence that there has been an increase in the intensity and frequency of extreme heat events and a decrease in the intensity and frequency of extreme cold events in recent decades (Alexander, 2016; Imada, Watanabe, Kawase, Shiogama, & Arai, 2019; Dunn et al., 2020). There is less to be argued for this as, according to Chen and Zhai (2017), Yin, Ma, and Wu (2018), and Qian, Zhang, and Li (2019), using regional studies in East Asia found that there was a warming trend in daily temperatures and an increase in extreme heat frequency since the beginning of the 20th century over the region. In west Asia, there is high confidence found in the studies of Erlat and Türkeş (2016), Imada et al. (2017), Rahimi-Moghaddam, Kambouzia, and Deihimfard (2018), and Rahimi and Hejabi (2018), suggesting that the frequency of cold events decreased but the warm season lengthened in most of the region.

The climate conditions in the SEA region can be categorized into two seasons: the winter season during the northeast monsoon and the summer season during the southeast monsoon (Rahman et al., 2015). The averages temperatures in Malaysia, the Philippines, and Thailand from 1971 to 2000 were in the range of 27.0°C to 27.8°C (Torsri, Octaviani, Manomaiphiboon, & Towprayoon, 2013), while the average temperatures in Cambodia, Vietnam, and Laos were in the range of 24°C to 28.4°C (World Bank, 2011). According to IPCC (2018) , the average surface temperature has increased by between 0.1°C and 0.3°C per decade across the SEA region. In April 2016, the SEA region's surface temperature, particularly for Cambodia, Laos, Myanmar, Thailand, Vietnam, and Peninsular Malaysia, surpassed the national record with an increment of over 2.0°C, caused by the strong El-Niño (Thirumalai, Dinezio, Okumura, & Deser, 2017). Global climate change has already had observable effects on Earth: sea ice

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loss, sea-level rise, intense heat waves, and coastal inundation. Although the global temperature will keep rising in the upcoming decade due to human activities, as suggested, the future evolution of the Earth's climate and its response to the present rapid rate of the increasing trend of CO_2 has no precise analogues in the past. It cannot be well understood through laboratory experiments (Hollis et al., 2019). To simulate the patterns, trends, and variability of surface temperature and the impact of human influence on changes in surface temperature, climate models have been used to reproduce large-scale climate variability over a time scale (McClymont et al., 2020).

Climate models are based on mathematical equations that represent the understanding of the fundamental laws of physics, chemistry, and biology that govern the behaviour of the atmosphere, oceans, land surface, ice, and other parts of the climate system. According to IPCC (2021), climate models need to represent the response of physical principles and the response of surface temperatures both to external forcing to be fit for detecting and simulating the impact of anthropogenic activities on global or regional surface temperatures over various time scales. A better understanding of climate uncertainties and the forcing applied to model simulation can lead to better simulation of surface temperatures and reconstruction of past climates (Haywood et al., 2020; Lunt et al., 2021) . Several different types of climate models can be used for climate change studies. Each model has different characteristics and functions that run on different climate scenarios and simulate projections of various parameters. The Global Climate Model (GCM) is primarily used to study weather and climate systems. With the climate forcing scenario, GCM can be used to investigate future climate behaviour (Lembo, Lucarini, & Ragone, 2020).

Furthermore, the construction of GCM is based on the physical properties of its components, interactions, and feedback processes that provide climate projections with a scale of a few hundred kilometres. Therefore, the output of this GCM is often in coarse resolution and inefficient at resolving complex terrains, islands, and coastlines (Jones, Forbes, Hagan, & Maute, 2014). Therefore, downscaling to a regional scale for higher resolution by a statistical and dynamic downscaling method using the Regional Climate Modelling (RCM) system was used for a more refined resolution model to overcome the limitations of GCM (Jeong, St-Hilaire, Ouarda, & Gachon, 2012; Sachindra, Huang, Barton, & Perera, 2014) . In addition, the primary purpose of this study is to establish the link between the climate change trends and the dynamics of Asian monsoon seasons and how it impacts the temperature and rainfall variability in the Southeast Asian region.

2. METHODOLOGY

2.1. Experimental design

The simulations were carried out in one nested horizontal domain in this study. The domain covered the Southeast Asia region, with 1-hour temporal resolution and 30 km x 30 km spatial resolution. The year 2013 was a neutral year for the El Niño–Southern Oscillation (ENSO) and was selected as the base year of the present-day simulation, and the future projection was for the years 2030, 2050, 2070, and 2100. The simulation was carried out for January and July of the selected years. For January, the projection started at 0000 UTC on the first of January and ended at 0000 UTC on the first of February. While for July, the projection time began at 0000 UTC on the first of July and ended at 0000 UTC on the first of August.

2.2. Dataset input: Initial boundary conditions

This study applied two time-dependent meteorological fields as initial and boundary conditions for the WRF model. For the present-day simulation, the time-dependent meteorological field was obtained from the global NCEP FNL (https://rda.ucar.edu/datasets/ds083.2), as mentioned. The NCEP FNL dataset consists of surface information with 26 mandatory levels (1000 millibars–10 millibars) of the surface boundary level. The meteorological parameters include the surface temperature, sea surface temperature, sea-level pressure, geopotential height, relative humidity, ice cover, vertical motion, vorticity, and winds (National Centers for Environmental Prediction, 1994). While for the future simulations, the NCAR's Community Earth System Model (CESM) from global bias-corrected climate model output datasets (Hurrell et al., 2013) was used and was obtained from (https://rda.ucar.edu/datasets/ds316.1). These future initial and boundary condition information were then downscaled into 30 km x 30 km resolution to fit for regional projection using the WRF model. In support of Coupled Model Intercomparison Experiment Phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012) and the Intergovernmental Panel on Climate Change Fifth Assessment Report (Flato et al., 2013), the CESM simulations, therefore, were utilized to produce future-day simulation, which has a better agreement in simulating temperature and precipitation globally compared with real-time observations (Knutti, Masson, & Gettelman, 2013).

2.3. Climate change scenarios

This study utilizes the climate change scenario that the IPCC developed in their Fifth Assessment Report (Flato et al., 2013). The climate change scenario provides more comprehensive external forcing scenarios and higher resolution than CMIP3 from IPCC AR4 (Knutti & Sedlacek, 2013). In this study, only two climate scenarios were used and discussed, namely the RCP4.5 and RCP8.5. The RCPs are input for climate and atmospheric chemistry modelling that documents the emissions, concentrations, and land-cover change projections. The four RCPs (RCP2.6, 4.5, 6.0, and 8.5) reflect the year 2100 greenhouse gas radiative forcing values from 2.6 to 8.5 Wm^{-2} (Nazarenko et al., 2015). The RCPs include the lowest forcing level scenario RCP2.6 (Van Vuuren et al., 2011), two median range or stabilization scenarios RCP4.5 (Thomson et al., 2011) and RCP6.0 (Masui et al., 2011), and the high-end or business-as-usual scenario RCP8.5 (Riahi et al., 2011). The future scenario of RCP4.5 applied in this study is a low-to-moderate emission scenario, where the greenhouse gases (GHGs) radiative forcing will reach 4.5 Wm^{-2} by the year 2100 (Thomson et al., 2011). It represents a scenario where various adaptive policies have been applied to limit the radiative forcing. At the same time, RCP8.5 indicates a higher emission scenario with GHGs radiative forcing that will reach 8.5 Wm^{-2} by the year 2100 (Riahi et al., 2011).

2.4. Climate model evaluation

Most researchers apply dynamical downscaling by RCMs from GCMs due to the uncertainties embedded within the GCMs, especially when resolving complex terrain (IPCC, 2001). Moreover, the error of GCMs with large-scale resolution can be transmitted to the RCM (Noguer, Jones, & Murphy, 1998). As a result, the validation or evaluation process is necessary for RCM, downscaled from GCMs before using it for the climate projection. The evaluation was carried out with observation datasets from the Climate Research Unit (CRU), University of East Anglia. The dataset spaced at $0.5^\circ \times 0.5^\circ$ resolution contained with full-set monthly mean surface climate (Harris, Jones, Osborn, & Lister, 2010). Since the spatial resolution and grid location between model and observation datasets are different, they are bilinearly interpolated into the same 30 km x 30 km grid covering the study area. To evaluate the model's performance, we used averages of only inland data from observation and model and used the following statistical techniques.

$$Normalized\ Mean\ Bias\ (NMB) = \sum_1^N (Sim - Obs) / \sum_1^N (Obs) \times 100\% \tag{2.1}$$

$$Fractional\ Bias\ (FB) = 2 \times \left(\frac{\sum_1^N (Sim - Obs)}{\sum_1^N (Sim + Obs)}\right) \tag{2.2}$$

$$Normalized\ Mean\ Square\ Error\ (NMSE) = \frac{\sum_{i=1}^n (obs - sim)^2}{\sum_{i=1}^n (obssim)} \tag{2.3}$$

$$A\ factor\ of\ two\ (Fa2) = Fraction\ of\ data\ which\ 0.5 \le \frac{sim}{obs} \le +2.0 \tag{2.4}$$

The selected statistical tests for this purpose were the FB (fractional bias test), NNM (normalized mean bias), and Fa2 (factor of two), referring to Zhang, Vijayaraghavan, Wen, Snell, and Jacobson (2009); Ojha and Kumar (2010); Penrod, Zhang, Wang, Wu, and Leung (2014) .These statistical tests evaluate a system error in the WRF climate variable compared with the real-time observation, represented in a number of their corresponding simulations (Sentian, Mackenzie, & Hewitt, 2009). These statistical analysis methods lie between a range of value of 4-8% for NMB, indicating a minimal error, $-0.5 \leq 0 \leq +0.5$ for FB, indicating a typical difference between observations and the model predictions, and smaller or close to zero NMSE value indicating model performance, and $0.80 \leq$ Fa2 ≥ 1.4 for Fa2 which represent a percentage of predictions within a factor of two of the observed values. Fa2 is the most robust statistical indicator and the ideal value for the factor of two is 1 (100%), which indicates an ideal or perfect simulation.

3. RESULTS AND DISCUSSION

3.1. Surface temperature

Under RCP4.5, the simulated mean surface temperatures in the SEA region for January of 2013, 2030, 2050, 2070, and 2100 were 22.88°C, 22.51°C, 23.48°C, 23.25°C, and 23.70°C respectively. In July, the mean surface temperatures for the same period were 26.66°C, 26.88°C, 27.43°C, 27.18°C, and 27.59°C, respectively (Table 1). Although the mean surface temperature was simulated to be colder during January 2030 (with a reduction of 0.37°C), the average surface temperature was projected to increase by 0.60–0.82°C during January and by 0.77–0.93°C during July in 2050 and 2100. During January of mid-century, the mainland SEA records a higher temperature change as Cambodia and Thailand set the highest temperature increment with 4.6°C (28.24°C to 32.96°C) and 4.7°C (from 22.08°C to 26.29°C), respectively (Figure 1). Both Myanmar and Laos experienced less significant warming of 0.89°C (from 16.24°C to 17.14°C) and 2.86°C (from 22.83°C to 26.84°C) during the mid-century and became colder at the end of the century with a reduction in the temperature of -5.17°C and -5.14°C, respectively. The mean average surface temperature anomaly toward the end of the century is less pronounced for other SEA countries except for Thailand, which is expected to become colder by 4.49°C.

However, during July, the mainland SEA showed a decrement in temperature, while the maritime continent of SEA showed an increment, most notably over the Indonesia region (Figure 2). In 2050, a decrement of 0.28°C (from 30.26°C to 29.98°C) in Vietnam and 0.24°C (from 23.82°C to 23.58°C) in Myanmar were observed. On the other hand, Indonesia showed a significant increment in temperature among SEA countries of 0.83°C (2030), 1.02°C (2050), 1.43°C (2070), and 1.64°C (2100), respectively. Additionally, the result from RCP4.5 also suggests that the surface temperature in mainland SEA is more varied during January compared to July for the entire simulation period. The climate of mainland SEA has a tropical maritime forcing; thus, there is not much surface temperature difference during the dry season (Nguyen, Shimadera, Uranishi, Matsuo, & Kondo, 2019). The tropical forcing (which is a part of global circulation) is an important element that helps to regulate the temperature of mainland SEA by transporting warm air (and replacing them with colder air from the western pacific) into higher latitudes, most notably during the monsoon season (Loo, Billa, & Singh, 2015).

The average mean surface temperature under RCP8.5 for January of the years 2013, 2030, 2050, 2070, and 2100 are 23.29°C, 22.95°C, 23.09°C, 24.65°C, and 25.40°C, respectively.

While in July, the mean surface temperature for the respective same year is 26.63°C, 27.39°C, 27.62°C, 28.51°C, and 29.13°C, respectively (Table 2). Like RCP4.5, surface temperature projection under RCP8.5 showed a drop in mean surface temperature in January with a decrement of -0.34°C in 2030 and -0.20°C in 2050. The spatial distribution of surface temperature simulation under RCP8.5 is shown in Figure 3 and Figure 4 for January and July, respectively. The results depict that during January, an increment of surface temperature con-

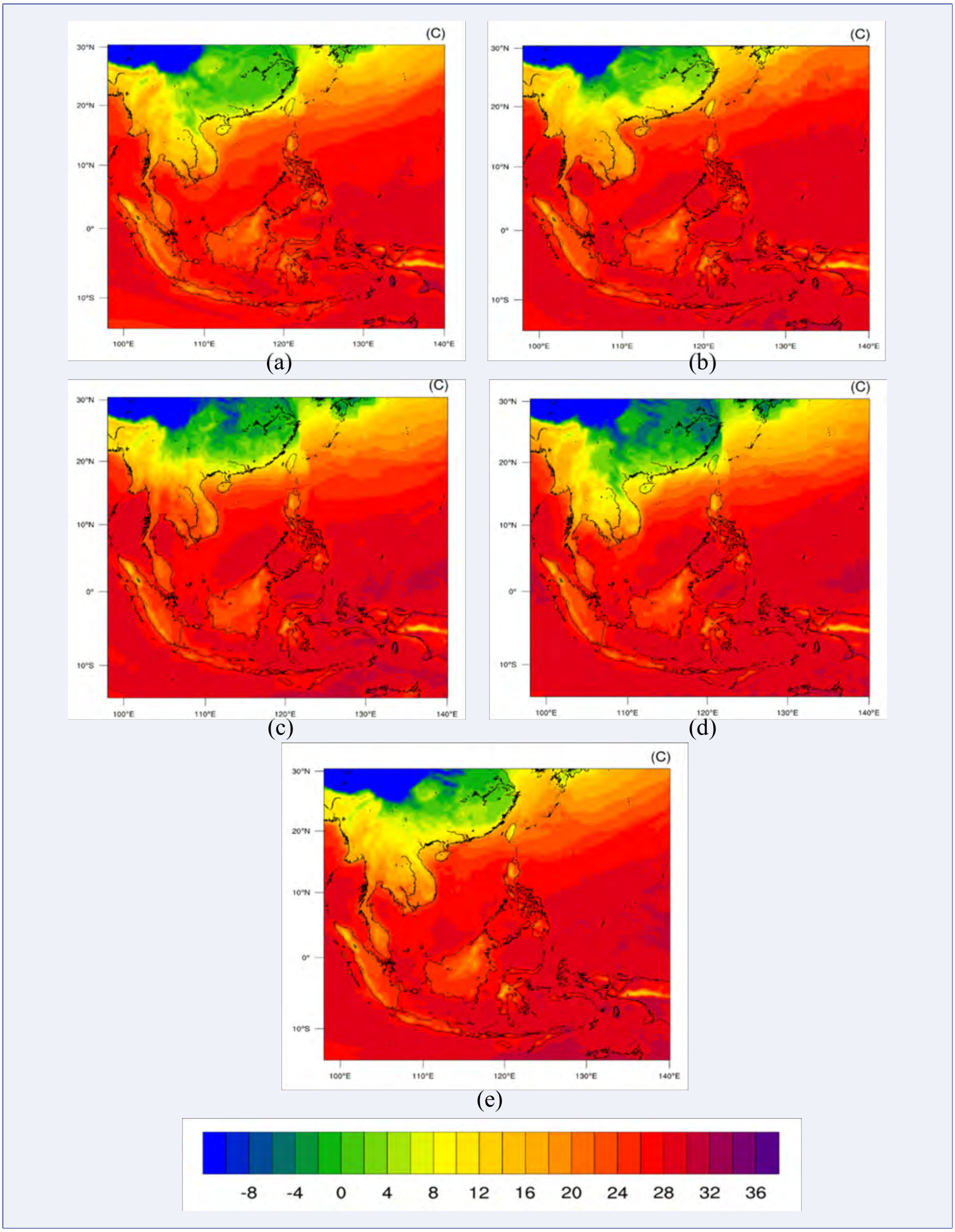

FIGURE 1. Mean surface temperature for SEA region under RCP4.5 during January of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

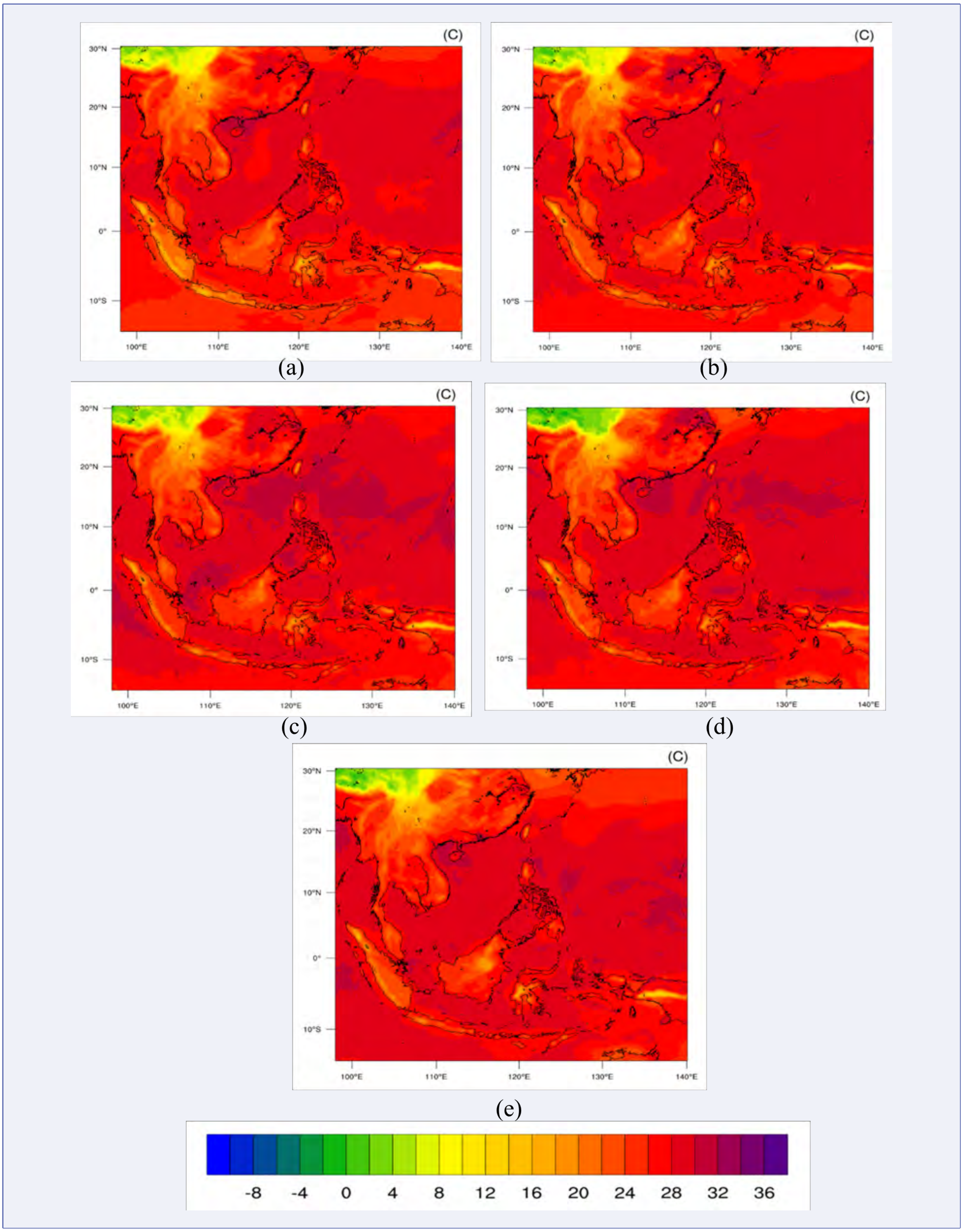

FIGURE 2. Mean surface temperature for SEA region under RCP4.5 during July of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

Year	Month	Surface Temperature (°C)	Changes (°C) / (%)
2013	January	22.88	-
	July	26.66	-
2030	January	22.51	-0.37 / (-1.62)
	July	26.88	0.22 / (0.83)
2050	January	23.48	0.60 / (2.62)
	July	27.43	0.77 / (2.89)
2070	January	23.25	0.37 / (1.62)
	July	27.18	0.52 / (1.95)
2100	January	23.70	0.82 / (3.58)
	July	27.59	0.93 / (3.49)

TABLE 1. Mean surface temperature of SEA under RCP4.5.

centrates over the SEA mainland region during mid-century, with Laos recording the highest temperature increment of 5.74°C (from 21.84°C–27.60°C), followed by Vietnam with 4.29°C (from 22.87°C–27.16°C), Thailand 4.18°C (from 25.46°C–21.28°C) and Cambodia 3.25°C (from 28.27–31.52°C). However, toward the end of the century, the mainland SEA becomes colder while the maritime continent (Indonesia, the Philippines and Malaysia) became warmer with an increment of between 1.63°C and 2.45°C. Seasonal monsoon changes over the region could be responsible for the temperature anomaly during the mid-and end of the century, as discussed by Loo et al. (2015) and Zhou et al. (2009).

Whereas in July, there was no notable increase in overall mean surface temperature in SEA countries, but the result of the RCP8.5 simulation expected that it would be colder in mid-century with temperature anomalies of -3.50°C in Thailand (from 28.90–25.40), -3.32°C in Laos (from 30.97°C–27.65°C), and -2.15°C over Vietnam (from 31.36°C–29.21°C). Towards the end of the century, the result of RCP8.5 simulations projected that Malaysia, the Philippines, Thailand, and Myanmar would experience warmer changes in temperatures ranging from 1.75°C to 2.28°C. The mainland SEA countries, especially Myanmar, Thailand, Vietnam, Laos and Thailand influenced by the large-scale seasonal reversals of wind regimes (Serreze & Barry, 2011). The two regimes of monsoon are the Southeast Asian summer monsoon (10°–20°N) and the western North Pacific summer monsoon (10°–20°N, 130°–150°E), which are separated by the South China Sea (Kripalani & Kulkarni, 1997). During winter, the tilting of the Earth allows less solar radiation in the northern hemisphere, and this resulted in rapid cooling followed by a pressure decrease in the atmosphere (Loo et al., 2015). Anticyclones develop over Siberia and the cold northeasterly air reaches the coastal waters of China before heading towards Southeast Asia (Malaysian Meteorological Department, 2013).

During the mid-century, there were high-temperature change anomalies projected over the sub-continent region in mainland SEA ranging from 0.88°C to 4.71°C and -3.32°C to 5.74°C under RCP4.5 and RCP8.5, respectively. Meanwhile, the maritime region would experience warmer temperature changes from 0.41°C to 1.16°C and 0.38°C to 0.98°C under RCP4.5 and RCP8.5, respectively. The simulation results also showed a higher temperature increment over the sub-continent region as compared to the earlier finding by Raghavan, Hur, and Liong (2018), which reported increasing between 0.8°C and 1.4°C under both RCP4.5 and RCP8.5 scenarios. However, an earlier study by Gasparrini et al. (2017) has projected a higher increment of between 3.5°C and 4.5°C at the end of the century for this region. Owing to the uncertainty associated with anticipated temperature changes across climate models and extrapolated climate–response relationships, the estimates of the net surface temperature change over this region might be hampered by poor precision, particularly in places projected to undergo a significant shift in

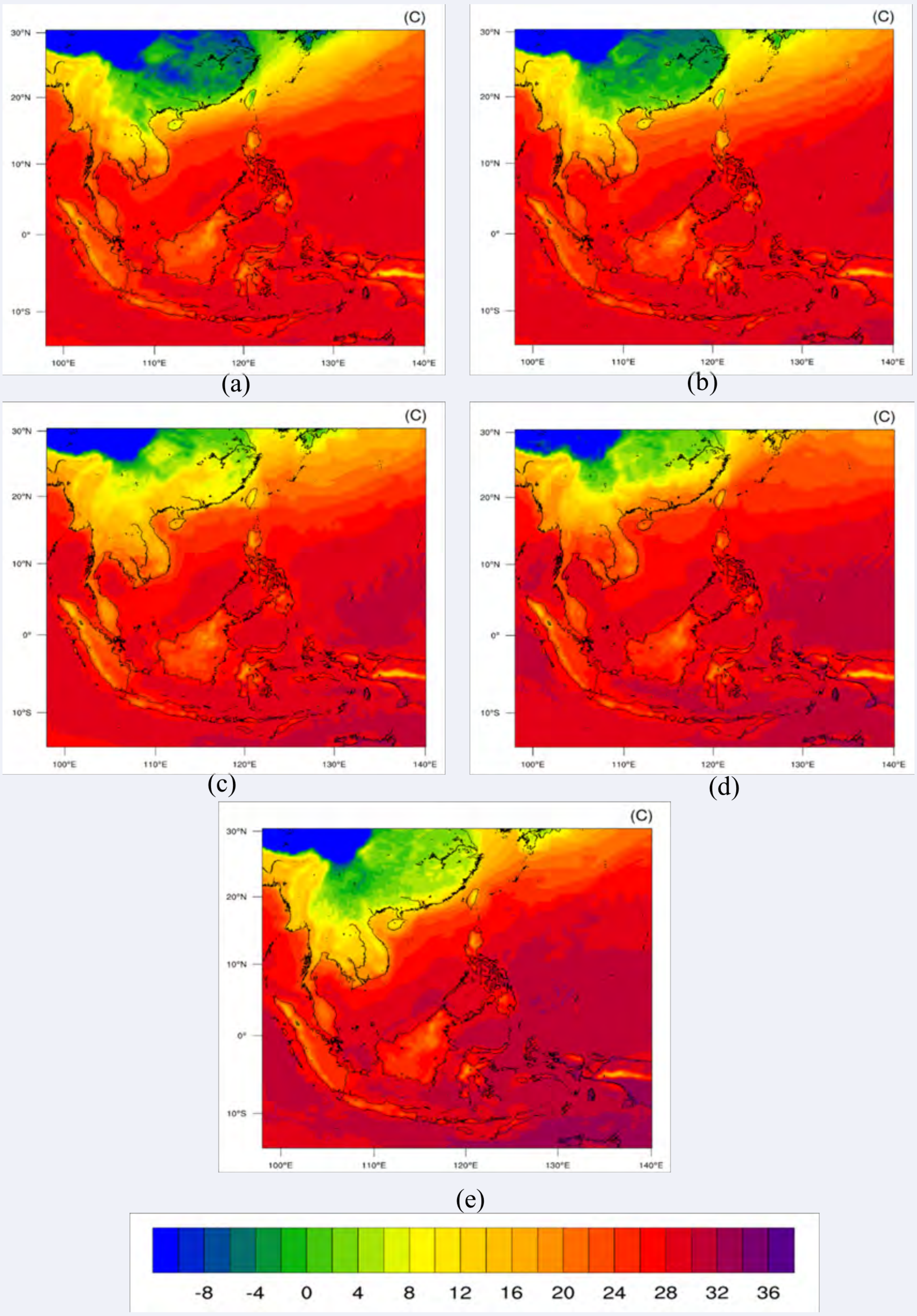

FIGURE 3. Mean surface temperature for SEA region under RCP8.5 during January of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

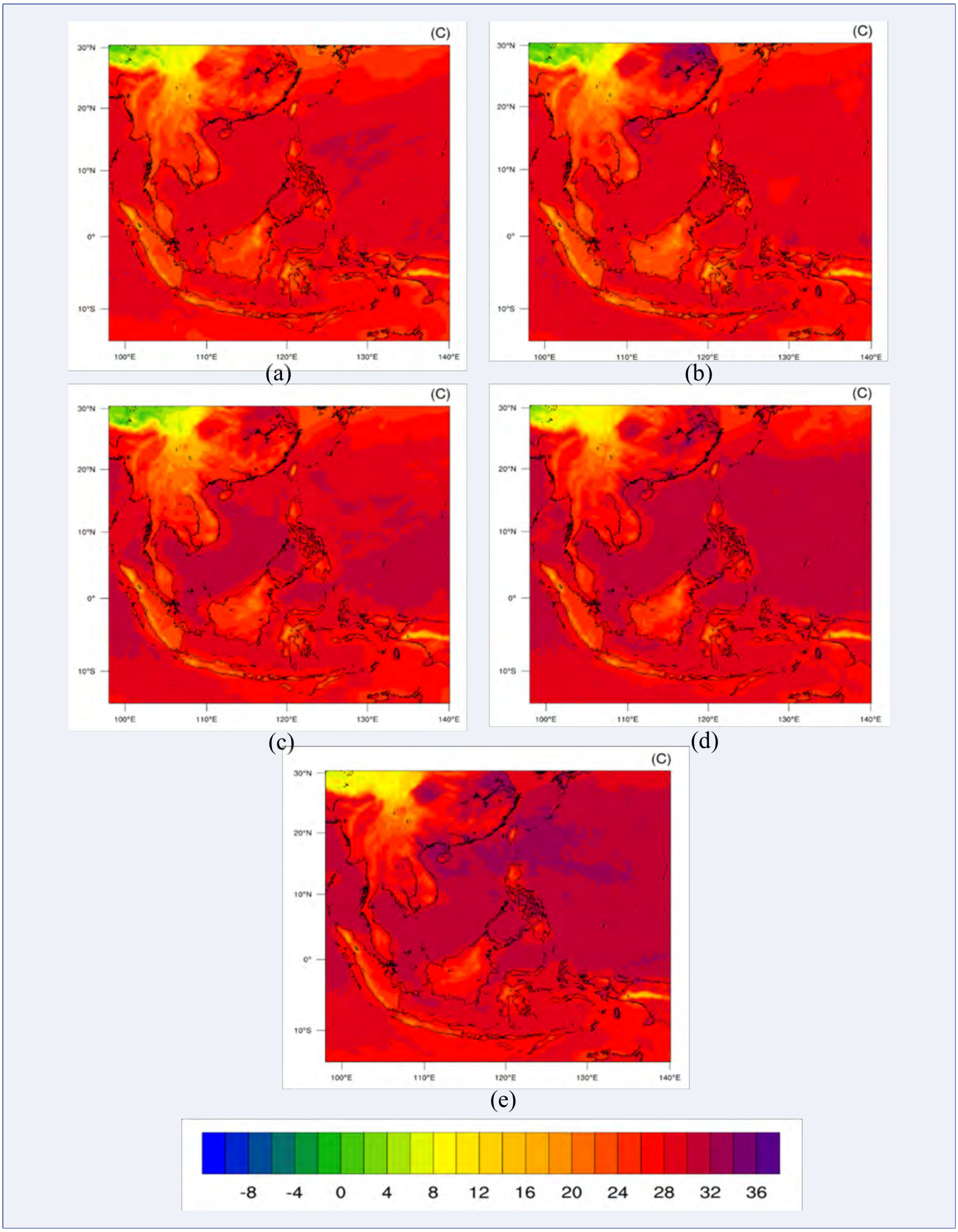

FIGURE 4. Mean surface temperature for SEA region under RCP8.5 during July of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

Year	Month	Surface Temperature (°C)	Changes (°C) / (%)
2013	January	23.29	-
	July	26.63	-
2030	January	22.95	-0.34 / (-1.45)
	July	27.39	0.76 / (2.85)
2050	January	23.09	-0.20 / (-0.86)
	July	27.62	0.99 / (3.72)
2070	January	24.65	1.36 / (5.83)
	July	28.51	1.87 / (7.03)
2100	January	25.40	2.11 / (9.05)
	July	29.13	2.50 / (9.37)

TABLE 2. Mean surface temperature of SEA under RCP8.5.

temperature (Almazroui et al., 2020; Dieng et al., 2022) .

3.2. Total precipitation

Under RCP4.5, the simulated monthly mean total precipitation in the SEA region for January 2013, 2030, 2050, 2070, and 2100 were 12.57 mm, 80.30 mm, 13.87 mm, 155.63 mm and 135.66 mm, respectively. In July, the mean surface temperatures were 100.53 mm, 90.40 mm, 169.94 mm, 120.23 mm and 90.76 mm, respectively (Table 3). Precipitation analyses under the RCP4.5 scenario showed that the total precipitation of July was higher than January in 2030. The total precipitation projection under RCP4.5 showed changes in the monthly mean of 1.29 mm to 123.08 mm during the January period and between 69.40 mm to -9.76 mm for the July period during the mid-and end-century, respectively. The spatial distributions of projected total precipitation under RCP4.5 are shown in Figures 5 and 6. The results show that total precipitation increments are concentrated over the insular region during January, with pronounced increments after the mid-century. Yet the total precipitation shifted to show an increment over the mainland SEA region during the July period despite having the signal reduced toward the end of the century. As depicted in Figure 5, Indonesia showed the highest total precipitation changes from 41.3 4 mm–284.24 mm, followed by Malaysia with 6.73 mm–225.24 mm and the Philippines from 3.08 mm–184.22 mm during the mid-century and end-of-century periods, respectively. The mainland SEA region only showed a significant increment at the end of the century, with Myanmar setting the highest total precipitation with 242.24 mm, followed by Cambodia (269.45 mm), Laos (160.81 mm) and Vietnam (146.42 mm).

In July, the total precipitation was simulated to increase over the whole domain area relative to the baseline period. Toward the end of the century, mainland SEA was expected to have a higher amount of precipitation than the insular region during the July period. The entire area receives the most increased total precipitation in 2050, with an increment of 69.40 during the mid-century and a reduction by 9.76 mm at the end of the century. The highest precipitation was observed over Myanmar, with monthly precipitation during July ranging between 131.91 mm–277.39 mm before decreasing to 147.15 mm–177.94 mm at the end of the century. Meanwhile, the rest of the mainland SEA region showed an increment of monthly total precipitation between 62.87 mm–202.92 mm before decreasing by 62.87 mm–105.86 mm at the end of the century (Figure 6). The seasonal total precipitation under the RCP4.5 simulation, particularly during January, was highly varied, especially over Malaysia, Indonesia and the Philippines. The high rainfall over these regions might be caused by the monsoonal winds that transport moisture from the South China Sea and enhance convergence, as discussed in Tangang, Chung, and Juneng (2020). Moreover, the high total rainfall, particularly over Malaysia and Indonesia, may also be influenced by the existence of the synoptic Borneo Vortex (Chen, Yen, & Matsumoto, 2013) and the moving oscillation

Year	Month	Total Precipitation (mm)	Changes (mm)
2013	January	12.57	-
	July	100.53	-
2030	January	80.30	67.72
	July	90.40	-10.12
2050	January	13.87	1.29
	July	169.94	69.40
2070	January	155.63	143.05
	July	120.23	19.69
2100	January	135.66	123.08
	July	90.76	-9.76

TABLE 3. Monthly mean total precipitation of SEA under RCP4.5.

of the Indian Ocean as known as Madden Jullian Oscillation (MJO) (Saragih, Fajarianti, & Winarso, 2018). The MJO and Borneo Vortex phenomena cause this area to become an active area of deep convection associated with heavy rainfall, especially during the wet season.

Under the RCP8.5 scenario, the monthly total precipitation in January for SEA was generally lower toward the end of the century compared with the RCP4.5 scenario. The mean total precipitation for January of 2013, 2030, 2050, 2070 and 2100 was projected at 92.98 mm, 169.68 mm, 84.82 mm, 16.10 mm, and 118.79 mm, respectively. While in July, the monthly total precipitation for the respective years was larger than under RCP4.5 simulation but showed a decreasing trend toward the end of the century with total simulated values of 248.86 mm, 258.96 mm, 245.77 mm, 218.25 mm and 92.42 mm, respectively (Table 4). Toward the end of the century, there was no significant increment of total precipitation over mainland SEA during January. However, from spatial distributions of projected total precipitation under RCP8.5 (Figure 7), there was considerable increment over the insular region, particularly toward the mid-century, with the highest increment of total precipitation observed in Indonesia (from 319.33 mm to 332.53 mm) followed by Malaysia (from 215.73 mm to 238.16 mm) and the Philippines (from 135.74 mm to 158.81 mm). A slightly lower marginal increment was observed over the same region toward the end of the century, with total precipitation of 256.67 mm, 51.57 mm, and 193.41 mm for Indonesia, Malaysia and the Philippines.

The analyses of total precipitation during the July period (Figure 8) revealed a significant increment of simulated precipitation over mainland SEA despite having the signal reduced toward the end of the century. Myanmar received the highest amount of rainfall with 388.71 mm in 2013, 294.04 mm in mid-century and 85.92 mm at the end of the century. Other regions in mainland SEA showed total precipitation ranging between 209.61 mm–256.06 mm in 2013, 236.46 mm–295.16 mm during mid-century and between 47.38 mm–105.56 mm at the end of the century. Although the insular region follows the same pattern, the simulated total precipitation over the Philippines was an all-time high with 316.57 mm in 2013, 273.27 mm in mid-century and 126.11 mm at the end of the century. In contrast, Indonesia and Malaysia are projected to receive a higher rainfall rate during July by the middle of 91.93 mm and 201.25 mm, but a lower rate at the end of the century, with total rainfall of 9.86 mm and 38.08 mm, respectively. The average surface temperature and total precipitation are recorded as higher anomalies under RCP8.5. These results suggest that significant changes, particularly in the surface temperature and precipitation, could potentially increase this region's climate-related risks and vulnerability.

The simulated total precipitation in this study was significantly different from the finding of Tangang et al. (2020) using the CORDEX-SEA multi-model simulation. Their study concluded that the robust significance of total precipitation reduc-

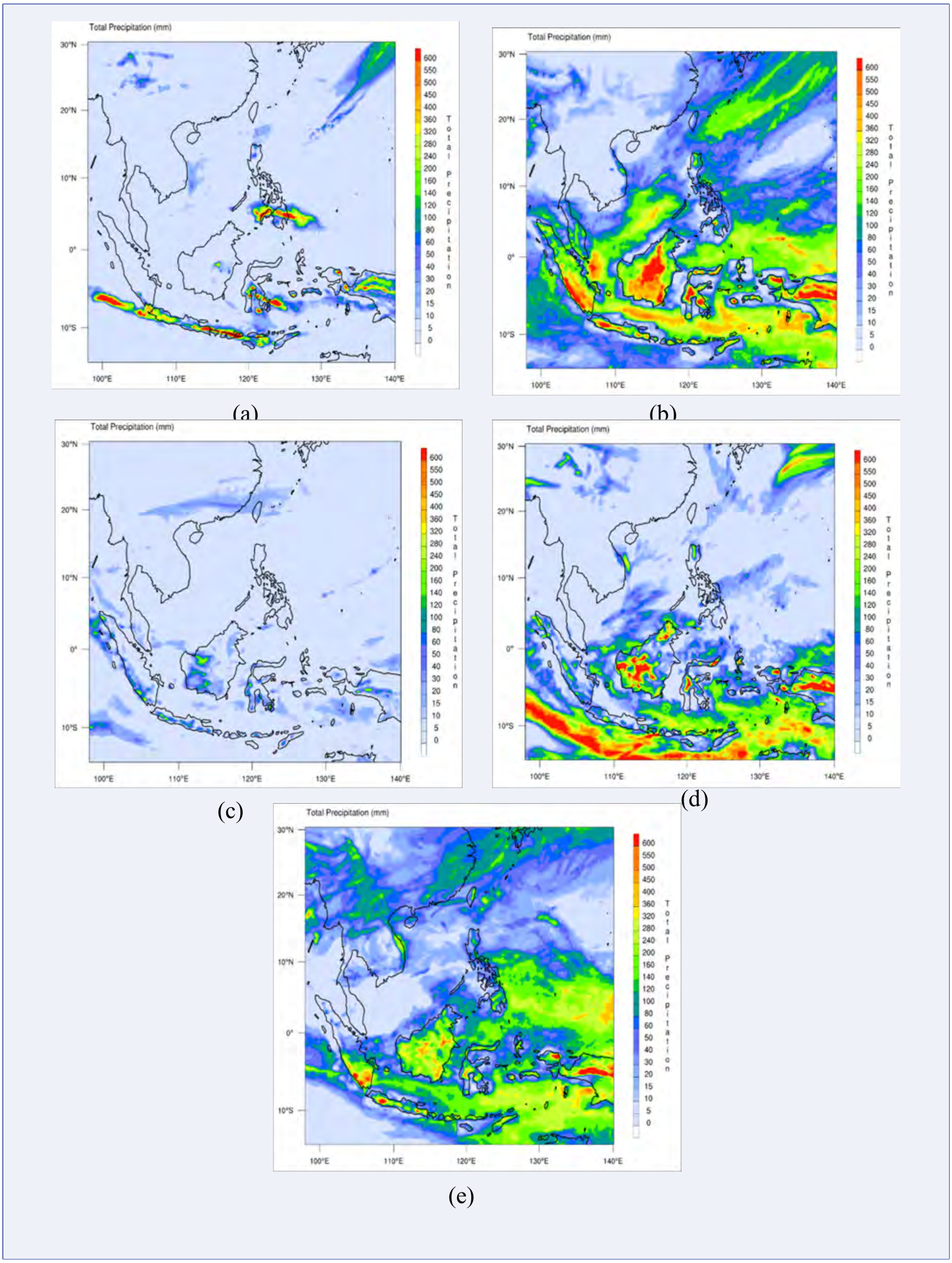

FIGURE 5. Total Precipitation for SEA region under RCP4.5 during January of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

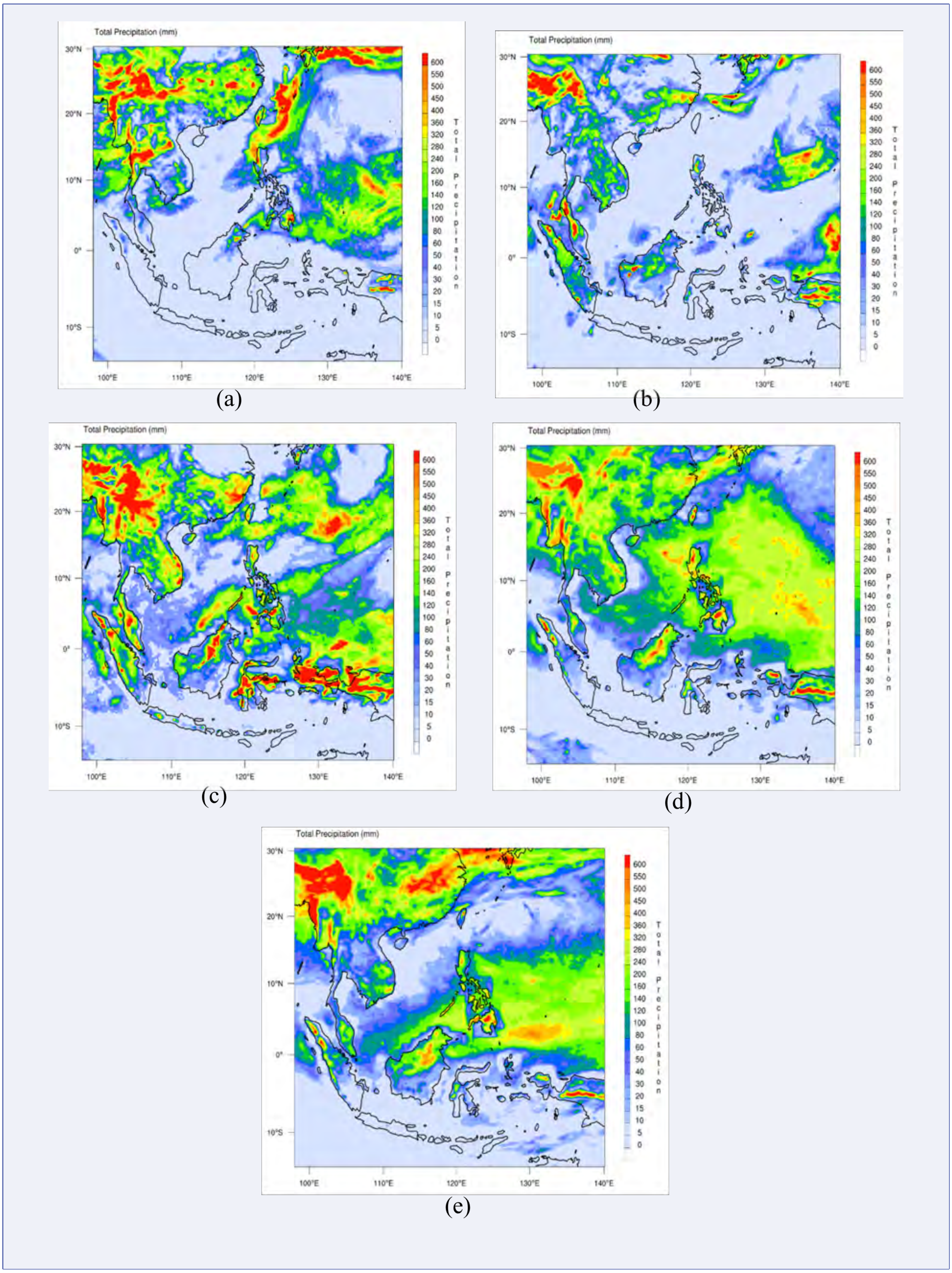

FIGURE 6. Total Precipitation for SEA region under RCP4.5 during July of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

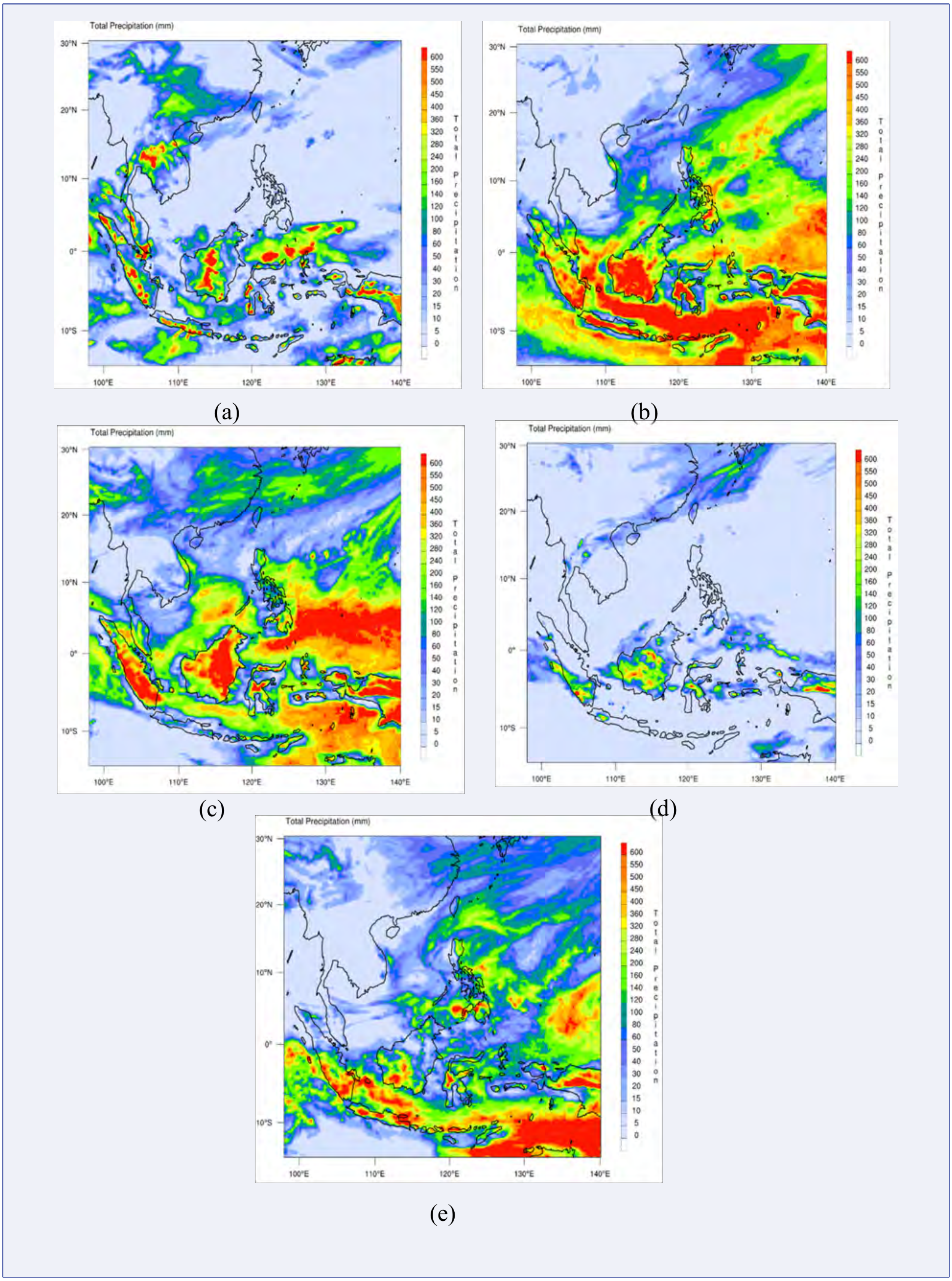

FIGURE 7. Total Precipitation for SEA region under RCP8.5 during January of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

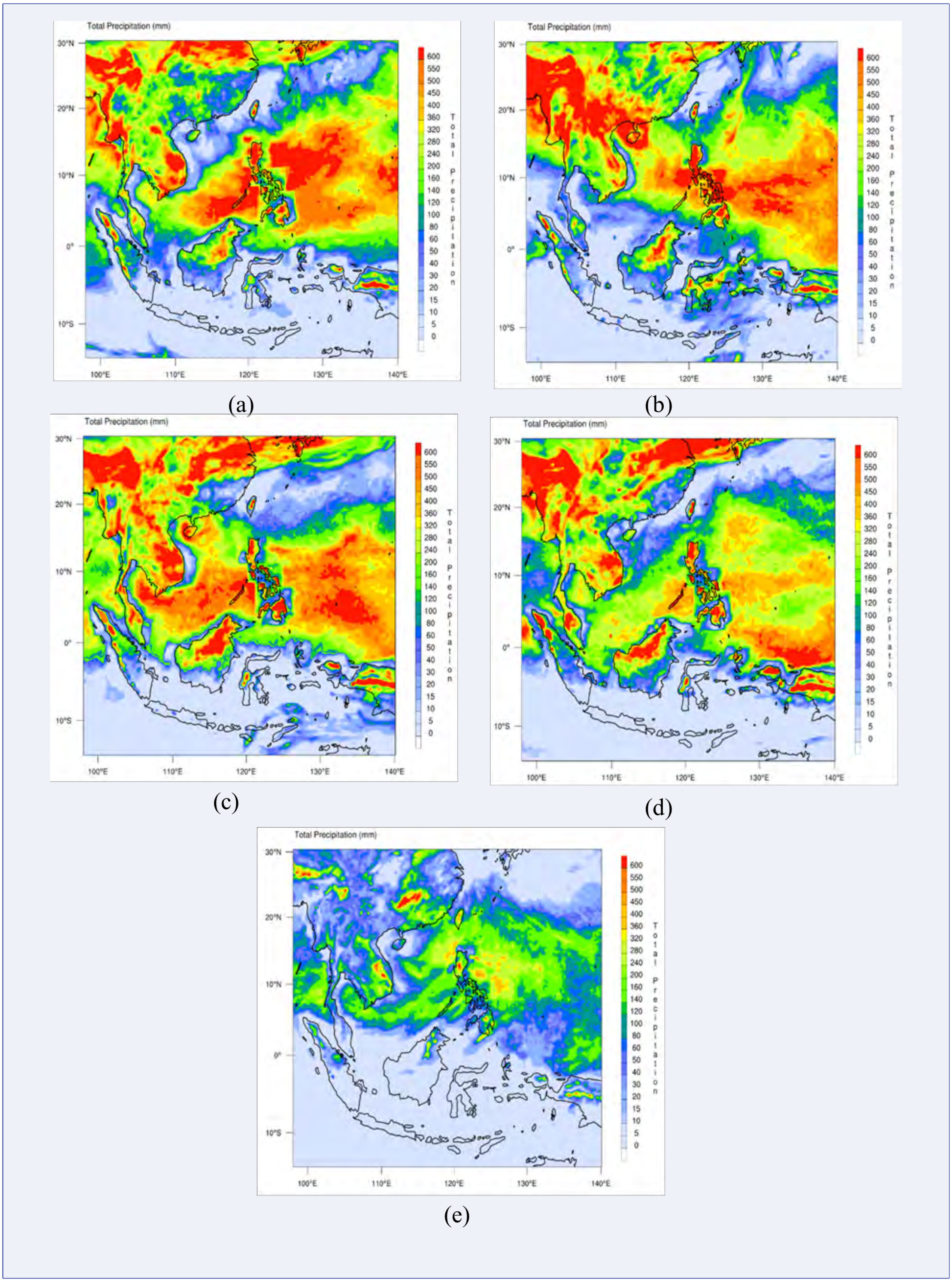

FIGURE 8. Total Precipitation for SEA region under RCP8.5 during July of 2013 (a), 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

Year	Month	Total Precipitation (mm)	Changes (mm)
2013	January	92.98	-
	July	248.86	-
2030	January	169.68	76.69
	July	258.96	10.09
2050	January	84.82	84.82
	July	245.77	-3.09
2070	January	16.10	-76.87
	July	218.25	-30.61
2100	January	118.79	25.80
	July	92.42	-156.44

TABLE 4. Monthly mean total precipitation of SEA under RCP8.5.

tion between 10-30% over maritime sub-continent regions, particularly over the Indonesia region during the dry season (June–August) under RCP4.5 and RCP8.5 by the middle and end of the century. However, during the wet season (December–February), there was a robust increment of 10–20% of the total precipitation observed over Indonesia and a 10–20% reduction over the Philippines in both RCPs. Tangang et al. (2020) further suggested that the mainland SEA region would experience a 10-15% increment in the total precipitation under both RCPs towards the end of the century except for Vietnam and Cambodia. The higher tendency of drying observed could be associated with enhanced divergence and subsidence effect over the Maritime Continent (Giorgi, Raffaele, & Coppola, 2019) caused by the deep tropical squeeze resulting from the equatorward contraction of the rising branch of the Hadley Circulation as the climate continues to warm (Fu, 2015).

3.3. Climate model evaluation

Table 5 shows the evaluation values of the surface temperature from the WRF model under RCP4.5 and RCP8.5 scenarios relative to the CRU observation dataset. The simulated surface temperature was 25.81°C in January and 27.41°C in July, under RCP4.5. Meanwhile, the RCP8.5 simulation showed a slightly lower temperature of 25.57°C in January and a higher temperature of 27.27°C in July compared with the CRU observation dataset. The model has a lower than 1% bias during January but a higher bias during July with 5.38% and 5.77% for both RCP4.5 and RCP8.5 scenarios, respectively. Meanwhile, the values of FB and NMSE were insignificant. The model has the Fa2 value of 1.0 during the January simulation, indicating an ideal simulation but a slightly higher value during the July simulation with a value of 1.1, indicating a slight overprediction within a factor of two of the observed values. The warm bias over this region could be due to a poor representation of land-atmosphere interactions, amplified by unresolved albedo feedback and further alleviated by large cloud biases (Garrido, González-Rouco, & Vivanco, 2020).

Table 6 shows the evaluation values of the total precipitation simulation under both RCPs scenarios relative to the CRU observation dataset. The simulated total precipitations were 29.6 mm and 117.3 mm in January and 159.6 mm and 288.6 mm in July for both RCPs, respectively. There were larger biases for both RCPs, which underestimated the total precipitation during January but overestimated during July. During July, under the RCP4.5 scenario, the values of FB and NMSE were lower than 0.5. Though the model has poor performance in simulating total precipitation during January based on the Fa2 value, it relatively performed well during July with a Fa2 value of 1.3. A similar observation by Kong and Sentian (2015) reported a high bias, especially in the mountainous area and interior region. The larger bias might be caused by poor representation of the convective parameterization and hydrological cycle by the model (Alves & Marengo, 2009; Salimun, Tangang, & Juneng, 2010; Sinha et al., 2013).

Variable	Temperature (°C)		NMB (%)	FB	NMSE	Fa2
Scenario	Model	CRU				
	January					
RCP 4.5	25.81	25.70	0.39	0.0038	0.00002	1.0
RCP 8.5	25.57	25.70	-0.78	-0.0078	0.00006	1.0
	July					
RCP 4.5	27.41	26.01	5.38	0.0524	0.00275	1.1
RCP 8.5	27.27	26.01	5.77	0.0560	0.00315	1.1

TABLE 5. Climate model assessment of surface temperature against the CRU dataset.

Variable	Precipitation (mm)		NMB (%)	FB	NMSE	Fa2
Scenario	Model	CRU				
	January					
RCP 4.5	29.6	244.5	-87.89	-1.5680	6.38120	0.1
RCP 8.5	117.3	244.5	-52.02	-0.7031	0.56415	0.5
	July					
RCP 4.5	159.6	122.4	30.39	0.2638	0.07084	1.3
RCP 8.5	288.6	122.4	135.78	0.8087	0.78196	2.4

TABLE 6. Climate model assessment of total precipitation against CRU dataset.

4. CONCLUSION

This study concluded that there are connections between climate change and the monsoonal seasonal changes seen in surface temperatures and precipitation, greatly influenced by the weather systems across Southeast Asia. It also shows a significant decadal variation over the precipitation and temperature anomalies. However, the overall temperature in this region showed an increment in the future under both climate change scenarios RCP4.5 and 8.5, which correspond with a decrement of precipitation anomalies for the same period. These shifting phenomena of the monsoon seasons in Southeast Asia will severely impact the region's vulnerability in human health, environment, food security, and economics. Therefore, policymakers urgently need to mitigate, adapt, and increase climate change resilience in their respective countries.

5. ACKNOWLEDGEMENT

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A multicriteria approach to assessing the sustainability of community-based ecotourism in Central Vietnam

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ABSTRACT

Nature exploration, or ecotourism, has been an essential part of tourism, and today takes on a much broader meaning beyond tourism that includes conserving nature and culture and improving people's lives, especially in the indigenous community. Community-based ecotourism (CBET) has specific benefits closely related to the sustainability of natural ecosystems and community development. CBET can be defined as nature-based tourism, helping shape the types of tourism services, planning and developing destinations provided by communities directly. CBET is supposed to be a sustainable alternative to mass tourism by its potential benefits in Vietnam. The study aims to evaluate the sustainability of four CBET destinations in Central Vietnam through a sustainable ecotourism index (SEI) formed by applying the Analytic Hierarchy Process (AHP) method. Based on the literature review, local people, and experts' recommendations, a set of fourteen criteria categorized into five groups reflecting the critical attributes of the sustainable CBET that include environmental conservation, economic benefits, community participation, cultural preservation, and empowerment are analyzed. The raw data is obtained from in-depth interviews with 21 experts and 42 households. After normalizing, the results indicate that out of four CBET destinations, one is identified as high sustainability (SEI>4.2), two are neutral (3.4<SEI<4.2), and one is lower than (SEI<3.4). These findings provide implications for extending the AHP theory in tourism and policy implications toward sustainable development in future tourism.

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KEYWORDS
Community-based ecotourism, Central Vietnam, sustainable ecotourism index (SEI), Analytic Hierarchy Process (AHP)

HIGHLIGHTS

- The criteria for assessing the sustainability of Community-Based Ecotourism (CBET) models are identified.
- The sustainability of coastal CBET models is higher than that of mountainous models.
- CBET's sustainability assessment needs stakeholder engagement.

1. INTRODUCTION

Thanks to technological advancements and improvements in mass media, tourism has continuously become one of the world's largest and fastest-growing economic sectors over the past decades. According to the United Nations World Tourism Organization (UNWTO, 2020), tourism is a mammoth industry that generated an estimated USD 1,481 billion in 2019. International tourist arrivals have increased from 25 million globally in 1950 to 278 million in 1980 and 1,460 million in 2019. Percy (2009) argued that, for instance, tourism activities lead to severe environmental degradation, while local cultures are also disrupted. The development of tourism infrastructures such as resorts, jetties, walkways, artificial lagoons, artificial beaches, and groins led to the loss of habitat, wildlife disturbance, reduced coral growth (Gladstone, Curley, & Shokri, 2013) and the harassment of wild animals in national parks (Himberg, 2006). In addition, tourism has not continuously operated in the interests of local people, resulting in an inauthentic representation (Tan, Fumikazu, & Dinh, 2019) and cultural alienation of ethnic minorities (Cuong, 2020), causing conflict between host and tourist.

There is a need for a new approach to tourism that ensures tourism policies should no longer concentrate on economic and technical necessities alone; but rather emphasize the demand for an unspoiled environment (Fennell, 2005) and considers the needs, concerns, and welfare of local communities (Scheyvens, 1999). Community-based ecotourism (CBET) emerged as the most appropriate alternative in that situation. As opposed to conventional mass tourism, the CBET can be defined as tourism owned and/or managed by communities and intended to deliver wider community benefits (Goodwin & Santilli, 2009). The CBET projects would strengthen institutions designed to enhance local participation and promote the popular majority's economic, social, and cultural well-being. It also seeks to strike a balanced and harmonious approach between economic development, environmental conservation, and cultural preservation (Brohman, 1996). Similarly, the CBET is certainly an effective way of implementing policy coordination, avoiding conflicts between different actors in tourism, and obtaining synergies based on the exchange of knowledge, analysis, and ability among all community members (Kibicho, 2008).

In Vietnam, CBET initiatives or ecotourism have been integrated into tourism development and poverty alleviation programs designed by the Vietnamese government since the late 1990s. The "eco" or "green" or "community-based" terms were initially introduced in the workshop on "Building ecotourism development strategy" in 1999, which emphasized, "this is a type of tourism that based on nature and indigenous culture, associated with environmental education, contributing to conservation and sustainable development efforts, with the active participation of the local community" (Ba et al., 2009, p. 84). The terms are gradually mentioned in the Tourism Law 2017 and the latest, National strategy for sustainable tourism development to 2020 and vision to 2030. With the diversity of natural resources penetrated by "commercialization and mass-tourism outfits" and the richness of cultural heritage, the Vietnamese government expects favourable opportunities for CBET development (Lam, 2002).

Despite presenting many efforts, the CBET programs are still facing severe problems and challenges, including pressure on the natural environment, livelihood and life quality impacts, interest conflicts amongst stakeholders, low capacity, and limited tourism skills of local communities (Hong & Saizen, 2019; Ngo, Lohmann, & Hales, 2018; Suntikul et al., 2016). Besides, the number of CBET destinations rapidly grew without specific planning and unclear criteria that caused negative impacts on environmental resources and harm to host communities' norms and identity (Tan et al., 2019; Thái, 2018). Notably, in addition to lacking a legal framework and detailed guidelines, most documents, even official reports issued by the government, do not use the term CBET or ecotourism explicitly and distinctly (Hoa, 2012). Such problems ultimately lead to an inflexible approach and unsustainable development. Although causing gaps and negative impacts on the indigenous community, evaluations of sustainability in tourism, especially emerging CBET projects in Vietnam, have not been comprehensively investigated. Given the above background, this study seeks to address gaps by answering the following questions: (1) What are the criteria for assessing the sustainability of a CBET site? and (2) What are the steps for assessing the sustainability of the CBET sites?

The analytical hierarchy process (AHP) is based on a pairwise comparison in ratio scale (Saaty, 1979). AHP method can compare each theme based on their relative importance for identifying potential zone (Saaty & Vargas, 2012). The AHP method will be applied for two reasons to achieve these goals. First, this multicriteria assessment approach helps to build decision-making issues in hierarchies that include goals, criteria, sub-criteria, and decision alternatives (Ma, Li, & Chan, 2018). Thus, it guarantees the adequacy of criteria and data connectivity. Second, equally important, the hierarchy of AHP helps stimulate participation and interaction among the people concerned both in the formulation and the quantitatively oriented solution of their problems (Saaty, 1977). Using this method can transform subjective opinions into objective measures for the decision-maker. Thus, this method ensures transparency and objectivity for making the best decisions among multiple alternatives.

2. LITERATURE REVIEW

2.1. Sustainable tourism and community-based ecotourism initiatives

The term sustainable tourism (ST) itself emerged from the broader sustainability movement, "sustainable development", which was thought to the first introduced in the early 1970s, and then officially popularized in the late 1980s through a report by the World Commission on Environment and Development (popularly known as the Brundtland Report) (Weaver, 2006). This report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED], 1987, p. 43). Based on this classic concept, the ST is thought of as the application of the sustainable development idea into the tourism industry, that is, "the needs of the present tourists and host regions while protecting and enhancing opportunities for the future" (UNWTO, 1998, p. 21, cited in Nguyen, Young, Johnson, and Wearing, 2019). To become popular as current, this discourse has gone through many different stages and statements depending on the specific author's view and field, and it is still evolving. Initially, the ST field seems to be a broad conceptualization covering three issues: environment, society, and economy (Bramwell, Higham, Lane, & Miller, 2017). From here, alternative forms of tourism, such as ecotourism or CBET, were formed to achieve sustainable goals in tourism (Ruhanen, lee Moyle,

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& Moyle, 2019). However, due to its infancy, it was plagued by definitional debates, many different perspectives, and misunderstanding of the nature and orientation of this concept (Bramwell & Lane, 2013).

During the early 2000s, with technological advancements alongside broader societal trends, this period witnessed an explosion and an increasing interest in sustainability. In turn, tourism has enormously increased its sustainability engagement by developing a more sustainable product range, assembled with different sustainability criteria, such as a friendly environment or products produced by local people (Ruhanen et al., 2019). Organizations worldwide, such as the United Nations (UN) and the UNWTO, stepped in with tougher measures and sustainability criteria through global summits or congresses. Notably, one of the considerable efforts to promote sustainability in tourism during this period was the publication of the guidebook 'Indicators of Sustainable Development for Tourism Destinations' edited by the UNWTO (2004, cited in Agyeiwaah, McKercher, and Suntikul, 2017). With a length of more than 500 pages alongside 13 aspects and 40 specific criteria, this manual covers all areas of tourism towards sustainable development, from macro issues, such as governance, climate change, environmental pollution and nature conservation, to micro problems such as local livelihood, seasonality, or the authenticity of a tourist destination (Agyeiwaah et al., 2017).

It has become almost universally recognized as a truly unique desired process by academics and developers (Weaver, 2006). The ST has regularly been attached to general expectations, including environmental preservation, biodiversity, equality between stakeholders and host-guest nexus, the promotion of human welfare and local community, cultural conservation, empowerment for vulnerable groups, transparency in policy, and many others (Bramwell & Lane, 2013; Fennell, 2005; UNWTO, 2017). However, many experts have argued that achieving all sustainability criteria is near impossible and argued that it should replace or revise for more suitable. Marzo-Navarro, Pedraja-Iglesias, and Vinzón (2015) implied that "we are overwhelmed by too many indicators". Similarly, Agyeiwaah et al. (2017) criticized it as ineffective mainly because it is simply too broad, comprehensive, and ambitious. Moreover, many indicators are inconsistent and not similar, so implementing sustainability principles is difficult. For example, economic sustainability can be measured immediately, while others, such as social and cultural aspects, may only be measured over many years (Agyeiwaah et al., 2017). Thus, it has been recognized that it should offer specific criteria based on each destination's specific context and time-related circumstances (Bramwell & Lane, 2013) rather than general ones.

Therefore, this study is based on the triple bottom line (TBL) sustainability framework (economic, environmental, and social), but with minor revisions to match the reality in Vietnam. Accordingly, this study supplements two elements to create a new research framework consisting of five main components: economic benefits, environmental conservation, cultural preservation, community participation, and empowerment (Figure 1). We argue that all five aspects will contribute to sustainability in CBET sites. In terms of measuring, such factors have been widely addressed.

First, the economic benefits are considered the priority to local communities, which should be distributed fairly (Choi & Sirakaya, 2006). CBET can bring direct and indirect economic benefits to local residents. On the one hand, it can promote local employment and income opportunities and diversify livelihoods that improve residents' quality of life (Lee, 2013; Ohe & Kurihara, 2013). On the other hand, CBET can enhance the local economy by selling local products and small shops around the destination. In this vein, economic benefits are not only for those who participate directly in the programs but also for the community as a whole.

Second, a fundamental characteristic of CBET initiatives is that the quality of the natural resources and wild species can not only be damaged, if possible, but also may be preserved by tourism (Choi & Sirakaya, 2006). Tourism activities not only raise awareness about environmental protection for guests but also for the indigenous people, who play an important role in keeping the surrounding environment clean and sustainable. Furthermore, tourism revenue helps improve local facilities and nature conservation funds (Kiss, 2004).

Third, CBET activities encourage local people to value their cultural heritage via the cultural exchange between host and guest. This also helps the local community to improve their awareness and understanding of the different cultures of different regions. Moreover, besides the types of goods, intangible services such as cultural identity and the indigenous lifestyle of the local community become attractive features for tourists. In this sense, they can be resilient and maintain ancient cultures and traditional festivals. CBET also provides opportunities for locals to increase their social or traditional cultural identity and promote the community's social coherence (Choi & Sirakaya, 2006).

Fourth, community participation is the most important dot to destination governance, which is recognized as a central key to achieving sustainable goals (Bramwell, 2011; Hall, 2011), especially in CBET projects. Research by Gurung and Seeland (2008) has shown that community participation ensures that ecotourism activities engage and cooperate between local communities, local authorities, and tourists to meet local needs while delivering conservation benefits. Involvement of local communities contributes to tourist satisfaction and ensures continuity of ecotourism activities (Stone & Wall, 2004).

Fifth, empowering vulnerable groups, especially women, remains an essential principle of ecotourism (Honey, 2008). This principle of ecotourism supports the defense of democracy and human rights movements and leads to greater empowerment of vulnerable groups who comprise the majority of local communities (Honey, 2008). Furthermore, many advocates of social equality applauded ecotourism due to its potential to create social benefits for improving vulnerable groups' lives and empowering local communities' rights (Scheyvens, 1999).

2.2. Applying the AHP method in tourism studies

The AHP is a general measurement theory and the widest application in multicriteria decision making, which Thomas Saaty developed in the 1970s. This model refers to decision-making based on several criteria, where each will be measured in a hierarchical structure according to its importance (Saaty, 1977). To identify the relative importance of several criteria, the pairwise comparisons method is often used at each level of the AHP (Ma et al., 2018). The AHP has many advantages in the decision-making process (Masroor et al., 2021) by transforming qualitative data into quantitative measurements (Saaty & Vargas, 2012). The approach has brought a wide variety of potential applications in academic fields and seems to be an effective instrument for bringing together the theory and practice of modelling (Saaty, 1979). Indeed, the AHP offers scholars a substantially different approach to addressing the problems of decision making, planning, conflict resolution, and forecasting through ratio scales in diverse areas, especially socio-economic, political, and technological fields (Saaty & Vargas, 2012). In recent years, this framework has contributed, for example, to sustainable solid waste management (Tsai, Bui, Tseng, Lim, & Tan, 2021), water quality management (Singh et al., 2021), the safety assessment of chemical plant production process (Song, Jiang, & Zheng, 2021) , effective management of water resource (Masroor et al., 2021), and solutions for the development of a green bond market (Tu, Rasoulinezhad, & Sarker, 2020).

In the tourism industry, this approach is considered an essential tool in identifying sustainability in tourism destinations (Tseng et al., 2018) and forecasting tourism demand (Athanasopoulos, Ahmed, & Hyndman, 2009; Hu, Qiu, Wu, & Song, 2021). In previous documents, this method was

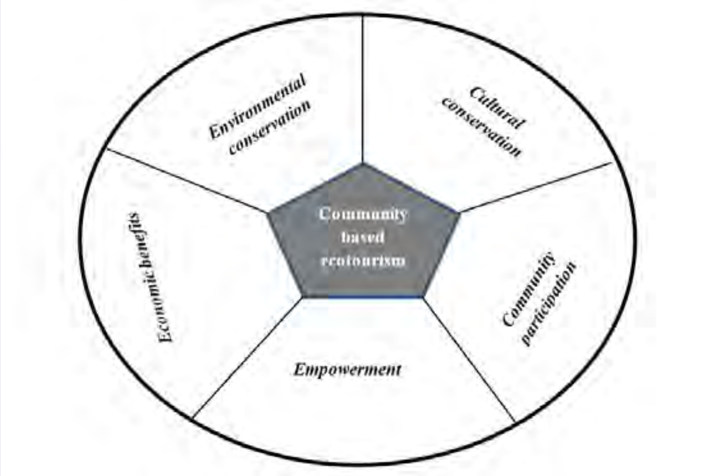

FIGURE 1. A research framework for CBET sustainability.

often combined with other packages, such as fuzzy theory (Tseng et al., 2018), SWOT analysis (Wickramasinghe & Takano, 2009), or the geographic information system (GIS) technique (Abed, Monavari, Karbasi, Farshchi, & Abedi, 2011) to quantify "equivocal concepts related to subjective human judgements in an uncertain environment" (Tseng et al., 2018). In recent decades, among different multiple criteria decision analysis (MCDA), the hierarchical process (AHP) has been an effective and widely used method in ecotourism (Chandio et al., 2013; Wong & Li, 2008). Bunruamkaew and Murayama (2012) applied the AHP method according to five criteria: landscape and nature, wildlife, topography, accessibility, and community characteristics to define ecotourism sites in Surat Thani province, Thailand. In India, research by Kumari, Behera, and Tewari (2010) applied the AHP method to identify potential ecotourism destinations based on wildlife, ecological value, ecotourism attractiveness, environmental resiliency, and ecotourism diversity. Gourabi, Ramezani, and Rad (2013) also applied AHP and GIS to ecotourism potential based on eight thematic groups, including sunny days, temperature, relative humidity, slope, direction, soil texture, water resources, and vegetation density in Iran. Nahuelhual, Carmona, Lozada, Jaramillo, and Aguayo (2013) combined GIS and participatory methods, including Delphi and AHP, to map recreation for ecotourism development at the municipality level. Dhami, Deng, Burns, and Pierskalla (2014) applied AHP to identify and map ecotourism sites in forested areas in West Virginia in the United States.

Despite such significant contributions, there is still a lack of research on the AHP method application in the CBET in Vietnam. This study aims to explore the capability of AHP for assessing the sustainability of CBET sites, and for this study, Thua Thien Hue province, Vietnam, has been taken into consideration. Through the AHP method, a useful tool including criteria of the sustainability of CBET zones will be established as a valuable tool for the decision-makers to identify suitable ecotourism locations. No such works relevant ecotourism field have been reported in the study area. Thus, this is both crucial and pioneering work in this field of study, with the potential of significantly contributing to ecotourism site development.

3. METHODOLOGY

This paper proposes using the AHP method to assess the sustainability of CBET sites in Central Vietnam. The specific steps in this methodology involved four steps: (1) Searching for the potential destinations, (2) identifying the goal and finding suitable criteria to use in the analysis, (3) identifying criteria priority (weight), and (4) determining and ranking the sustainability index of each destination.

3.1. Search for the potential ecotourism destinations

Thua Thien Hue province in Central Vietnam is renowned for the complex of Hue Ancient Capital, a UNESCO world heritage site with a range of scenic beauty destinations, such as tombs and ancient pagodas systems with extensive historical architecture (People's Committee of Thua Thien Hue province [PCTTH], 2017). Further, Thua Thien Hue is known for its famous festivals and Nha Nhac (royal music). With the diversity of traditional craft villages and the preservation of cultural and historical values, tourism (in general) and CBET (in particular) are integrated into strategies for economic development, poverty alleviation, and local livelihood improvement (PCTTH, 2021). It is not surprising that tourism has been identified as a key financial sector based on its significant contribution to GDP in recent years. The determination of the main research sites was considered based on an analysis of five criteria of CBET, including tourism activities associated with nature, cultural activities, participatory activities, etc. of local communities, bringing economic benefits and empowering vulnerable groups such as women and ethnic minorities. Based on these criteria, the study conducted consultations with experts of the Department of Tourism and some pilot trips to select appropriate destinations in ecotourism regions, including the lagoonal area, coastal area, highland and remote highland areas with four specific destinations of Hong Ha, Loc Binh, Quang Loi and Thuong Lo. The general background is described in Table 1.

The four study sites are located in different regions and have unique tourism features. Loc Binh and Quang Loi are located in coastal areas, where three local rivers merge to form the largest lagoon system in Southeast Asia (Tam Giang – Cau Hai lagoon) before emptying into the East Sea. The remaining two locations belong to the two poorest mountainous districts in this province, characterized by agricultural lifestyles of ethnic minority groups. All four areas are located in rural areas. The Thuong Lo village is considered the first CBET model of the province since the early 2000s, followed by Quang Loi, while Hong Ha and Loc Binh have just been established in recent years. At first glance, although it was formed the earliest, income from tourism in the Thuong Lo destination appears low compared to other places, especially emerging tourist areas like Loc Binh. In short, the diversity of geographical locations, ethnic minority representation, history, and different types of services meet our objectives and guarantee equality and dialectical views.

3.2. Identification of criteria for the sustainability of ecotourism destinations

As noted, the province is most renowned for the UNESCO world heritage site of Hue Ancient Capital has been world heritage listed by UNESCO (PCTTH, 2017), with Thua Thien Hue known for its famous festivals and Nha Nhac (royal music).

Although various attributes in tourism, especially the ST, have been investigated previously, the complex reality and multi-goals of the CBET initiative have led to a broad range of challenges for scholarly authors (Budeanu, Miller, Moscardo, & Ooi, 2016). Based on the literature, this study provides a set of 17 criteria that represent five aspects: environmental conservation (A1), cultural preservation (A2), community participation (A3), economic benefits (A4), and empowerment (A5), as indicated in Table 2. To avoid subjective attributes to this study, the criteria were trial-tested by some local respondents and then confirmed by local authorities to obtain the final measures for guaranteeing reliability. A community-based approach to tourism recognizes the need to promote the quality of life of people, their culture and the conservation of resources (Scheyvens, 1999). The environmental issue is a crucial aspect of the tourism sector. CBET can effectively incentivise communities to take conservation action directly or indirectly (Kiss, 2004). For example, tourism incomes are very high that "people deliberately protect biodiversity to protect that income" (Kiss, 2004, p. 234). To achieve this goal, raising awareness of both the community (C1) and visitors

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Feature	Hong Ha	Loc Binh	Quang Loi	Thuong Lo
Year established	2013	2013	2008	2001
Current local members	13	14	15	19
Location	Highland	Coastal	Lagoonal	Remote highland
Ethnic minority	Yes	No	No	Yes
Annual income per household (USD, 2019)	720.32	941.03	1,532.21	230.23
Main tourism types	• Natural exploration • Homestays • Farmstays • Folk arts	• Natural exploration • Agricultural/food experiences • Homestays	• Fishery experiences • Homestays • Sightseeing on the lagoon • Outdoor activities • Visiting traditional craft village	• Visiting traditional craft village • Natural exploration • Homestays • Folk arts

TABLE 1. Some primary characteristics in four case studies.

(C2) are the factors mentioned in the previous literature (Honey, 2008; SNV, 2007). In addition, reducing and minimizing the negative impacts of the tourism industry on the environment (C3) are also goals of any CBET project. From another perspective, tourism, especially in the CBET field, comprises a complex set of social and economic activities that use large amounts of local resources and involve various functions and stakeholders (Tsai et al., 2021). CBET may enhance the social attachment and opportunities for villagers to increase their social or traditional cultural identity (Choi & Sirakaya, 2006). By assessing residents' (C4) and visitors' (C5) perspectives on cultural education, managers can understand the residents' perceptions of tourism impacts and how it influences their culture and life (Lee & Jan, 2019). Moreover, cultural exchange (C6) also plays an important role in a tourism destination's cultural preservation and community norms (Cuong, 2020).

Community participation also contributes to sustainability in a destination. The participation of local communities in tourism planning (C7), especially CBET projects, is both a mandatory criterion and a tourism product (Thái, 2018). In the former, their participation ensures fairness and transparency in tourism activities (C9) and guarantees the most profit belongs to them under legal policy (C10). The latter is a way to showcase their unique culture and their hospitality, thereby promoting more tourists (C8). To avoid the traps of many past ventures, which disempowered local communities, Scheyvens (1999) proposed four levels of empowerment in the framework: psychological, social, political and economic empowerment. This aspect is applied to emphasize the importance of local communities having a level of control over and benefit-sharing from tourism in their respective areas (Scheyvens, 1999), especially for vulnerable groups like women (C16), and poor and ethnic minority households (C17). While some authors emphasize the CBET potential in the cultural heritage of local peoples, their involvement and their environments, others mention economic benefits and profits from tourism. Economic benefit for the local community is an important aspect of CBET sustainability (Marzo-Navarro et al., 2015). Kernel (2005) has argued that the economic aspect of tourism development involves maximizing profits derived from tourism, based mainly on the tourist arrivals in specific destinations that are important for both private sectors and local community groups (C14). CBET is also implemented based on bringing economic benefits to the communities involved in tourism, especially those living in/around protected areas. This approach advocates promoting recycling and saving energy (C13) to maximize economic benefits for local communities (Weaver, 2006). Finally, supporting local economic development (C15) involves increasing the number of jobs (C11), creating a fund for environmental protection

Aspects		Criteria		Measurement	Score	Source
A1	Environmental conservation	C1	Local community's awareness of the environment	Extremely low Low Medium	1 2 3	(Honey, 2008)
		C2	Tourist's awareness of the environment	High Extremely high	4 5	(SNV, 2007)
		C3	Minimize impacts on the environment			(Kiss, 2004; Marzo-Navarro et al., 2015)
A2	Cultural preservation	C4	Cultural education for the local community	Extremely low Low	1 2	Choi and Sirakaya (2006); Lee and Jan (2019)
		C5	Cultural education for tourists	Medium High	3 4	(Choi & Sirakaya, 2006; Lee & Jan, 2019)
		C6	Cultural exchange	Extremely high	5	(Cuong, 2020; Honey, 2008)
A3	Community participation	C7	Community participation in tourism planning	Extremely low Low	1 2	(Thái, 2018)
		C8	Tourists satisfied with community participation	Medium High	3 4	(Stone & Wall, 2004)
		C9	Community participation in tourism development	Extremely high	5	(Stone & Wall, 2004)
		C10	Managing by local government			(Gurung & Seeland, 2008)
A4	Economic benefits	C11	Increasing employment	Extremely low Low	1 2	(Marzo-Navarro et al., 2015; SNV, 2007)
		C12	Creating a fund for environmental protection	Medium High	3 4	(SNV, 2007)
		C13	Reduction in energy usage	Extremely high	5	(Agyeiwaah et al., 2017; Weaver, 2006)
		C14	Ensuring salary			Kernel (2005); Tseng et al. (2018)
		C15	Support for local economic development			(Honey, 2008)
A5	Empowerment	C16	Empowerment of women	Extremely low Low	1 2	(Agyeiwaah et al., 2017; Honey, 2008)
		C17	Empowerment of poor or ethnic groups	Medium High Extremely high	3 4 5	(Scheyvens, 1999)

TABLE 2. The proposed hierarchical framework for sustainable aspects.

incomes (C12) and considering salaries (Tseng et al., 2018).

3.3. Identify criteria priority (weight)

As analyzed earlier, the AHP creates decision-making issues in hierarchies. In this study, we apply AHP to evaluate its relative value through three basic steps.

Step 1: Identifying the goals and the criteria and organizing them into a hierarchy

The simplest form of the customary AHP consists of three levels of goals, aspects and decision alternatives. In the study, the goal is a sustainable ecotourism index (SEI) at the top level, followed by a second level consisting of five main criteria by which the alternatives (are case studies), located in the third level, will be sorted out (Figure 2). Such hierarchical systems have advantages in judging the importance of the elements in a given level with respect to the components in the adjacent level above (Saaty & Vargas, 2012). It also provides an overarching overview of all issues after complete structuring. After that, a set of 17 sub-criteria with five main criteria (aspects) is identified and systematically organized in a hierarchy, as shown in

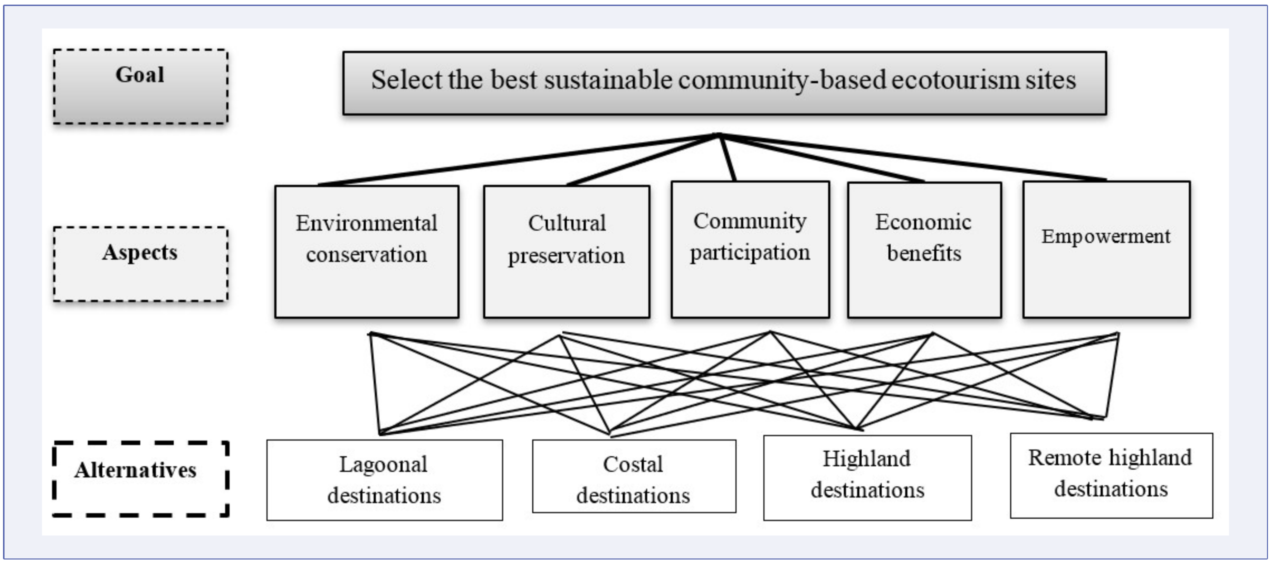

FIGURE 2. Three levels in a hierarchical structure.

Table 2.

Step 2: Comparing pairwise criteria

First, a 9-point scale is used to identify the relative importance of each attribute, as introduced by Saaty and Vargas (2012) (see Table 3). Data was collected using semi-structural questionnaires by two groups. To maximize the efficiency of the group decision-making process using the AHP survey, purposeful sampling was used to identify key informants and local experts in both the private and public sectors. Specifically, two tourism professionals from Hue University (top 10 ranking in Vietnam), two from the department of tourism, two from the department of rural development of Thua Thien Hue province, four district managers and eleven local key informants were interviewed. The team of experts conducted their comparative assessments for each pair of aspects. The inputs were analyzed to determine the relative priority of each aspect. Concurrently, they also proposed views concerning adding or removing some criteria in the general aspect set.

The judgement matrice forms are illustrated in Table 4. Each matrix is denoted with the equation W = (C_{ij})m*n, where Cij denotes the weighting given to criterion C_i and criterion C_j for target W (Ma et al., 2018).

Next, the validity of the judgement matrices was examined by a consistency test as Saaty's suggestions that includes three most important indexes: the Random Index (RI), Consistency Ratio (CR), and a Consistency Index (CI). As suggested by Saaty and Vargas (2012), the values of the RI are available in Table 5. The CI value is calculated based on λ_{max} (Equation (1)), as illustrated in Equation (2). Meanwhile, the CR index measures how far a decision maker's judgements are from perfect consistency (Kim, Park, & Choi, 2017), which is calculated as Equation (3). The judgements are consistent and acceptable if the CR value is less

Scale	Definition
1	Equal importance
3	Moderate importance
5	Essential importance
7	Demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgements
Reciprocals of above nonzero	Reciprocal values for inverse comparison

TABLE 3. The fundamental scale and its definition. Source: Saaty (1977).

W	C_1	...	C_j	...	C_n
C_1	C_{11}	...	C_{1j}	...	C_{1n}
...		...		...	...
C_i	C_{i1}	...	C_{ij}	...	C_{in}
...		...		...	
C_m	C_{m1}	...	C_{MJ}	...	C_{mn}

TABLE 4. General forms of judgment matrices.

than 0.1. Conversely, if the CR is more than 0.1, it indicates an inconsistent judgement (Kim et al., 2017). In those cases, it will be revised until it meets the requirement.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\{\frac{\sum_{j=1}^{n} a_{ij} * w_j}{w_i}\} \quad (1)$$

Where: λ_{max} indicates the principal eigenvector, n is the matrix size, a_{ij} denotes an element of the pairwise comparison matrix, and w_j and w_i represent the j^{th} and i^{th} element of values of eigenvector, respectively.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

Where: CI is the consistency data of the judgement matrices; RI is the average random consistency index; CR is the consistency ratio.

Step 3: Calculating weights of indicators at each level

After passing consistency tests, the weight of each aspect (W_i) in the matrix will be calculated as a mathematical formula, as Equation (4) shown below.

$$W_i = \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{i=1}^{n} \cdot \sum_{j=1}^{n} b_{ij}} \quad (4)$$

Where: $\sum_{i=1}^{n} Wi \ = 1$; W_i denotes the weight vector of i^{th} aspect; n is the number of weighted aspects, and b_{ij} is the importance of aspect b_i relative to aspect b_j.

3.4. Determining the sustainability index of each destination

To determine the sustainable ecotourism index of each tourist destination, the study carried out three steps: (1) definition of the sustainable ecotourism index, (2) data collection, and (3) data analysis.

3.4.1. Sustainable Ecotourism Index (SEI)

After obtaining the weights of indicators at each level, the SEI is calculated as Equation (5). The SEI provides a single numeric value and categorizes sustainability in a tourism destination. The study synchronizes and sorts them according to five levels corresponding to the level of sustainability of each tourist destination (Table 6).

$$SI = \sum_{i=1}^{n} W_i * U_i \quad (5)$$

Where: SEI is the sustainable ecotourism index; W_i normalized weight of i^{th} aspect; and the rated quality U_i based on the value of i^{th} aspect.

Sustainability level	SEI	Sustainability score
Extremely high (level 1)	4.2 – 5	5
High (level 2)	3.4 – 4.2	4
Medium (level 3)	2.6 – 3.4	3
Low (level 4)	1.8 – 2.6	2
Extremely low (level 5)	1 – 1.8	1

TABLE 6. Sustainability index hierarchy.

3.4.2. Data collection

The data were conducted through a household survey participating in ecotourism sites. The study selected 61 households at four ecotourism sites, including 13 households in Hong Ha, 14 in Quang Loi, 15 in Loc Binh and 19 in Thuong Lo. A structured questionnaire covers five sustainability aspects, including environmental conservation, cultural conservation, community participation, economic benefits and empowerment, and 17 corresponding criteria. The criteria scale is designed according to a 5-point Likert scale corresponding to 5 levels of sustainability: 1 – extremely low, 2 – low, 3 – medium, 4 – high, and 5 – extremely high. After revising based on experts' perspectives, a final semi-structural questionnaire was developed. An empirical survey was officially conducted in four case studies with participants from 61 households. Each interview took around 90 minutes.

3.4.3. Data analysis

Data was analyzed by Microsoft Excel version 16.0. The characteristics of ecotourism sites and sustainability criteria were performed using descriptive statistics. The weighting of the criteria was done through pairwise criteria according to the AHP process. Actual data and weights were

Matrix size	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49	1.52	1.54	1.56	1.58	1.59

TABLE 5. Average random consistency index according to matrix size. Source: Saaty and Vargas (2012).

combined to calculate the ecotourism sustainability index of destinations and ranking.

4. RESULTS

4.1. Weighting aspects of sustainable ecotourism from AHP analysis results

In this study, the AHP method supports three main results. First, it converts the responses (countable or uncountable) into AHP numbers that can compare between attributes (aspects) (Table 7). Then, an interrelationship matrix of the aspects is generated, and the weights of each aspect (W_i) are determined (Table 8). Accordingly, environmental conservation (A1) is determined to be the highest weight (0.28), followed by economic benefits (A4=0.22), community participation (A3=0.20), and empowerment (A5=0.13). The CI and RI values are 0.02 and 1.11, respectively. The CR value is calculated as 0.002, lower than the 0.1 threshold, which indicates that this judgement matrix is consistent and acceptable.

4.2. Descriptive sustainable ecotourism indicators in destinations

Regarding environmental conservation, the analysis results in Table 9 show that lagoon and coastal tourist destinations have high and very high scores, while tourist destinations in mountainous areas have medium to high scores. Notably, some indicators of tourists' awareness of the environment or reduction of environmental impacts in the mountainous regions are at low to moderate levels, respectively (2.85 and 2.95).

4.3. Ranking the sustainability level of tourist destinations

After obtaining the weight of aspects, the SEI is calculated to identify the sustainability level in each tourism destination. The results indicate that the sustainability level differs between tourism destinations, as shown in Table 10. Overall, respondents evaluated that Quang Loi is ranked as the region with the mos sustainable tourism with an SEI score of 4.25, followed by Loc Binh (3.90) and Thuong Lo (3.46). Meanwhile, Hong Ha is considered less sustainable (SEI<3.4). Notably, this result illustrates significant gaps between the relative sustainable values of each aspect separately. Accordingly, the environment perspective (A1) has the highest SEI, ranging from 1.4 to 2.33. In contrast, the indicators of empowerment for the local community (A5) are the lowest, not exceeding the 0.92 threshold. This means that respondents consider five factors to be of unequal importance in contributing to the sustainable value. We will analyze the issues intensively in the next section.

5. DISCUSSION

The sustainability of CBET in Thua Thien Hue province was assessed through 5 criteria with corresponding weights, including Environmental Conservation at 0.28, Economic Benefit at 0.22, Community Participation at 0.20, Cultural Conservation at 0.17, and Empowerment to Vulnerable Groups at 0.13. Based on the AHP method, 4 points representing CBET activities are ranked for sustainability, Quang Loi: very sustainable (S=4.25), Loc Binh: highly sustainable (S=3.90), Thuong Lo (S= .46), and Hong Ha: medium sustainability (S=3.23).

Based on the hierarchical analysis process, our research has evaluated the sustainability of CBET sites based on five aspects with weights from high to low, respectively, including environmental conservation, economic benefits, participation, cultural preservation, and empowerment. Research results show that the role of environmental protection and economic benefits from tourism is more important than other factors. The cause of this situation is that after prioritizing economic development, the ecotourism sites at the study site have been strongly affected by environmental pollution; therefore, the criteria for environmental protec-

	Environmental conservation	Cultural preservation	Community participation	Economic benefits	Empowerment
Environmental conservation	1.00	1.60	1.73	1.49	1.74
Cultural preservation	0.62	1.00	0.65	0.68	1.74
Community participation	0.58	1.55	1.00	0.69	1.69
Economic benefits	0.67	1.48	1.45	1.00	1.40
Empowerment	0.58	0.58	0.59	0.71	1.00
Total	3.45	6.21	5.42	4.57	7.57

TABLE 7. Crisp values for aspects.

	Environmental conservation	Cultural preservation	Community participation	Economic benefits	Empowerment	The weight (W_i)
Environmental conservation	0.29	0.36	0.32	0.33	0.23	0.28
Cultural preservation	0.18	0.16	0.12	0.15	0.23	0.17
Community participation	0.17	0.25	0.18	0.15	0.22	0.20
Economic benefits	0.19	0.24	0.27	0.22	0.19	0.22
Empowerment	0.17	0.09	0.11	0.16	0.13	0.13
Λmax = 5.08 CI = 0.02 RI= 1.11 (n=5) CR = 0.018 (<0.1)						

TABLE 8. Inter-relationship matrix of the aspects.

tion are assessed as the most important by people and experts. Besides, the living standard of local people in CBET is low, so economic factors are considered necessary. This result differs from some studies by Tan et al. (2019), where economics is the leading factor, and by Lee and Jan (2019) , where culture is an essential factor. This study's findings support Gladstone et al. (2013) and Kiss (2004) when the environment is the most crucial factor in ecotourism.

This study shows that the lagoon and coastal tourism models are extremely high and high sustainable CBET destinations with SEI indexes of 4.25 and 3.90, respectively. This can be due to the following reasons: First, the lagoon and coastal tourist spots are close to the city centres and urban areas, so they attract more frequent visitors than other ecotourism destinations in the distance. This brings economic benefits to tourists. Secondly, environmental protection awareness in these communities is higher because many projects on environmental protection and ecosystem conservation associated with improving local livelihoods have been implemented in this area before. Experiencing severe environmental pollution in the past has helped the local community in the lagoon and the coastal regions have a higher sense of environmental protection than other communities (Hoang, Momtaz, & Schreider, 2020; Uy et al., 2021). Third, tourism activities in the lagoon area are well organized with authorities, community organizations, and people. In lagoon areas, Fishery associations (FAs) are well-organized community organizations. When these organizations are involved in community-based tourism, they have helped develop community-based tourism sustainably. Our findings are consistent with studies by Tan et al. (2019) and Uy et al. (2021) when community participation is a tourist attraction. Another study suggested that the high awareness of environmental protection of

Aspects	Criteria	Sustainable tourism score by indicators in destinations			
		Highland (Hong Ha) N = 13	Inner lagoon (Quang Loi) N = 14	Lagoon and coastal (Log Binh) N = 15	Remote highland (Thuong Lo) N = 19
Environmental conservation	Local community's awareness of the environment	3.38	4.00	4.60	3.79
	Tourist's awareness of the environment	2.85	4.29	4.53	3.74
	Minimize impacts on the environment	3.08	4.07	4.20	2.95
Cultural preservation	Cultural education for the local community	3.31	4.36	4.53	3.79
	Cultural education for tourists	3.38	4.33	4.47	3.79
Community participation	Community participation in tourism planning	2.92	4.17	4.00	3.74
	Tourist's satisfaction with community participation	3.38	4.17	4.40	3.58
	Community participation in tourism development	3.08	3.67	4.80	3.47
	Managing by local government	3.23	4.00	4.47	3.11
Economic benefits	Increasing employment	3.46	4.00	4.73	3.32
	Creating a fund for environmental protection	2.54	3.11	3.20	2.16
	Supporting local economic development	2.77	3.22	3.60	2.79
Empowerment	Empowerment for women	3.92	4.43	4.87	4.05
	Empowerment for poor or ethnic groups	4.08	2,50	3.00	4.16

TABLE 9. Description of sustainable ecotourism indicators in destinations.

tourists and the community has brought sustainability to tourism in China (Stone & Wall, 2004), Sri Lanka (Wickramasinghe & Takano, 2009), and Japan (Tang, 2021).

Tourism in mountainous locations, including highland and remote highland, has medium and high ecotourism sustainability with SEI indexes of 3.23 and 3.46, respectively. There are several reasons for this problem. Firstly, the difficult traffic is why the number of tourists to these destinations is complex. Second, limited management and organizational skills could have made the operating time of these tourist attractions infrequent. Third, ecotourism sites in mountainous areas are under environmental pressure due to waste and spontaneous business development, which may cause environmental and landscape changes. Finally, people in mountainous areas often prioritize short-term livelihoods due to economic and daily life difficulties. They often prioritize livelihood activities with quick income to ensure food security for their families and communities, such as hired labour.

6. CONCLUSION AND RECOMMENDATIONS

Community-based ecotourism receives excellent attention from the authorities, residents, experts, and tourists at the research sites. This tourism model can actively promote the sustainability of natural ecosystems associated with economic and social development for local communities. The CBET is suitable for many locations, from mountainous areas to coastal plains in Central Vietnam.

From the research results, it is necessary to maintain and strengthen the sustainability criteria groups on environmental sustainability, community participation, and economic benefit for CBET destinations with very high and high points of sustainability. In addition, it is necessary to diversify more activities to develop the local culture further and create opportunities for disadvantaged groups in the community to participate in tourism activities. For CBET destinations that are at an average level, more investment is needed to complete

Aspects (weigh)	The sustainable ecotourism index (SEI)				
	Criteria	**Inner lagoon (Loc Binh) N = 15**	**Coastal (Quang Loi) N = 14**	**Remote highland (Thuong Lo) N = 19**	**Highland (Hong Ha) N = 13**
Environmental conservation (0.28)	Local community's awareness of the environment	0.43	0.37	0.35	0.32
	Tourist's awareness of the environment	0.42	0.40	0.35	0.27
	Minimize impacts on the environment	0.39	0.38	0.28	0.29
	SEI_1	1.24	1.15	0.98	0.87
Cultural preservation (0.17)	Cultural education for local community	0.39	0.37	0.32	0.28
	Cultural education for tourists	0.38	0.37	0.32	0.29
	SEI_2	0.77	0.74	0.64	0.57
Community participation (0.20)	Community participation in tourism planning	0.20	0.21	0.19	0.15
	Tourists satisfied with community participation	0.22	0.21	0.18	0.17
	Community participation in tourism development	0.24	0.18	0.17	0.15
	Managing by local government	0.22	0.20	0.16	0.16
	SEI_3	0.88	0.80	0.70	0.63
Economic benefits (0.22)	Increasing employment	0.35	0.29	0.24	0.25
	Creating a fund for environmental protection	0.23	0.23	0.16	0.19
	Supporting local economic development	0.26	0.24	0.20	0.20
	SEI_4	0.85	0.76	0.61	0.64
Empowerment (0.13)	Empowerment for women	0.32	0.29	0.26	0.25
	Empowerment for poor or ethnic groups	0.20	0.16	0.27	0.27
	SEI_5	0.51	0.45	0.53	0.52
Goal		4.25	3.90	3.46	3.23
Rank		1	2	3	4
Sustainability level		Extremely high	High	High	Medium

TABLE 10. Ranking the sustainability level of tourist destinations.

CBET criteria, especially activities aimed at raising awareness for tourists and the community about environmental protection and improving quality services to attract visitors to experience more, bring economic benefits to participants as well as develop the local economy.

This study's results suggest that many policies need specific activities in selecting potential ecotourism sites to avoid rampant development, lack of management, and waste of state and community resources. In particular, CBETs are lacking in management and communication skills. These are important factors for maintaining and developing CBET in the future. Therefore, the Department of Tourism and local authorities need to organize training courses and capacity building for the people. These training courses need to apply participatory training methods so that people can easily understand and absorb knowledge. Learners also need to visit and study successful CBET models in Vietnam.

In addition, there should be specific plans and guidelines to support CBET sites to carry out activities aimed at developing criteria of sustainable tourist destinations, with special attention to environmental conservation, bringing about economic benefits to the community, and increasing the community's participation in ecotourism activities.

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Supporting regional and international cooperation in research on extremes in climate prediction and projection ensembles: Workshop summary

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ABSTRACT

Weather and climate extremes have enormous impacts on society, and are becoming more severe and frequent as the world warms. Most developing countries in the Asia-Pacific region are highly vulnerable to risks associated with heatwaves and cold spells, droughts and floods, tropical cyclones, wildfires, and other extremes. To support regional and international cooperation for research on weather and climate extremes in the Asia-Pacific region, the World Climate Research Programme (WCRP) hosted an online workshop on Extremes in Climate Prediction Ensembles (ExCPEns) from 25 to 28 October 2021 with the support of Asia-Pacific Network for Global Change Research (APN). The workshop aimed to advance the rapidly emerging science of exploiting subseasonal, seasonal, annual to decadal and long-term prediction ensembles to improve the prediction and understanding of weather and climate extreme events. An Early Career Scientist (ECS) event followed the ExCPEns workshop and consisted of a discussion and networking forum for ECS from APN member developing countries, along with a series of ECS training lectures and discussion sessions. Through the workshop and discussions among stakeholders, important scientific results on prediction and future changes in weather and climate extremes were communicated. Moreover, new research topics spanning these different time scales were identified and prioritized.

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KEYWORDS

Weather and climate extremes, subseasonal to decadal prediction, climate change, early career scientists, APN member developing countries

HIGHLIGHTS

- There is an urgent need for capacity building to better explain and predict extremes.
- Regional and international cooperation should be enhanced in the Asia-Pacific region.
- The workshop helped to guide ECS in their research and future career.

1. INTRODUCTION

As weather and climate extremes become more severe under climate change, the availability of early warnings for such events is becoming increasingly important. Weather forecasts can provide warnings for specific extreme events but have limited accuracy more than two weeks ahead (e.g., Judt, 2018). Nonetheless, longer-term predictions of climate are possible, and much progress has been made in predicting future climate from weeks to a decade or more ahead. This has been enabled largely by applying comprehensive climate models that represent Earth system components and processes responsible for predictability on these time scales (Merryfield et al., 2020). Fundamentally, ensembles of many predictions from similar observation-based initial conditions are needed to represent the uncertainties inherent in these longer ranges. In addition, climate predictions must be aggregated in time, considering mean conditions (or events within) a particular week, month, season or year, rather than aiming to predict what will occur on a particular day, which is inherently unpredictable at long range (Shukla, 1998).

Such climate prediction ensembles (CPEs) are increasingly being used to predict future climate on subseasonal, seasonal and decadal time scales (Meehl et al., 2021). These predictions often consist of probabilities that mean conditions during the forecast period fall within particular ranges, typically the lower, middle and upper third of the climatological probability distribution (Figure 1A). Although high probabilities for the lower or upper categories suggest elevated chances of weather or climate extremes, this standard framing does not directly quantify those probabilities or the likely magnitudes of any extremes. However, this lack of predictive information specific to extremes is not due to any fundamental limitation. CPEs can, in principle, predict the entire probability distribution—including the tails—and should be able to quantify the likelihood that shorter-term extremes, such as heatwaves or exceptionally rainy spells, will occur within the predicted period. For such predictions to be useful they must have demonstrable skill, which poses a challenge given the limited number of past cases (at most a few dozen) on which to base an assessment. Moreover, a necessary condition for skill is that natural predictability exists for the predicted phenomenon.

Despite these challenges there has been some initial progress. For example, skill in predicting probabilities for exceeding outer percentiles (5-15%, 85-95%) of the seasonal climatological probability distribution has been demonstrated for single-model and multi-model CPEs (Becker, van den Dool, & Peña, 2013; Becker & Van Den Dool, 2018). Similarly, skill has been demonstrated for predicting the chances that extreme daily events will occur on seasonal (Hamilton et al., 2012) and decadal (Eade, Hamilton, Smith, Graham, & Scaife, 2012) time scales. Significant challenges nonetheless remain. First, the availability of such predictions from operational systems has lagged, partly due to persistent barriers in migrating research outcomes to operations, although some centres are beginning to provide probabilities for outcomes more extreme than the standard tercile categories (Figure 1B). Second, further research is needed to quantify the capabilities of CPEs to predict extremes across different variables, regions, time scales, etc. Third, co-designing sector-specific climate extreme information relevant to impacts, vulnerability and adaptation is needed. Finally, advancements in basic science relating to definitions and identification of extremes, physical mechanisms that must be accurately modelled, etc. are required for CPEs to realize their potential for predicting weather and climate extremes.

An additional scientific application of CPEs starting to be explored is for ensemble members to serve as many independent realizations of present-day climate evolution in order to better quantify the likelihood of extreme weather and climate events, including unprecedented extremes, in the current epoch (Thompson et al., 2017, 2019).

To accelerate progress in meeting these challenges and advancing the science of CPEs given the disproportionate human and economic costs of these extremes that are borne by developing countries (Field, Barros, Stocker, & Dahe, 2012), the World Climate Research Programme (WCRP) organized a scientific workshop on "Extremes in Climate Prediction Ensembles (ExCPEns)" in conjunction with a training and networking event primarily for early-career scientists (ECS) from developing countries of Asia-Pacific Network for Global Change Research (APN). These meetings were conceived to be closely connected. The workshop aimed to consolidate recent scientific progress and stimulate further progress in using CPEs to predict and quantify the likelihoods of weather and climate extremes, inviting participation and perspectives of the ECS; the training and networking event enabled ECS to learn from and network with experienced scientists and each other, to assist in overcoming challenges that ECS from the developing world face in their research efforts and career paths.

2. METHODOLOGY

The WCRP ExCPEns Workshop and associated ECS programme were originally scheduled to be held in-person in Busan, Republic of Korea, in October 2020. The events were postponed for approximately one year as a result of the COVID-19 global pandemic and eventually held primarily virtually via Webex. The ExCPEns workshop took place from 25 to 27 October 2021, and the ECS programme immediately afterwards on 27 to 28 October. APN provided sponsorship under its Scientific Capacity Development programme (CAPaBLE). Initially intended for ECS travel, this funding was mainly applied to operating the online workshop and editing workshop recordings. Additional sponsorship and organizational support were provided by the APEC Climate Center (APCC), which facilitated the associated webspace, registration, and online functioning, as well as WCRP and Pusan National University (PNU).

The ExCPEns workshop featured 42 oral and 26 poster presentations, organized in the six themed sessions described in Section 3.1. These presentations were scheduled in five programmes, starting in the morning, afternoon and early evening of Korean Standard Time (GMT+9) to accommodate global participation. The programmes allowed 15 minutes for each oral presentation, with 2 minutes to summarize each poster before dedicated breakout sessions for poster presentations. Information about the presenters, including gender, career stage, and countries represented by their institutions, is summarized in Table 1. Links to the presentation files and recordings, as well as the programme and abstract book, are provided on the ExCPEns web page, https://www.apcc21.org/act/workView.do?lang=en&bbsId=BBSMSTR_000000000024&nttId=7395.

The ECS Networking and Discussion Forum, reserved for ECS from APN developing countries, was held in the early evening hours (Korean time) of 27 October, following the final session of the ExCPEns workshop. An initial plenary introduction highlighted WCRP's commitment to a geographi-

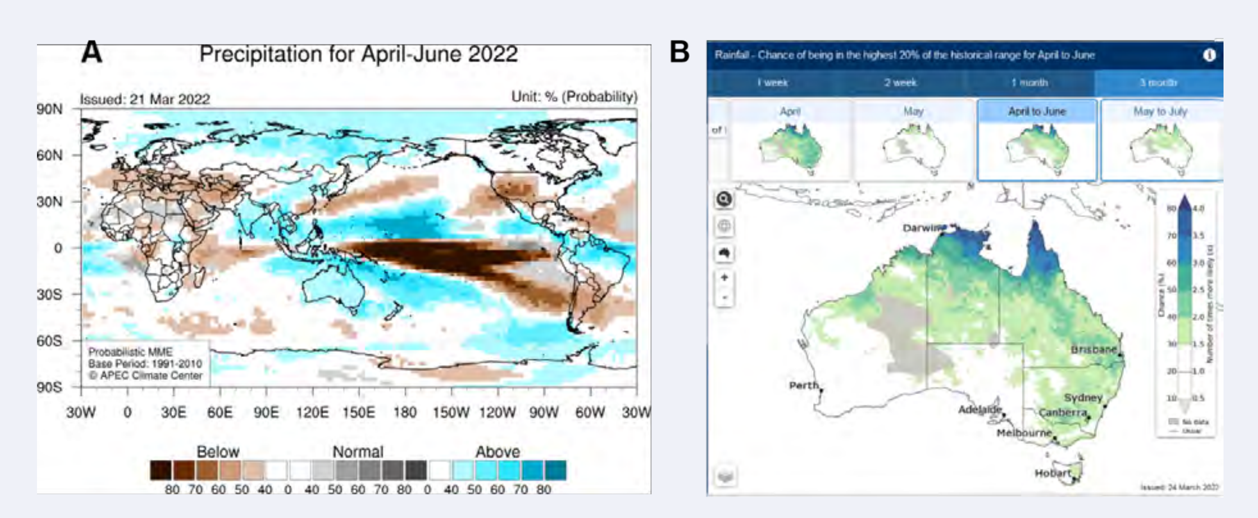

FIGURE 1. Panel (A). Seasonal forecast from the APEC Climate Centre, showing probabilities that precipitation in April-June 2022 falls in the lower (below normal), middle (near normal), or upper (above normal) thirds of the climatological distribution for 1991-2010. Colours indicate probabilities for the most probable category, and white where no category is more probable than 40%. Panel (B). Forecast for the same period from the Australian Bureau of Meteorology shows probabilities for extremely high seasonal precipitation, defined as in the upper fifth (20%) of the historical range. This more specifically describes chances for an extremely wet season than the information in Panel (A) and indicates to the right of the colour bar factors by which occurrence of such an extreme is more (or less) likely than usual.

Category	Oral presenters	Poster presenters	Total
Overall	42	26	68
Female	19	10	29
Male	23	16	39
Student/Postdoc	11	13	24
Faculty/Research Professional	19	9	28
Senior Faculty/Research Professional	12	4	16
APN Member Developing Countries	4	5	9
Other APN Member or Approved Countries	21	12	33
Non-APN Countries	17	9	26

TABLE 1. Summary information for ExCPEns workshop presenter genders, career stages, and countries of home institutions.

cally, culturally, and socially diverse global research community and promoted Young Earth System Scientists (YESS), a global community resource for ECS. Following a round of introductions, 43 qualifying EC were divided into six breakout discussion groups, each led by an experienced scientist. Each group focused on three discussion questions, two of which were common across the groups, whereas each of the group leaders formulated the third question. One ECS in each group served as rapporteur and reported on their group's discussions during a concluding plenary gathering.

The ECS programme continued with a series of six Training Lectures that were held in separate afternoon and evening sessions on 28 October. Each lecture was allocated 30 minutes and was followed by 15 minutes for questions and discussion. The lecturers were subject matter experts in the US, Canada, UK, Switzerland, and China, and 59 ECS from 21 countries participated. The topics covered, and the outcomes of the ECS networking discussions are reported in Section 3.2. Figure 2 contains a partial group portrait taken during the workshop's opening session, and Figure 3 indicates countries represented by workshop and ECS session registrants, showing the status of those countries concerning APN.

3. RESULTS AND DISCUSSION

3.1. Workshop outcomes

The workshop was built around six research themes on weather and climate extremes chosen

FIGURE 2. Group portrait of ExCPEns Workshop and Early Career Scientist Training Sessions participants.

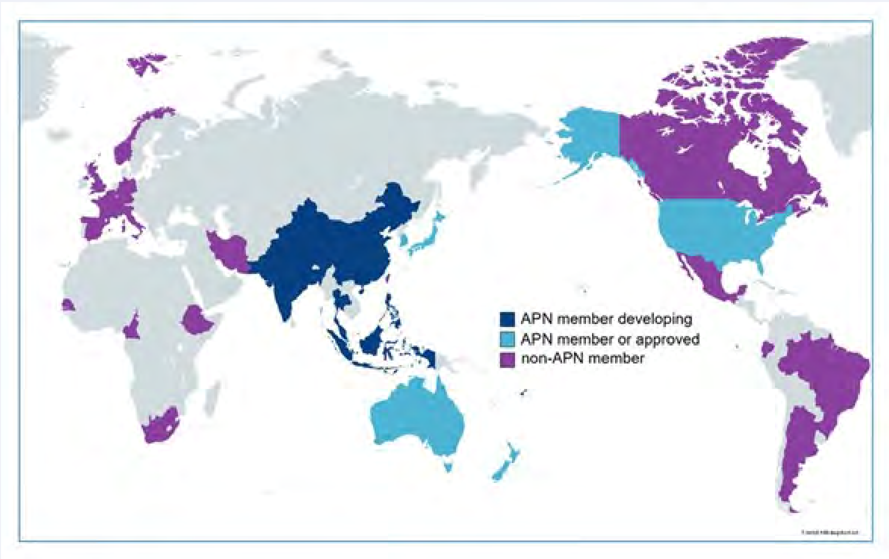

FIGURE 3. Countries represented by Workshop and Early Career Scientist Training Session registrants.(Dark blue: APN member developing countries. Light blue: other APN members or approved countries. Purple: non-APN member countries). Figure created using mapchart.net.

as high-priority research areas. These themes are described in the subsections below, each of which summarizes key aspects from the presentations, areas of consensus and, in some cases, caveats that were raised about certain methods and results, and further research priorities.

3.1.1. Identification of extremes in observation and climate prediction ensemble

The first important step for assessing the impact of extremes in the societal context and the potential for their prediction is the identification of extremes. Presentations in this theme focused on aspects of extremes such as their spatiotemporal footprints, cataloguing of classes of simulated and observed extremes, their characterization in climate projection ensembles, combining information from decadal predictions and multi-decadal projections, and verification of forecasts of local heatwave indices. A common element was that algorithms for detecting extremes need to be formulated carefully to avoid missing or falsely identifying events of interest and that these methods should take into consideration the impacts of particular types of extremes in terms of their severity, duration and regional extent (Prodhomme et al., 2021). In addition, model simulations were viewed as valid data sources either to multiply sets of infrequent events used for risk assessments (e.g. Lockwood et al., 2022), or to "fill in" unobserved features of an event using simulations constrained by available observations (e.g. Mogen et al., 2022), provided the simulations are carefully validated and bias corrected. Research priorities in this theme that were identified include (i) assessment of definitions and characterizations of climate extremes, and methodologies for identification of extremes in observational data, (ii) identification of limitations in different observational datasets for the characterization of extremes and their influences, (iii) validation of extremes in climate prediction ensembles against observational estimates, and (iv) quantification of biases in extremes in climate prediction ensembles, associated implications for prediction, and possible model deficiencies responsible for biases in simulation of extremes.

3.1.2. *Physical mechanisms of extremes in observations and climate prediction ensembles*

Understanding physical mechanisms and large-scale drivers for weather and climate extremes is a prerequisite for improving the prediction of extremes. Presentations on this theme emphasized the origins and impacts of phenomena such as rare Antarctic sudden stratospheric warmings (Lim et al., 2021) and local and remote drivers of heat, drought, and rainfall extremes. Examples of local drivers examined include low soil moisture amplifying dry and heat extremes, and variations in atmospheric moisture supply leading to drought onset and termination. In contrast, remote drivers include sea surface temperature variability and the Madden-Julian Oscillation (MJO) and Quasi-Biennial Oscillations. Areas of consensus were that climate extremes are often influenced by confluences of multiple large-scale drivers (e.g. Holgate et al., 2020 ; Jia et al., 2022), and that soil moisture can be an especially important driver for heat extremes (e.g. Materia et al., 2022). Some caveats were that relationships between large-scale drivers and local extremes might not be stationary in a warming climate, and that very high resolution may be needed to accurately model sea surface temperature and other influences on precipitation extremes (Chen, Hsu, Liang, Chiu, & Tu, 2022). Research priorities in this theme that were identified are (i) a better understanding of mechanisms of extremes in observation, (ii) better identification of large-scale drivers and important feedback processes for extremes, and (iii) verification of mechanisms of extremes captured by CPEs, linking predictability and their initial state dependency.

3.1.3. *Regional climate extreme information relevant to impacts, vulnerability and adaptation*

Accurate and regionally well-tailored climate information has become important for early warning and risk management to adapt to more frequent and severe weather and climate extremes. Presentations on this topic highlighted aspects of particular socioeconomic relevance including co-developed communication of probabilistic forecasts of extremes for sectoral applications, using observed large-scale climate variations as predictors to estimate future flood economic loss risk, and identifying impactful future changes in rainfall extremes in long-term climate projection ensembles. Contrasting approaches included determining statistical connections between climate patterns and economic loss (Hu, Wang, Liu, Gong, & Kantz, 2021) , and interfacing with sectorial users to develop climate extreme forecast information that applies to decision-making in the agricultural sector (Hayman & Hudson, 2021). Two research areas prioritized in this theme were (i) assessment of regional climate extreme information currently used and additionally required to enhance early warning systems for robust decision-making, to maximize the socioeconomic benefits and to minimize the costs of extreme events, particularly for highly vulnerable regions and countries; and (ii) development of effective delivery and shaping of climate information to promote understanding and communicating with regional society.

3.1.4. Prediction and predictability of large-scale climate variability relevant to extreme events

Patterns of large-scale climate variability, including the MJO, El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Boreal Summer Intraseasonal Oscillation (BSISO) and Northern and Southern Annular Modes, can increase the likelihood of climate extremes in particular regions and seasons. Presentations under this theme focused on using climate prediction ensembles to examine how climate extremes are influenced by large-scale climate variability patterns and warming trends on subseasonal to multi-decadal time scales and to what degree skill in predicting large-scale patterns enables skilful prediction of local extremes. One point of agreement was that for models to realize predictability and skill due to tropical patterns of variability (MJO, ENSO, IOD, BSISO), it is necessary both to accurately predict those patterns and correctly represent the corresponding teleconnections (Doi, Behera, & Yamagata, 2020; Feng, Klingaman, Hodges, & Guo, 2020). Biases in representing large-scale environmental conditions can degrade modelled teleconnections, which points to a reduction of systematic model errors as one way to improve prediction skill (Xie, Yu, Chen, & Hsu, 2020; Imada & Kawase, 2021) , although accuracy of the initialization also plays a role (Long et al., 2021). The prioritized research topics in this theme include (i) the use of CPEs to predict and evaluate the predictability of large-scale climate variability patterns and associated climate/Earth system extremes, and (ii) examination of the nature and impacts of large-scale climate events on more severe extremes than any yet observed in individual CPE realizations.

3.1.5. Prediction and predictability of specific extreme events (>10 days)

There is increasing interest in predictability and prediction of extreme weather beyond ten days, which is sometimes considered a limiting range for useful weather predictions. Skillful forecasts of extreme events beyond ten days would help to develop early warning systems for better preparedness that would benefit society. However, model systematic errors make it challenging for models to adequately represent extreme events. Presentations in this theme highlighted the current state of prediction of heatwaves, hydrological and hydrometeorological extremes, tropical cyclones, low-pressure monsoon systems, and lightning utilizing subseasonal to seasonal (S2S) and other subseasonal ensemble prediction systems, including applications of machine learning for post-processing to enhance the skill. One perspective common to several of the presentations is that predictability of specific extreme events can be conditional; for example, dry Australian hydrological extremes are predicted more skillfully than wet extremes (Vogel et al., 2021), and Indian heat waves are predicted skillfully beyond week two for certain regions and probability ranges (Mandal et al., 2019). Caveats that were raised include that predicted magnitudes of extreme events are often underestimated by the ensemble mean even when other aspects of an event are predicted accurately (Domeisen et al., 2022); some events may not be predicted as well as expected from the accuracy of historical predictions (Tsai, Lu, Sui, & Cho, 2021); and multi-model ensembles do not always outperform the best-performing individual model (Deoras, Hunt, & Turner, 2021). The research topics to be further focused upon include (i) prediction and predictability of the onset, evolution and decay of large-scale, long-lasting extreme events (e.g., heat or cold waves, droughts) at all time scales beyond ten days, and (ii) prediction and predictability of changes in the probability of occurrence over a large region and large period of time of some extreme events, such as tropical cyclones, tornadoes, and heavy rain episodes, for which individual occurrence is usually not predictable beyond ten days.

3.1.6. Quantifying current and future risks of climate extremes

Observations provide just one of many potential realizations of the chaotic evolution of the climate system and may not adequately represent the full range of extreme events that can occur in a changing climate. Realistic climate prediction ensembles overcome these limitations by providing many more realizations of potential extreme events. Presentations in this theme focused on extracting information about current and future probabilities of weather and climate extremes, including unprecedented extremes, from climate prediction and projection ensembles and high-resolution simulations. Innovative methods applied include the UNprecedented Simulated Extremes using ENsembles (UNSEE) approach, whereby large seasonal and decadal prediction ensembles are used as a "multiplier" of the single observed record of climate variability (Kay et al., 2022), and rare event algorithms that enhance sample sizes in the tails of distributions (Ragone & Bouchet, 2021). Additional studies focused on estimating how anthropogenic warming has influenced the severity of recent observed droughts (Kam, Min, Wolski, & Kug, 2021) and possible recurrences of a historical drought (Baker, Shaffrey, & Hawkins, 2021), as well as extreme precipitation severity more generally under historical and future warming (Paik et al., 2020; Mizuta & Endo, 2020). Common elements included that model outputs need to be validated carefully against observations and, if necessary, bias corrected, and that finite computational resources need to be allocated based on the problem being addressed. For example, although very high resolution is essential for accurately representing tropical cyclones, century-long simulations are sufficient for examining changes in their global statistics (Chu et al., 2020), in contrast to the thousands of simulated years needed to represent occurrences of the rarest events (e.g. Thompson et al., 2019). For this theme the research priority is better quantifying the changes of extremes in the current climate, including unprecedented events, and how they will evolve in the future.

3.2. Early career scientist training and networking outcomes

In conjunction with the ExCPEns workshop, an ECS Training and Networking programme was held from 27 to 28 October 2021. The programme aimed to build global research capacities for understanding, predicting, and assessing risks and impacts of weather and climate extremes.

3.2.1. ECS Training Programme

Table 2 summarizes the ECS Training programme, which took place in two sessions. In Session 1 on Extreme Detection and Prediction, Sookyung Kim of the Palo Alto Research Center lectured on the detection of extreme events using machine learning, including data challenges in scientific research, detection and localization of extreme climate events, super-resolution models for downscaling key processes, and tracking and predicting extreme climate events. Megan Kirchmeier-Young of Environment and Climate Change Canada lectured on extreme event attribution, including an illustrative introduction to event attribution, focusing on simple, popular methods and suggesting references to consult for additional details. Frederic Vitart from the European Centre for Medium-Range Weather Forecasts reviewed the predictability of extreme events on S2S time scales highlighting sources of S2S predictability such as MJO, soil moisture, stratospheric initial conditions, Rossby waves, sea surface temperatures, sea-ice, and aerosols.

Session 2 on Projection of Future Climate Extremes focused on outcomes from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). Jin-Ho Yoon of Gwangju Institute of Science and Technology introduced the important regional assessment results in AR6 (Gutiérrez et al., 2021) and demonstrated how to use the IPCC AR6

Session	Lecture Title	Lecturer
Session 1. Extreme Detection and Prediction	Detection of extreme events using Machine Learning	Dr Sookyung Kim (Palo-Alto Research Center)
	Extreme event attribution	Dr Megan Kirchmeier (Environment and Climate Change Canada)
	Predictability of extreme events in S2S time scales	Dr Frederic Vitart (European Centre for Medium-Range Weather Forecasts)
Session 2. Projection of Future Climate Extremes	How to use the AR6 WGI interactive Atlas for climate change studies	Prof. Jin-Ho Yoon (Gwangju Institute of Science and Technology)
	Low likelihood high impact events assessed in AR6 WGI Chapter 4	Prof. Erich Fischer (ETH Zurich)
	Change of extremes assessed in AR6 WGI Chapter 11	Dr Xuebin Zhang (Environment and Climate Change Canada)

TABLE 2. Summary of ECS training programme including sessions, lecture titles and lecturer information.

Interactive Atlas (https://interactive-atlas.ipcc.ch/). He highlighted that climate change is affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes. Erich Fischer of ETH Zurich lectured on high-warming storylines mainly based on Chapter 4 of the Working Group I (WGI) contribution to AR6 (Lee et al., 2021) and very rare extremes. He emphasized that (1) low-likelihood outcomes are often associated with the greatest risks, (2) warming substantially larger than the best estimate cannot be ruled out, (3) we need to prepare for events of unprecedented intensity, and (4) different independent approaches can help us understand low-likelihood high impact events in the near future. The last lecture was given by Xuebin Zhang of Environment and Climate Change Canada on weather and climate extremes in a changing climate. He highlighted observed changes in extremes and their attribution, projected changes in extremes, projected changes in extremes at the regional scale, and key messages throughout Chapter 11 of the WGI contribution to AR6 (Seneviratne et al., 2021).

3.2.2. *Networking and Discussion Forum for ECS from APN Developing Countries*

The ECS networking forum centered on breakout sessions matching ECS small groups with experienced scientists. Two questions were discussed by all of the groups. The first was about what the most important scientific challenges are for predicting weather and climate extremes and how we can tackle them. The outcomes of the discussion were as follows:

- Some challenges are posed by modelling limitations, such as limited resolution and imperfect parameterizations, leading to errors in representing teleconnection patterns and limitations for providing information at local scales.
- Additional challenges result from the limited length of the modern observational record, particularly land variables such as soil moisture and the rareness of some extreme events leading to insufficient samples for forecast calibration and verification.
- Possible solutions include the application of machine learning to improve model parameterizations and correct model errors through post-processing, longer hindcast periods to increase the sample of rare events and better understand climate change impacts on predictability and skill, and downscaling of global model outputs to better represent small-scale processes and orographic effects contributing to extremes.

The second question concerned the difficulties faced by ECS in developing countries and what some possible solutions are. The outcomes of the discussion were as follows:

- Among the barriers discussed were lack of state-of-the-art computational facilities and difficulties with data accessibility in ECS home countries, lack of training opportunities for keeping up with rapidly changing technology and scientific developments and for scientific communication, and above all, limited opportunities for finding relevant employment after graduation.
- WCRP and other international organizations could help by providing or connecting ECS to training courses covering scientific developments, basic climate dynamics and academic writing, and by providing fellowships or otherwise facilitating postdoctoral employment for ECS from developing countries.
- Both of these questions bear on the critical need for improving capabilities for extreme event prediction in APN developing countries and the Global South more broadly, as these regions are particularly exposed and vulnerable to associated adverse impacts (IPCC, 2022). Types of weather and climate extremes identified by the ECS as especially threatening to their regions include tropical storms (typhoons, cyclones and hurricanes), extreme rainfalls, heatwaves, and lightning, and especially compound extremes, such as combined heatwaves, and drought. Scientific advances in predicting such events, including on local scales, will be enormously beneficial and should be an international research priority. Strengthening career development opportunities for ECS in these countries will accelerate such advances by providing new capacities for targeted research and associated services tailored to local needs. ExCPEns, through its scientific presentations and lectures, as well as connecting experienced scientists with ECS, sought to contribute to these objectives.

4. CONCLUSION

This project aimed to advance the rapidly emerging science of exploiting subseasonal, seasonal, annual to decadal and long-term prediction ensembles to improve the prediction and understanding of weather and climate extreme events by hosting the WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns) and Early Career Scientists Training and Networking Programme. During the workshop, 68 presentations were made during six sessions. About 300 participants from all over the world attended the workshop. The Early Career Scientist (ECS) event followed the ExCPEns workshop and consisted of a networking and discussion forum for ECS from APN member developing countries, along with a series of ECS training lectures and discussion sessions open to all ECS registrants.

Through the workshop and discussion among stakeholders, the project team identified the following high-priority research topics addressing end-user requirements in the Asia-Pacific region:

- Improvement of high-frequency and high-resolution observation, especially for land processes such as soil moisture, by integrating information across in situ and satellite observations, reconstructions, and reanalyses;
- Development of tailored regional forecasts of weather and climate extremes;
- Advanced dynamical or statistical downscaling of global model ensembles to better represent small-scale processes and orographic effects contributing to extremes;
- Better understanding of climate change impacts on predictability and prediction skills for large-scale variability relevant to extremes;
- Production of longer hindcasts to increase the sample size of rare events;
- Application of machine learning to improve model parameterizations and correct model errors through post-processing.

By bringing together researchers from across regions and career stages, the ExCPEns Workshop and ECS Programme helped to consolidate and stimulate research on understanding and predicting weather and climate extremes from subseasonal to climate change time scales. By engaging with ECS primarily from APN developing countries that tend to be most impacted by extremes, these events additionally enabled learning and networking to assist the next generation of scientists in tackling critical research challenges that must be met to increase the resilience of vulnerable regions in a changing climate.

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Technical report

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Facilitating knowledge sharing and co-creation between communities of climate research and its users

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ABSTRACT

Climate impacts and risks involve climatic impact drivers, the exposure and vulnerability of natural and socioeconomic systems, and a strong interdependency exists between climate, nature and human society. Effective climate change adaptation requires effective knowledge sharing and co-creation between communities of climate research and its users. This pilot project of the World Climate Research Programme, supported by the Asia-Pacific Network for Global Change Research and other funders, brought together experts and future leaders from the two communities to familiarise themselves with the aspects of the other discipline. The project demonstrated that knowledge-sharing and co-creation benefit everyone involved and good progress in bridging the gap between the two communities can be made. We also learned that going beyond one's own training is challenging and fixing the gap requires both communities' long-term and sustained commitment.

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Climate change, knowledge sharing, World Climate Research Programme (WCRP)

HIGHLIGHTS

- Empowerment of stakeholders on climate information and adaptation.
- Joint exploration of stakeholders on key topics such as climate changes, extreme climate, climate forecast and risk management.
- Efforts to involve early-career scientists in climate science leadership.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC), in its 6th Assessment Report (AR6), removed any doubt about the human nature of climate change, stating that "it is unequivocal that human influence has warmed the atmosphere, ocean and land" and that "human-induced climate change is already affecting many weather and climate extremes in every region across the globe" (IPCC, 2021, p. 4). Human influence has resulted in changes in weather and climate extremes. For example, hot extremes (including heatwaves over land and marine heatwaves) have increased and cold events have decreased in every region assessed in the IPCC AR6 WGI report (Seneviratne et al., 2021). There are clear increases in the frequency and intensity of heavy precipitation in every region and increases in agricultural and ecological droughts in almost all regions that are prone to drought, such as the Mediterranean region. In addition to changes in weather and climate extremes, climate change has also resulted in changes in the magnitude, frequency, duration and seasonality of many other climatic impact-drivers, such as growing season (Table TS.5 of Arias et al., 2021).

Climate change has also resulted in widespread impacts on nature and people. The impacts range from increased heat-related human mortality, reduced water and food security, increased loss and damage due to tropical cyclones and wildfires in some regions, and warm-water-related coral bleaching (Figure SPM.2 of IPCC, 2022). For example, human-induced climate change had a substantial influence on the November 2021 flood in British Columbia, Canada, that resulted in the loss of lives and the destruction of infrastructure, including bridges, roads and railways, etc. (Gillett et al., 2022). Warming will continue until at least the middle of the 21st century, regardless of mitigation efforts, and very large warming is expected if deep reductions in the emission of greenhouse gases are not achieved in the coming decades. Many changes in weather and climate extremes that have been experienced on global and regional scales will continue and become larger with additional warming (Seneviratne et al., 2021). Undoubtedly, future changes in the climate will lead to increased and more severe impacts.

The impacts of climate change and climate risks involve climatic impact drivers, the exposure of natural and socioeconomic systems that provide service to society, and the vulnerability of these systems. There is a strong interdependency between climate, nature and human society. Climate impacts and risks can be reduced or mitigated by a reduction in the intensity and frequency of climate hazards and climate adaptation through a reduction in exposure, a reduction in vulnerability by increasing resilience, or a combination of the two. There are multiple ways to reduce hazards, vulnerability and exposure (Figure 1) (Abram et al., 2019). For example, the use of water reservoirs can not only reduce floods but also buffer low flows and water scarcity. A sponge city concept (Xia et al., 2017) for urban construction can reduce urban flooding and water resource shortages because this urban development model attempts to distribute and retain water at its source; slow down water as

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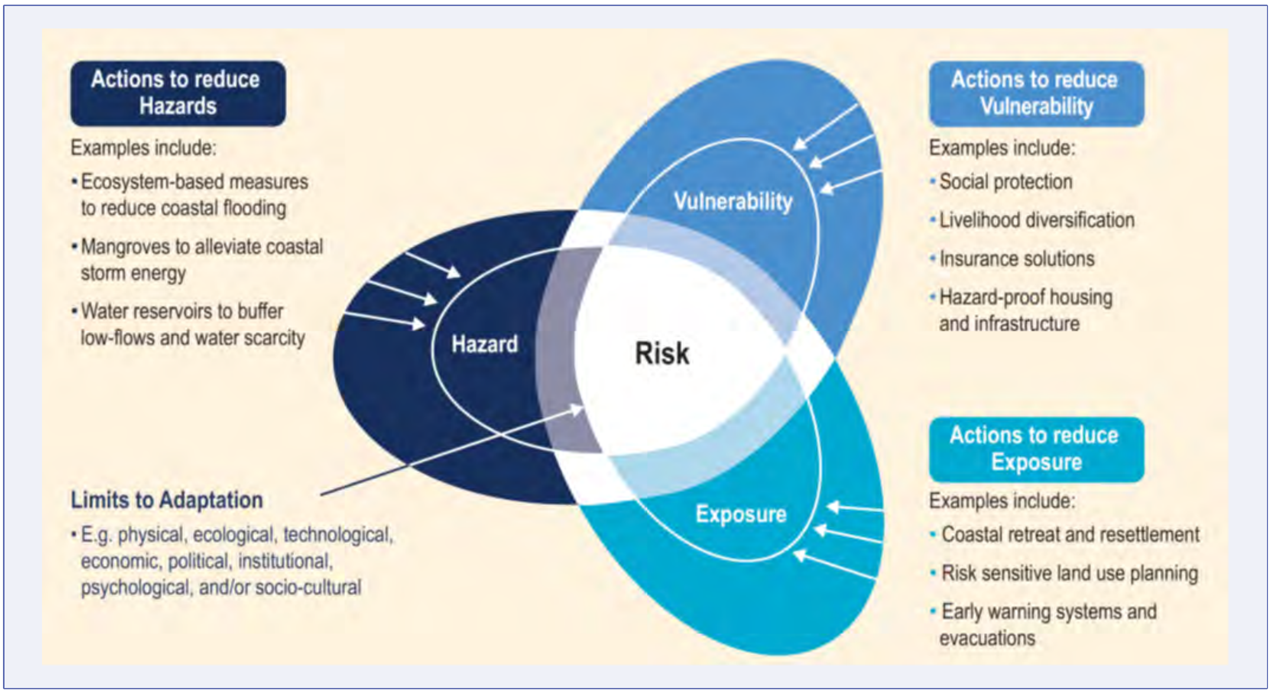

FIGURE 1. The IPCC risk framework shows options for risk reduction through adaptation by addressing one or more of the three risk factors: vulnerability, exposure and/or hazard, until limits to adaptation are reached (reproduced with permission from IPCC, Figure CB2.1 of Abram et al., 2019).

it flows away from its source; clean water naturally; and be adaptive to water at the sink when water accumulates. Considering climate change in infrastructure design reduces the vulnerability of infrastructure in a changing climate. A zoning change that prevents housing construction on flood plains decreases exposure. The efficiency and efficacy of all these adaptive measures can be significantly improved if knowledge of past and future climate change is used and properly interpreted when developing and implementing climate adaptation.

On the one hand, while it is certain human emissions have resulted in changes in climate on a global scale, knowledge about future climate is still highly uncertain on the scale of space and time, which are most relevant to local and regional climate change adaptation, such as design precipitation for urban planning in a city. On the other hand, the hazard, vulnerability and exposure can be quite dynamic depending on adaptation. Sharing and co-creating climate change knowledge between the climate research community and its user community, including, for example, policymakers of various levels of government, city planners and practitioners, cannot only enable the proper interpretation of climate change knowledge by the users but also help the climate research community identify areas that are urgently needed for improvement and prioritise their research and communication. Nevertheless, there have been barriers to such knowledge sharing and co-creation.

2. EFFORTS

The aforementioned barriers have been increasingly recognised and are being actively addressed. The World Climate Research Programme (WCRP) has been promoting knowledge sharing and co-production along with other programmes, including Future Earth and the Integrated Research on Disaster Risk (IRDR) programme. The Institute of Advanced Studies in Climate Extremes and Risk Management (Figure 2, https://www.wcrp-climate.org/extremes-risk-summer-school-overview), held in Nanjing, China, from 21 October to 1 November 2019, was one such attempt. The Institute was established and organised by WCRP in collaboration with the Nanjing University of Science and Technology (NUIST), IRDR, and the SysTem for Analysis, Research and Training (START), funded by multiple agencies with a significant contribution from the Asia-Pacific Network for Global Change Research (APN).

The Institute promoted an active exchange of knowledge and integration across climate research and its users, focusing on disaster risk reduction and management. World-leading experts from the two communities were brought together to familiarise themselves with the aspects of the other discipline. Five of the six lecturers were involved in the IPCC WGI and WGII assessments as lead authors or coordinating lead authors with expertise ranging from physical aspects of climate extremes to impacts of climate change and risk management. The attendees included 29 participants from 17 countries and ten local students from China. The majority of participants were early-career scientists from Africa, Asia and South America, selected from over 400 applications. Some participants were PhD students in an advanced stage, but most were recent PhD graduates. Participants had backgrounds in climate science or applications of climate science in various sectors, including water resources management, forestry and agriculture, and finance and policy.

This event served as the basis for an interdisciplinary study for collaborative research on the following key topics (Jiang, Zhang, Lee, & Han, 2019):

- Attribution of changes in the frequency and intensity of extremes
- Climate risk from compound events
- Projections and predictions of extreme events
- Climate risk reduction and management

3. PROGRAMME CONDUCTED

This event was conducted in the format of a summer school. The training took place in the morning, covering the basics of climate science, fundamentals of risk evaluation and management, and in-depth excursions to the current frontiers of some aspects of research on extremes with the latest case studies and research methods. Other aspects covered also included past and future changes in temperature and precipitation extremes, extreme compound events, future projections of floods relevant to hydro-power operations, and the IPCC risk framework (Jiang et al., 2019). Sessions continued in the afternoons and the remaining evenings on the practical application of material covered during the lectures, centred on a set of research problems developed prior to the event. Each lecturer led a team of six to seven participants from different backgrounds and geographical regions to work on a specific research question. Working with a specific research question in such a setting provides a platform for networking, in-depth knowledge exchange and integration across disciplines. Some questions required additional work after the summer school and led to peer-reviewed publications (Santos et al., 2021; Li et al., 2022). Poster sessions were also held for participants to present their research work. Participants and expert lecturers gained significant benefits from the interactive training throughout the course, especially on the topic of extremes and risk management.

After the programme had concluded, the participants were invited to submit evaluation reports focusing on the following questions: overall reflection of the event, including highlights (both good and bad), practical utility of the event, including participant's presentations and posters and suitability of assigned research subject and problems studied, networking opportunities, follow-up plans and applications both in the near- and long term, and lessons learnt. Based on the feedback from the participants, it appears that in addition to the increased knowledge and information on the specific subjects covered, the activity has resulted in the following (Jiang et al., 2019):

- Enhanced comprehension by the participants in subjects covered at the summer school through lectures, question/answer sessions and research projects
- Mutual recognition and awareness of the developments within the climate research and the risk management communities on

FIGURE 2. Group photo of the summer school participants, lecturers and organisers, 21 October 2019.

individual, regional and global scales

- Facilitating the development of cross-disciplinary partnership and collaborations to support, especially among young scientists, in enhancing ongoing and future scientific progress in risk reduction and building resilience to climate change and extreme events
- Creating collaborative research initiatives for young scientists for extreme event research and risk analysis/management
- Providing opportunities for early-career scientists to network and interact with peers and senior scientists around the world

Participants also identified areas for future improvement and/or consideration. For example, while information about the lecturers was provided prior to the event, detailed information such as their expertise and research interest was disseminated only in the middle of the first week. Some participants thought the provision of such information prior to or early in the event would have facilitated networking better. More classroom lectures would have benefited some participants better, but more hands-on exercises would have suited better for other participants, suggesting the need to consider better the different levels of expertise of the participants.

4. OUTCOMES AND WAY FORWARD

This activity provides valuable experience for similar programmes in the future. Similar activities should continue to be developed and provided. The success is rewarding, but it takes a strong commitment from the organisers, lecturers and participants before, during and after the active training event for a lasting legacy. We also learned that while there are clear needs for bridging climate research and its user communities, going beyond one's training is challenging. The gap is so large that fixing it requires both communities' long-term and sustained commitment. The programme also demonstrated that good progress could be made as long as there is insistence and persistence from the community.

The new WCRP Strategic Plan 2019 made bridging climate science and society one of the four scientific objectives of WCRP. To this end, WCRP has launched several new initiatives. The new core project Regional Information for Society (RIfS, https://www.wcrp-climate.org/rifs-overview) will focus on growing the foundations for effective links between climate research and the information needs of society. The My Climate Risk Lighthouse Activity will develop and mainstream a "bottom-up" approach to regional climate risk, involving experts from the climate research community but also users of climate information.

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Technical report

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Enhancing capacity of scientists and practitioners for promoting more sustainable and resilient food systems in Indonesia and the South Pacific

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ABSTRACT

Three Resilient Food Systems training workshops were delivered in Bogor, Indonesia, Suva, Fiji, and Port Vila, Vanuatu. The workshops provided young and early-career professionals with the latest international thinking on food systems and resilience. The workshop teaching material was based on the IFSTAL (Interdisciplinary Food System Teaching and Learning; www.ifstal.ac.uk) programme initially developed in the United Kingdom. The intensive six-day workshop programme integrates learning across three connected themes: food systems and resilience concepts, soft system methodology, and personal skills and development. Each workshop is locally contextualised with field trips, local inspirational guest speakers, and local real-world food system case studies. Throughout the duration of the workshop, participants apply new concepts and methodologies to their case studies, thereby enhancing their understanding and learning. Participant evaluation of the workshops was overwhelmingly positive, and pleasingly, participants reported positive learning outcomes across all three learning themes. These workshops represent just the initial step in a necessarily long and sustained effort to establish a community of food system professionals across Indonesia and Pacific Island states.

KEYWORDS

Food systems, resilience, food security, Indonesia, Pacific Island States

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HIGHLIGHTS

- Human capacity for food systems analysis, design and intervention is very low in target countries.
- Demand for professional training for developing resilient food systems was high.
- Innovative training workshops were very positively received by participants.
- There is an ongoing need to embed these teaching resources in local education and training institutions.

1. INTRODUCTION

Food insecurity remains a complex challenge for both developed and developing countries. Recent developments, such as the global pandemic, have highlighted vulnerabilities in current food systems and pushed millions more into food insecurity. The ongoing war in Ukraine has highlighted the unpredictable nature of geopolitical shocks and their consequences for global food commodity markets. Even before these two recent examples, traditional challenges such as global climate change, dietary changes, population growth, poverty, and environmental degradation have emphasised the dynamic, complex, and contested nature of food security.

It is precisely because of the complex nature of food security that a food systems approach is needed. This has promoted recognition of the need to 'transform the food system', a phrase now often seen in academic (Fanzo et al., 2021; InterAcademy Partnership, 2018; Ruben, Cavatassi, Lipper, Smaling, & Winters, 2021) and policy (e.g. Sonnino et al., 2020; USDA, 2022) literatures. But what is meant by these calls to transform the food system? Transformation from whose perspective? What will be the balance between winners and losers from the proposed transformation? Will the transformation require a transition period? Is their political will in support of the transformation, or perhaps more likely, resistance to the transformation from powerful vested interests? What is the time frame for the transformation? And perhaps most importantly, what exactly needs to be transformed? (Ingram & Thornton, 2022). These are essential questions if we are to develop healthier, more sustainable and resilient, and fairer food systems. The pathways to such food systems will be complex and contested, and a new kind of food system professional is required to guide this transformation.

Furthermore, most scientists and professionals currently engaged in food security and related challenges listed above have not received formal training in food systems. This capacity building project represents the beginning of an educational and training journey to build capacity for developing food systems resilience in Indonesia and the Pacific Island states of Solomon Islands, Vanuatu, Fiji, and Samoa. This paper describes the demand for food systems training in the target countries, novel aspects of the training workshops, participant outputs and participant evaluation of the workshops. We conclude with suggestions for future activity to enhance food system resilience in Indonesia and the Pacific.

2. KEY CONCEPTS FOR RESILIENT FOOD SYSTEMS

By necessity, food system approaches engage many actors, ranging from producers to consumers, from researchers to policymakers, and from public to private sectors. This diversity of actors (and their associated motives and purposes) creates a communication challenge and food system researchers need to strive for shared understanding of key terms and concepts. Several food system frameworks have

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been developed for different purposes (Ingram, 2020; Hasnain, Ingram, & Zurek, 2020), and a common feature is linking food system activities (producing, processing, distributing, consuming food) with food system outcomes (food security, economic, social, health, environmental) and food system drivers (e.g., climate change, global pandemic, war, etc.)

The Foresight4Food (F4F) Initiative's conceptual model (Figure 1) brings these aspects together by combining:

- the GECAFS food system model (Ericksen, 2008) for the emphasis on trade-offs and direct and indirect drivers of change, and
- the Making Markets Work for the Poor (M4) approach (Springfield Centre, 2014) on the interface of system rules and supporting functions with a set of core activities organised around supply and demand functions.
- the Wageningen University and Research food system model (Van Berkum, Dengerink, & Ruben, 2018), distinguished particularly by detail of food environments, enabling environments, and business services, and by the breakdown of socio-economic and environmental drivers.

The clustering of drivers and outcomes allows for a multi-scale analysis at the state and regional levels, where the scale, programme objectives, and stakeholder insights will enable a structured determination of the depth of analysis. This enables a high-level exploration of the embeddedness of the activities and stakeholders within the system so that existing feedback mechanisms can be best taken advantage of in multiple spheres of interest.

The key function of the food system framework is to facilitate a shared understanding of a specific food system of concern and encourages the use of language in a deliberate and precise manner. The framework is used extensively throughout the training workshops to provide opportunities for in-depth discussion and debate, and to encourage participants to identify points of interventions and desired or undesired consequences, including feedback loops.

The food system framework also facilitates understanding and operationalising of the concept of resilience. But what is a resilient food system, and how do we move towards more resilient food systems? The term resilience has different meanings for different practitioners and scientific disciplines. This diversity of meanings can lead to confusion and unnecessary conflict among stakeholders.

In order to avoid the risk of resilience becoming a hollow concept and an empty statement and to further progress and operationalise the concept of resilience in food systems, we support the use of the four resilience framing questions proposed by Helfgott (2018) in the context of Figure 1:

1. Resilience of what? Is it the key outcomes we want from food systems that are food security, livelihoods, environmental sustainability, etc. or a given activity, such as farming?
2. Resilience to what? The focus here is on the disturbances or drivers of the system in question.
3. Resilience for whom? Perspectives on resilience differ among stakeholders, so it is important to be clear about whose perspective is being included or excluded from the system in question.
4. Over what time frame? Food systems are highly dynamic over various time scales, and various activities and outcomes operate over shorter or longer time frames.

In the process of working through these questions, stakeholders are required to confront their own assumptions and biases, including their preconceived notions of boundaries to the food system of interest, to achieve a common goal. This requires negotiation (Hansen, Ingram, & Midgley, 2020), and to this end, the food systems framework provides a valuable aid for facilitating these discussions.

Answering these four questions 'scopes' the nature of the issue, which then allows for a

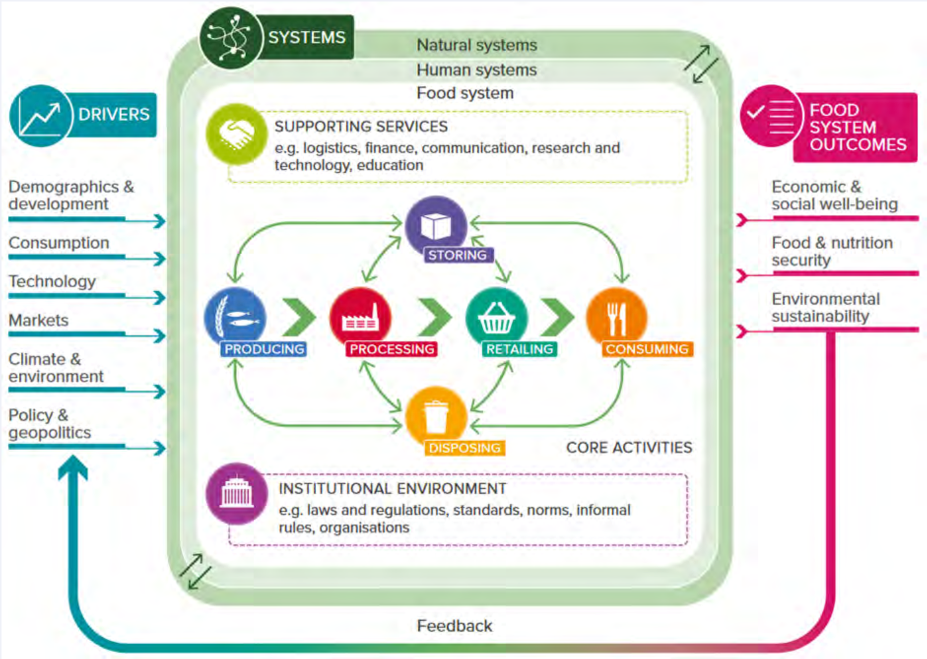

FIGURE 1. The food system framework developed by Foresight4Food (https://foresight4food.net/).

clear discussion about what action to take to enhance resilience. Here we recognise three broad approaches as described by Zurek et al. (2022) :

1. Robustness, where the aim is to resist the shock or stress so as to maintain existing functions and outcomes; preserve the status quo.
2. Recovery, where the system of interest recovers from a disturbance to deliver pre-disturbance functions and outcomes; return to the status quo.
3. Reorientation, where alternative systems outcomes are accepted; reject the status quo.

3. CURRENT CAPACITY AND DEMAND FOR FOOD SYSTEMS TRAINING

Prior to delivering the training workshops, each country was visited by the project leaders. The purpose of these visits was to:

- communicate the key concepts underpinning resilient food systems,
- promote awareness of the opportunity to attend the training workshops,
- identify local champions who could assist with practical organisation and delivery,
- identify local keynote speakers,
- select potential businesses or organisations that could host a field visit,
- identify local food system case studies to be used by workshop participants, and
- select the workshop dates, venue, accommodation and catering.

In addition to these core tasks, the project leaders were able to gain an overall impression of the current state of capacity for the analysis of food systems and the potential demand for food system resilience training. Key observations include:

1. There was weak capacity for analysing existing food systems or for designing interventions aimed at delivering more resilient food systems. This was despite all countries recognising the acute need for healthier, more sustainable, and more equitable food systems. There are, however, many people working in specific separate aspects of food systems, especially agriculture and fisheries.
2. There was a large gap between national strategies and capacity to deliver at the local level. For example, all countries had excellent high-level national food security strate-

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gies, but capacity to deliver these strategies at the local level was weak.

3. There was a very high level of 'siloing' between different government departments and other organisations. One very common example; government departments of health had only weak engagement with departments of agriculture, if any, although both stated that they were addressing food security. Similarly, departments of trade, business, environment, rural development, etc., were mainly working in isolation from each other.
4. Human capacity and physical infrastructure is often very limited at the local level. This is a well-recognised constraint in geographically large and distributed island nations such as Indonesia and the Pacific. The reality is that this constraint will continue to stretch budgets, making it difficult to allocate new funding to food system resilience, even though such an investment would deliver greater returns than business-as-usual.
5. There was wide-ranging support for the notion of enhancing capacity for developing resilient food systems. This was expressed by the number of young and early-career applicants for the limited workshop places and by senior managers and leaders of government, business and civil society organisations.

4. RESILIENT FOOD SYSTEMS TRAINING WORKSHOPS

The aims of the workshops were to raise awareness of food systems approaches and equip participants with new concepts and practical skills they could apply in their daily work practice. The workshop programme was designed to integrate three learning themes:

1. Resilient food systems concepts,
2. Soft systems methodologies, and
3. Personal skills and development.

The first strand covers key food systems concepts, including the food systems framework (Figure 1) that integrates Drivers, Activities and Outcomes; and a definition of resilience that requires the four questions introduced above to be answered. The second strand includes Soft Systems Methodologies, including Rich Picture Framing, Stakeholder Analysis, BATWOVE (Beneficiaries, Actors, Transformation, Worldview, Owners, Victims, Environment) and Theory of Change. These methodologies were applied within the resilient food system framework. The third strand developed personal skills in communication (listening, speaking), teamwork, and leadership. All three strands are closely integrated through participant group work on real-world local food system Case Studies. Throughout the week-long workshop, participants returned to their Case Studies to apply newly introduced concepts and methodologies. In this manner, participant-to-participant teaching and learning were maximised. The group work culminated in participant presentations on their proposed food system intervention.

4.1. Workshop Programme and Student Outputs

The workshop programme and pedagogy were based on the successful IFSTAL (Interdisciplinary Food System Teaching and Learning; www.ifstal.ac.uk) teaching resources developed in the United Kingdom. Local context was provided through local food system Case Studies, a mid-workshop Field Trip, and local guest speakers. The Resilient Food System workshops typically run for six days and an example programme from Bogor, Indonesia, is provided below (Table 1).

Workshop participants were randomly allocated to one of five groups. Each group of six participants would work on a local food system project for the duration of the training workshop. Group activities were designed to give participants experience in applying new food systems concepts and methodologies to their specific project topic (Figure 2). In Indonesia, the five project topics were:

FIGURE 2. Workshop participants applying new knowledge and skills to their specific food systems project (Suva, Fiji).

1. Delivering the national strategy on stunting at the local level
2. Adding value on-farm for local nutritious food
3. Socialisation the reduction of plastic bag use at the market or shopping mall
4. Diversification of staple foods in East Indonesia
5. Distribution and quality improvement of Bulog subsidised rice

As the participant groups worked through the different methodologies (Figure 2), their outputs were displayed on a wall in the main workshop room (Figure 3). In this way, all participants could compare their output with others and learn from each other. During morning and afternoon tea and during lunch, participants were encouraged to monitor the progress of the whole workshop as each day, new work was added to the wall. This 'participant-to-participant' learning led to deeper understanding, effective communication, and team building. The final workshop, 'wall of wonder,' is arranged with groups in columns and separate soft system methodologies in rows (Figure 3).

Similar workshop programmes and participant outputs were delivered in Suva, Fiji, and Port Vila, Vanuatu. The final day of the workshop was devoted to student group presentations (Figure 4) and participant evaluation of the workshops. A fourth workshop planned for Apia, Samoa, was abandoned due to the COVID-19 pandemic and associated travel restrictions.

4.2. Participant Evaluation

On completion of the workshop, participants were administered a survey seeking their reactions and feedback on the workshop. The results were anonymous. Nine questions used a Likert scale from 'Strongly agree' to 'Strongly disagree' (results from the Bogor Workshop are shown in Figure 5. Of these, the first three questions related to how the course was conducted and the overall management of expectations. The next three questions related to course content and accessibility of the course (including time management). Finally, the last three questions related to how the overall project was conducted including accommodation and catering facilities.

	Day 1	Day 2	Day 3	Day 4	Day 5
09:00	Opening LC scene setting PSD ice breaker	Introduction PSD Zoom teamwork game	LC Field trip to inspect local food businesses	Introduction SSM Theory of Change	PSD Group project presentations Five groups present and compete for judges scores
10:00	RFS Food system concepts	RFS Framing and Boundaries	Workshop participants apply new concepts and skills in real-world context	SSM Workshop: Implementing Theory of Change	
11:00	RFS Workshop: key features of Indonesian food systems	RFS Workshop: Identifying stakeholders			
13:00	LC Invited industry speaker	LC Invited government speaker		LC Invited NGO speaker	PSD Collaborate game
14:00	RFS Food system thinking	SSM BATWOVE tool		SSM Effective communication	Feedback from workshop participants
15:00	SSM Rich Picture	SSM Workshop: Applying BATWOVE		RFS Revision of key concepts	
16:00	PSD Group Project	PSD Group Project		PSD Group Project	Close of workshop
18:00	PSD Free to work on group projects	Workshop Dinner		PSD Free to work on projects	

TABLE 1. Resilient Food Systems training workshop programme. RFS – resilient food system concepts, SSM –soft system methodologies, PSD – personal skills and development, LC – local context. This is a generic outline only, and more detailed programmes were developed for each specific location.

Workshop participants responded mainly with 'Strongly Agree' or 'Agree' to all nine statements indicating a high overall satisfaction with the workshop content, processes, and general administration (Figure 5). Similar results were recorded for the Vanuatu and Fiji workshops.

A further four questions sought qualitative responses in the form of text (responses varied from one-word answers to several sentences) and are summarised below for the Bogor workshop (Table 2). Overall, participants provided positive responses to the four qualitative questions. Most participants enjoyed the workshop experience and reported a positive learning experience. However, there was criticism of the perceived level of repetition of key concepts and, conversely, a desire for wider coverage of topics related to food systems.

This feedback describes how the workshop largely met, and sometimes fell short of, participant expectations. Overall, quantitative and qualitative feedback was positive from all three workshops (Bogor, Port Vila, Suva). Pleasingly, participants reported positive learning experiences across all three learning themes (food system concepts, soft system methodology, and personal skills and development). Several negative responses were related to the intensity of the six-day workshop and the desire for greater time to explore new material in greater depth. This shortcoming is acknowledged and, in the long-term, this material would ideally be incorporated into more traditional delivery formats allowing participants greater time to digest and assimilate new information. Different participants have different learning styles, and

FIGURE 3. Bogor Wonder Wall showing outputs from five groups (columns) for Rich Picture (top), Stakeholder Analysis (middle) and BATWOVE (bottom) applied to local food system case studies.

FIGURE 4. Workshop participants presented a summary of their group projects on the final day of the workshop. These presentations provided an opportunity to showcase newly acquired knowledge and skills to a real world, local food security challenge (Suva, Fiji).

the format of these workshops was deliberately intensive and targeted towards young and early-career professionals.

5. KEY FINDINGS AND FUTURE DIRECTIONS

Key findings include:

- Demand for food systems training in Indonesia and the Pacific is high. Increasing complexity and ongoing challenges to food security (e.g., climate change, pandemic, governance, trade and business, public health) have created greater awareness of the need for food systems approaches, but capacity to implement food systems interventions remains weak.

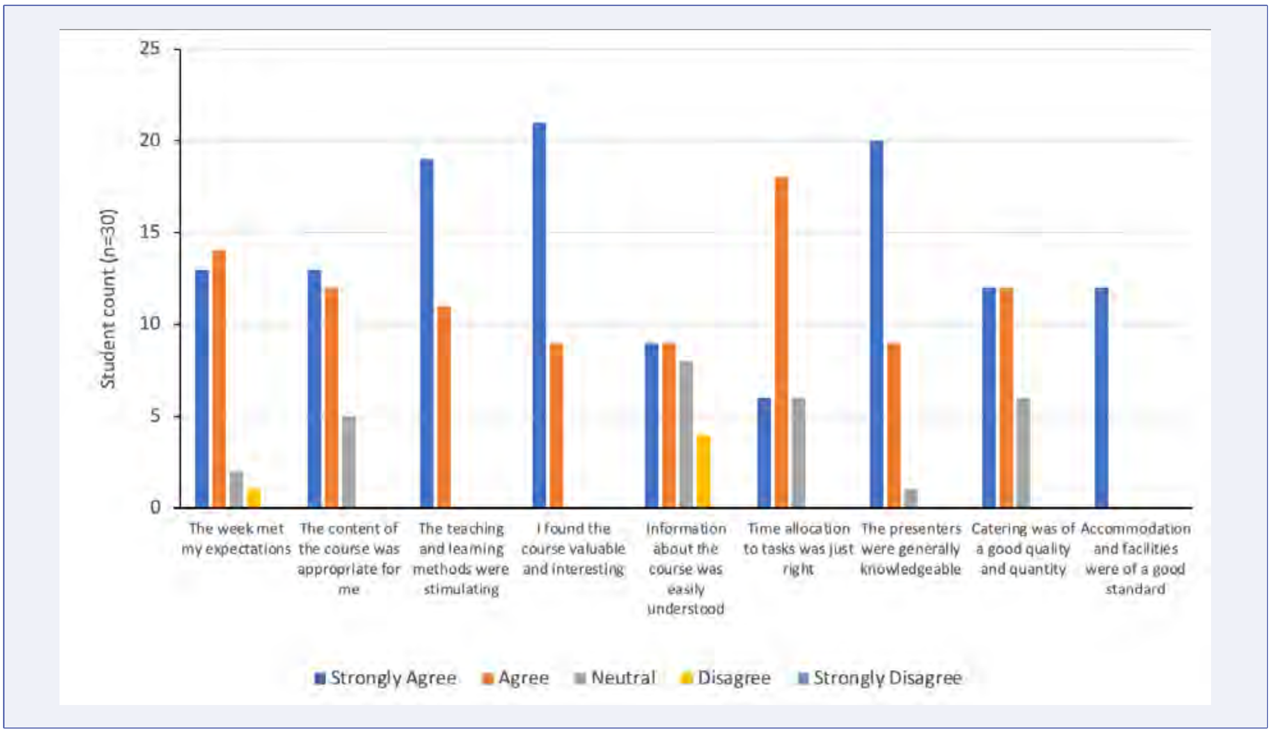

FIGURE 5. Feedback from Bogor workshop participants (number equals 30). Likert scores from Strongly Agree to Strongly Disagree, questions covered workshop content, delivery and general housekeeping.

Positive feedback	Negative feedback
1. What did you hope to gain from the week?	
• Problem solving skills • Networking with peers • Confidence to apply new skills and knowledge • Food system approach to solve food security challenges	• Not applicable
2. What did you find most useful in the course and why?	
• Developing systemic thinking • Games were brilliant • The field trip • Problem solving • Soft System Methodology and tools • Methods for engaging stakeholders • Informative lectures	• No negatives
3. What did you find least useful in the course and why?	
• Nothing, all round great package	• Repetition/Overlap • Need more time to process new concepts • ‘Ice-breakers’ unnecessary • Starting time was too late • Food system concepts not relevant to me • Would like to explore other group’s topics
4. Were there any areas not covered in the course which you would like to have been addressed?	
• Encourage more institutions to embrace food systems approach • Greater emphasis on selecting indicators for monitoring food system performance	• Current status of food security • Food safety needs more attention • Greater business perspective • Gender and environment issues • Food regulations and laws relating to food • Greater focus on ‘Theory of Change’

TABLE 2. Summary of qualitative feedback from Bogor workshop participants.

- Full account of local environmental, social, and cultural diversity is necessary in designing locally relevant food systems workshops. The lesson is to establish local relations and identify local champions to drive local preparation for successful food system workshops.
- To the degree that it is possible, contingency plans need to be developed to prepare for unplanned absences of teaching staff and participants. This could take the place of flexible timing of workshops (difficult with international trainers) and identification of reserve participants who could step in at short notice.
- It follows from the considerations above that food systems workshops need to be in-country, and even regional within a country, to as great an extent as possible. Local food systems are nested within larger regional and international food systems, but the consumer is primarily a local actor.
- The COVID-19 pandemic has increased food insecurity, exposing shortcomings in existing food systems. Disruptions to livelihoods from trade and travel restrictions has emerged as a key vulnerability to food insecurity. New and innovative approaches are needed to address these systemic failings in food security.

6. FUTURE DIRECTIONS

This project represents just the first step in a necessarily long and sustained training and education journey. Ultimately, the desired outcome is a community of food systems professionals working across government, education, business, and civil society sectors. A crucial first step towards this outcome is to establish local ownership and stewardship of the teaching resources developed in this project. Suitable educational institutions exist in Indonesia and the Pacific. In Indonesia, the Bogor Agricultural University (IPB, Institut Pertanian Bogor) has the necessary breadth and depth to support resilient food systems training and education. IBP has national reach and extensive experience in delivering training programmes to meet local needs. In the Pacific, The University of South Pacific (USP) is well placed to provide a ‘home’ for resilient food systems teaching resources. For vocational and professional participants, the USP CVET (College of Continuing Vocational Education and Training) would be a logical choice with existing processes and quality assurances and with reach across the Pacific. For postgraduate coursework participants, the USP Pace-SD (Pacific Centre for Environment and Sustainable Development) would be a great option. Both these USP units have an existing focus on climate change, resilience, development, and food.

The challenge of developing resilient food systems that can provide food security for all is an acute challenge for Indonesia and Pacific Island nations. Local capacity for analysis of food systems and design of systemic interventions will make a significant contribution to food security over the coming decades. For these reasons, it is important that the small steps described in this project are nurtured so that food systems thinking can continue to grow and flourish in Indonesia and the Pacific.

7. ACKNOWLEDGEMENT

The financial support of the Asia-Pacific Network for Global Change Research (APN) and The University of Queensland is gratefully acknowledged. The provision of IFSTAL teaching resources as the basis of the Indonesian and Pacific food systems resilience workshops made this project possible. The support of Institut Pertanian Bogor, The University of South Pacific and the Solomon Islands National University (SINU) in the form of workshop venues, facilities, accommodation, and staff time is gratefully acknowledged. Most importantly, the enthusiasm, energy, and curiosity of all our wonderful workshop participants are what made each of these workshops such an enjoyable experience for all involved. May you take that energy forward on your food systems journey.

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Pathways to strengthening capabilities: A case for the adoption of climate-smart agriculture in Pakistan

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ABSTRACT

Pakistan has an agro-based economy with a high dependency on the sector, contributing 19.2% to the country's GDP. The country's geographical position makes agriculture highly vulnerable to climate change as it frequently faces periods of extreme weather events - flooding, droughts, and heatwaves. Due to growing environmental issues and institutional incapacities, there is an observed trend of urbanisation and depleting natural resources. Changes in land use and water scarcity cause reduced productivity and compromised economic growth. The country needs to adopt Climate-Smart Agriculture (CSA) as an adaptation measure against climate change. CSA is an approach to adopting agricultural systems strategies to minimise climate impacts and preserve natural resources. This study explores the intervention that enhanced the capabilities of provincial agriculture service-delivery organisations in the adoption of CSA. It produced a country-specific CSA resource kit and delivered training for agriculture extension officers and frontline government officers in Balochistan and Khyber Pakhtunkhwa provinces. The Pakistan Agriculture Research Council (PARC) and the Asia-Pacific Network for Global Change Research (APN) jointly delivered the project in line with the broader mission of research support, building government capacities and suggesting science-based response strategies as adaptation measures. The project experience highly recommends the adoption of CSA in Pakistan.

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KEYWORDS

Adaptation, capacity building, climate-smart agriculture, food security, high-efficiency irrigation systems, sustainable development

HIGHLIGHTS

- Expert review of the existing training curricula led to the formulation of an updated Climate-Smart Agriculture (CSA) resource kit
- Country-specific knowledge resources on CSA adoption have been developed
- The agriculture officers from Baluchistan and Khyber Pakhtunkhwa benefited from the capacity development programme
- Knowledge products have been produced on i) high-efficiency irrigation systems, ii) integrated pest management, iii)stress tolerant crops, iv) crop rotation, and v) crop diversification
- Country-specific knowledge products have been translated into the local language, Urdu

1. MAIN BODY

1.1. Introduction

Climate change affects many elements of life worldwide, including human health, agriculture, food security, water supply, transportation, energy, and ecosystems, among others. Agriculture is one of the most vulnerable sectors to the anticipated climate change. Crop failures and animal losses will rise because of changing and unpredictable rainfall patterns, droughts, higher temperatures, increased and amplified severe weather, and pest and disease outbreaks. Pakistan's agro-based economy depends significantly on the agriculture sector's performance. The economy has resisted change towards an industrial base. The agriculture sector is still the second largest contributor to the economy with 19.2% GDP share, 38.5% employment opportunities. Around 70% of the population, mostly rural, depends on the sector for their livelihood (Government of Pakistan, 2021a). The agriculture sector has grown tremendously over the past seven decades. The growth mainly originated from expansion in the irrigation water network, improved production, harvesting technologies, improved seeds with high production and resistance to diseases, better fertilisers, and efficient usage, liberalisation of price and marketing policy and other public policies. However, the overall agricultural productivity is lower than the global average, and the country could not achieve self-sufficiency in food production (Husain, 2019). The lower agricultural productivity can be linked to various aspects such as existing archaic practices in various parts of the country, changing climate, lower adaptive capacity, and lack of access to country-specific scientific and applicable knowledge on Climate-Smart Agriculture (CSA), which has become a need of the hour.

Climate change is occurring globally with varying effects on regions, whereas developing countries are least prepared to adapt. Pakistan has experienced almost all types of natural calamities, such as droughts, heatwaves, increased melting of glaciers, glacial lake outburst floods (GLOFs), and massive flooding. The country remains the fifth most affected by climate change shocks from 1990 through 2018 and the 36th least-ready country in the ND-Gain Country Index (World Bank Group, 2021). Currently, like neighbouring India, Pakistan is also experiencing an unprecedented heatwave that marked a "year without spring", which is highly unlikely to occur without the influence of global warming. Droughts and heatwaves have also taken a toll on human lives over the past three decades, as a country-specific study has reported that Pakistan has experienced 126 heatwaves of varying duration in different parts of the country from 1997 to 2015 and is likely to increase in the future (Harvey, 2022; World Bank Group, 2021).

Historically, Pakistan remains highly vulnerable to climate change. Statistics from 2000 to 2019 have ranked the country among the top ten most climate-affected countries in the Global Climate Risk Index 2021, which is an indication of a climatic future as well - proved by 2022 "super-floods" (German Watch, 2021). Natural calamities cause unprecedented losses and Pakistan remains a rare example globally, with approximately USD 4.5 billion in losses through natural calamities alone in 2010, with severe effects on the agriculture sector (FAO, 2018). Recently, the country has been facing a catastrophe of unknown precedent in 2022 as torrential rains caused super flooding, one-third of the country is inundated with floodwater, and more than 30 million people have been internally displaced. This flooding has played havoc with infrastructure, dwellings, basic facilities, and agricultural land. Besides the losses to human lives, hundreds of thousands of livestock perished, and standing crops on millions of hectares of land were destroyed, causing food shortages (Kawoosa, Bhargava, Katakam, & Sharma, 2022; UNHCR, 2022). The focused areas, particularly Khyber Pakhtunkhwa, are highly vulnerable to natural calamities and even hit hard by the 2022 countrywide flooding; Balochistan, the largest province by area, has faced frequent droughts and is severely affected by water scarcity although it largely depends on the agriculture sector for livelihoods and employment – also been massively affected by recent floods.

Being an open industry, the agricultural sector is the first and foremost witness to environmental changes. Though predicting future climate and weather patterns remain quite difficult, the IPCC observed that climate change is already affecting through increasing temperatures, changing precipitation patterns and frequent occurrences of extreme events. Studies suggest that the agriculture sector will face the loss of crops, the loss of agro-biodiversity and ecosystem services, and the incidence of pest and disease outbreaks with increasing temperature (FAO, 2016; Asian Development Bank, 2017). Climate change has varying effects in every region, whereas most developing countries have been hit hard. Based on indigenous and local knowledge, climate change is affecting food security in drylands, particularly in Asia, among other regions. Yields of some crops, e.g., maise and wheat, in many lower-latitude regions have been affected negatively (Mbow et al., 2019).

The rising temperature shall modify the growth cycles of various crops and livestock sub-sectors, leading to reduced yields. It is estimated that with the rise in temperature (+0.500°C–2.00°C), agricultural productivity will decrease by around 8% to 10% by 2040 (Dehlavi, Gorst, Groom, & Zaman, 2015). The changing temperature will further lead to frequent and intense flooding, salinisation of farmlands, soil erosion and reduced pasture output affecting crop and livestock production. Further, faster melting of glaciers in northern areas will result in the loss of standing crops and trigger climate-induced migration, which has been observed in the country (Khan, Sultan, & Khan, 2022). Similarly, increased temperatures, change in rainfall patterns, and increased frequency of extreme weather events also adversely affect livestock productivity. The negative effects of high temperatures on feed intake, reproduction, and livestock performance are evident. An increase in temperatures also causes decreased forage quality and availability, reduced water availability, increased heat stress, and the emergence of diseases in livestock.

Water is a key agricultural input, which is becoming scarce in Pakistan due to growing consumption, lack of reservoirs and storage, and persistent environmental issues. The country's water resources comprise surface water and groundwater. Numerous rivers in the country drain water from glaciers of the Hindukush Karakoram

Himalaya (HKH) region that contribute up to 80% of the flow in the Indus River system. Monsoon rains also contribute a huge amount of water, which is a source of irrigation and hydroelectric power generation; however, water from these monsoon rains cannot be utilised properly for irrigation as Pakistan does not have enough storage capacity. Sometimes these rains cause major flooding in the country. Despite that, the per capita water availability is below 1,000 cubic meters compared to 5,000 cubic meters in 1950, which is alarming. The country consumes 90% of available water in agriculture, whereas 50% of this available water resource goes waste due to archaic irrigation practices. The per capita water availability is receding fast due to unchecked water extraction, climate change, and poor water management practices (Siddiqui, 2013; Sultan, 2019). Under worsening climate and seasonal weather patterns, water reservation capacity, and irrigation practices, the water crisis will likely deepen in the country, challenging the agriculture sector at large. The country must address the issue by adopting high-efficiency irrigation systems.

Although Pakistan has made significant progress in land utilisation over the years, deforestation and land use change have become major concerns in the last two decades. The growing population and urbanisation trend have put pressure on agricultural production and urban housing, which has led to the plunder of agricultural land. One such example is a major housing project on the outskirts of the historic city Multan, which, jointly with other housing projects, has cleared around 2,000 acres of mango orchards. In a country already facing various environmental and economic challenges, this is severe yet not the only example of an onslaught of real estate development in the country that has reduced agricultural land over the past two decades (Ahmed, 2017; Rashid & Moulvi, 2021) . This change in land-use issue certainly requires a policy response for the protection and efficient utilisation of agricultural land. Considering the limited land resources and economic dependence on a single crop, local farmers must adopt crop diversification strategy. Efficient land use can ensure improved agricultural productivity and yields and lower dependence on a single crop, which is a common practice in the country (Husain, 2019).

FAO frameworks on enabling policy environment for CSA recommend that the interventions on adopting climate-smart agriculture systems should focus on filling policy gaps and contribute to the country-driven capacity development programs (FAO, 2018). This study aims to explore the intervention toward adopting CSA that addresses the multifaceted challenges of the agriculture sector. The project has produced scientific knowledge resources; designed and delivered capacity-building programs to enhance the capabilities of agriculture extension services in Balochistan and Khyber Pakhtunkhwa. The final product came out in the form of locally applicable and ready-to-use scientific solutions, nature-based adaptation strategies, and enhanced institutional capabilities, which would contribute to the country's sustainable development efforts and the larger mission of the global fight against climate change. The intervention has widely benefited the agriculture extension services in Pakistan by enhancing the capabilities of provincial Agriculture Service Delivery Organizations (ASDOs) on CSA and further embedding CSA capabilities development in the mandate of provincial agriculture departments.

2. METHODS

One of the project's key objectives was to strengthen linkages between science and practices, which remains a leading force throughout the project implementation. The project brought together CSA experts and leaders from national and provincial partner organisations. The experts defined methodologies and designed a capacity-building framework for enhancing the capabilities of provincial agriculture extension officers and Agriculture Training Institutes (ATIs). Following the capacity-building framework and various methods, the project has delivered institutional

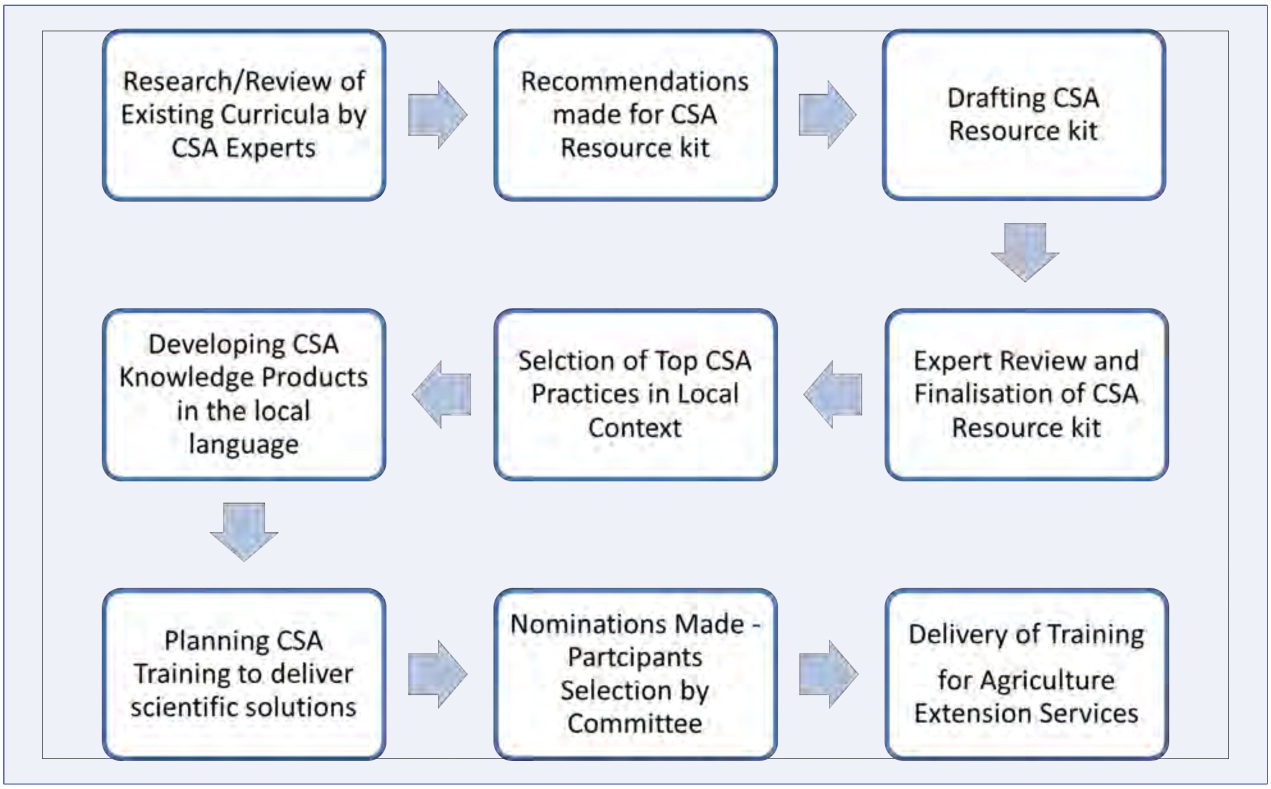

FIGURE 1. The Capacity Building Framework

capacity-building programmes on CSA, which will, in turn, function to strengthen the linkages between scientific solutions and agricultural practice in the larger context of Climate Compatible Development (CCD) in the country.

2.1. Review of existing curricula

To address the challenges in the milieu of climate change, the project adopted the approach of review and research, which started with an expert review of existing curricula available and widely used at the provincial ATIs. Most of the Agriculture Extension Officers in Pakistan enter into the service after completing a graduate degree in agriculture – gain conventional environmental and agricultural knowledge that local universities' curriculum offer – and for professional training, they solely depend on the provincial ATIs. Globally, climate change science has become a highly specialised and top priority to achieve sustainable development, particularly agriculture growth. However, a thorough expert review brought to attention that the existing curricula within governmental organisations in the country lack country-specific scientific adaptation strategies and knowledge on climate change and adaptation.

Considering all these factors, the curricula review brought recommendations to prepare a comprehensive CSA resource kit backed by science and applicable in the local context to be utilised for the project's capacity-building component. Later, this resource was shared with ATIs, agriculture extension services, and other organisations working towards agricultural advancement in the country.

2.2. Research approach

To develop country-specific resources, the project team conducted desk research under the close supervision of Climate-Smart Agriculture experts at Pakistan Agricultural Research Council (PARC) and prepared scientific knowledge resources, which are suitable in the local context. Further, the experts prioritised five key strategies that led to the development of accessible knowledge products for communities that were translated into a local language to educate farmers on CSA approaches. During the research phase, resources at PARC, Climate Change Centre, The University of Agriculture Peshawar, Agriculture Department of Balochistan, curricula of Agriculture Training Institute Peshawar, LEAD Pakistan's library, various online knowledge portals and research by bilateral organisations, and advisory support by CSA experts were widely utilised.

2.3. Capacity building approach

The project adopted the capacity-building approach to enhance the capabilities of provincial Agriculture Service Delivery Organisations (ASDOs). For that purpose, the project has followed the capacity-building framework and built the capacities of District Agriculture Officers of the Balochistan and Khyber Pakhtunkhwa provinces. This training was designed in close coordination among PARC, provincial partners, and ASDOs. The provincial agriculture departments made nominations for the training, whereas a committee selected two batches comprising 31 training beneficiaries through a rigorous process considering the diverse agro-ecologies in the country.

A newly developed comprehensive resource kit was utilised to deliver the training on CSA technologies and adoption strategies. These were in-person training, where experts from various organisations joined to deliver sessions. Each session was precise, insightful, well-designed, and delivered by experts through participatory approaches. The participants acknowledged that sessions were useful and directly related to their day-to-day job. Various supplies were utilised, such as PowerPoint slides, videos, documentaries and local case studies – and knowledge resources were provided to all participants in printed form and in portable drives. Most beneficiaries have marked the training as comprehensive and exceptionally up-to-date through post-evaluation written feedback. The participants were frontline agriculture officers and it is expected that CSA adoption strategies would be implemented at a grassroots level. This project initially benefited two provincial institutes; however, it will further contribute to the larger process of sustainable development in the country through improved capabilities of governmental organisations.

2.4. Consultation Workshop

A national-level consultation workshop brought together agriculture extension experts from Balochistan, Khyber Pakhtunkhwa, Punjab, and Sindh, intending to disseminate knowledge resources and replicate the lessons in other parts of the country. Key stakeholders such as agricultural training institutes, industry experts, policymakers, non-profits, and bilateral organisations working on agricultural advancement in the country were also invited. The consultation workshop aims to share project experience, sensitise policymakers on adopting CSA practices and technologies, and further improve coordination to meet the common objectives. The forum has strongly recommended the integration of the newly developed CSA resource kit into the curricula of ATIs of all provinces in Pakistan.

3. RESULTS AND DISCUSSION

3.1. Climate-smart agriculture (CSA)

FAO estimates that the world population will increase by one-third and an additional 2 billion people will be living in developing countries by 2050. To meet the expected food demand, the agriculture sector must transform to meet the challenges and increase production by 60% (FAO, 2013a). According to the Pakistan Economic Survey 2020-21, Pakistan is already the fifth most populous country in the world (Government of Pakistan, 2021b) . Increasing population and urbanisation, coupled with changing climate over the past two decades, is affecting overall economic performance and creating an urgency to go through a transformation, making a case for the adoption of CSA to meet ever-growing needs in all provinces.

CSA is the idea of adopting agricultural practices that help transform the agriculture sector and effectively supports the broader sustainable development goals and food security in the context of a changing climate, particularly for smallholders. This is done by enhancing farm

FIGURE 2. Three pillars of CSA – the triple win. (FAO, 2016; World Bank Group, 2021)

and entrepreneurship management through better use of natural resources and adopting appropriate methods and technologies (FAO, 2013a; Khan et al., 2022). The concept aims to address three areas: sustainably increasing agricultural production and incomes, adaption and resilience to climate change, and reduction of greenhouse gas emissions (FAO, 2013a). CSA can be applied through various strategies to fulfil global food demands and ensure food security whilst implementing sustainable practices in the agriculture sector.

A CSA model for any specific location is the integrated landscape approach, which is based on rational management and utilisation of natural resources in an ecosystem (FAO, 2013a). This aims to improve livelihood options, especially for smallholders, through enhanced capabilities to rationally utilise the available resources such as quality seeds, fertilisers, pastures and livestock feed, land, water and energy; and manage the production, post-harvest and marketing practices tactfully. The CSA model aims to enhance resilience, improve the adaptive capacity of farmers, and decrease pressure on scarce resources (FAO, 2013a; Khan et al., 2022).

However, it is a well-established fact that sustainable agricultural production and CSA alone cannot meet the expectations for meeting challenges posed by climate change. In the coming years, there will be tremendous pressure on agriculture to meet the food demands of the ever-increasing population under climate change scenarios. Current food wastage, around one-third of the produced food, which is roughly 1.3 billion tons, is wasted worldwide every single year (FAO, 2013b) and is aggravating the overall impacts of climate change. Reducing food losses from the whole production and supply chain require integrating the value chain approach within the landscape approach, thereby increasing the resilience of all stakeholders. Therefore, the CSA approach takes into account the social, economic, and environmental well-being of all the stakeholders and components, including farming communities, consumers, ecosystems, and natural resources.

3.2. Climate-smart agriculture: A reference manual

The United Nations Framework Convention on Climate Change (UNFCCC) report states that there is a need for integrated programs in developing countries, which should take into account the role of research, capacity building, and strengthening existing resources. They should develop new capacity-building resources for enhancing capabilities, technical knowledge, and skills for adaptation (United Nations Framework Convention on Climate Change, 2002). FAO states that CSA is not one specific agricultural technology or a single practice that can be applied universally but rather various approaches that address climate change, create synergies and benefits, reduce trade-offs, and are applied appropriately considering social, economic and environmental aspects of a country or in a site-specific context (FAO, 2013a).

In Pakistan, there was a need to develop a comprehensive training module to build the capacities of agriculture extension officers to understand climate change and its impacts on agriculture and natural resources in the country context. PARC and APN, alongside provincial partners, have taken a knowledge-advancing capacity-building initiative by developing a country-specific training module on CSA to fill this knowledge gap. This is a comprehensive capacity building knowledge product that comprises updated and detailed technical information on climate change, impacts on agriculture, climate smart technologies, practices and adoption techniques. Considering other aspects, experts suggest that adopting CSA in all provinces can potentially contribute to the Nationally Determined Contributions targets of the country.

The training module comprises four sections. The first part of the module comprises basic knowledge and key concepts of climate science, such as atmosphere, weather, climate variability, climate change, global warming, greenhouse gases, and natural and anthropogenic drivers of climate change. The second part covers the overall impacts of climate change, impacts on agriculture and food security with a special focus on agronomic crops, horticultural crops and livestock, fisheries, forestry, soil, and water resources. The third section of the module covers CSA, which is the core topic; it discusses the landscape approach and its importance for agricultural transformation, salient practices of CSA, and their relevance to local agricultural conditions. The section also includes the concept and its relation to adaptation, mitigation and food security. The fourth module covers the concept of climate and gender inclusion, enabling environment, institutional capacity building, policy advancement relevant to CSA, and barriers and opportunities for CSA in Pakistan (Khan et al., 2022).

3.3. CSA knowledge products

During the project implementation, it was observed that the major inhibiting factors in mainstreaming CSA in Pakistan are the limited capacities of agriculture extension departments. We learned from the analysis of the existing knowledge resources that available materials are complex, and the climate aspect is not being covered. Further, existing archaic practices by small landholders and lack of advisory build the case for developing updated knowledge resources that should address the challenges of climate change (Khan et al., 2022). For the inclusion of local farmers, CSA experts recommend educating farmers through simplified knowledge products on CSA practices. The CSA knowledge products, which consist of technical yet simplified information on the adoption of CSA practices, have been translated into a local language, Urdu.

3.3.1 High-efficiency irrigation systems (HEIS): Water scarcity in Pakistan is acute and there is a significant decrease in groundwater level. With increasing temperatures and irregular rainfall patterns, areas such as Balochistan have reported fast-declining groundwater of up to three metres per year. The agriculture sector consumes the largest chunk of available water; further existing irrigation practices would lead to stress on water resources (World Bank Group, 2021). The CSA experts have recommended promoting and implementing the HEIS, such as sprinkler irrigation, drip or trickle irrigation – surface and sub-surface – bubbler irrigation, rain guns, and centre pivot irrigation system. These modern irrigation systems are suitable for most soil types and landscapes and non-levelled surfaces, save a considerable amount of water and serve as valuable adaptation measures.

3.3.2 Integrated pest management (IPM): A study by FAO defines the IPM as a holistic approach that finds sustainable solutions for pest problems and supports sustainable agricultural production. It helps in the prevention and control of pests through the integration of appropriate biological, cultural,

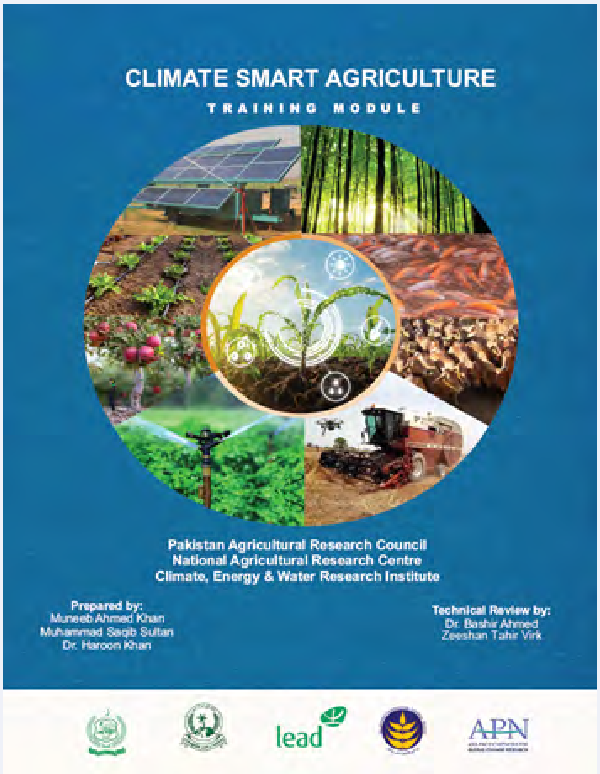

FIGURE 3. CSA training module– A reference manual. (Khan et al., 2022).

physical, and chemical measures to minimise economic costs and reduce health and environmental risks (FAO, 2020).

CSA experts recommend that the adoption of the IPM approach will protect biodiversity and improve pollination mechanisms leading to a non-chemical cure for the pest problem (Khan et al., 2022). Under the IPM, the overuse of pesticides is discouraged as it creates a problem for the overall health of the crop ecosystem; only selective and ecologically least disruptive pesticides should be used alongside the non-chemical pest control measures (Royer, Mulder, & Cuperus, 1999). Judicious use of pesticides helps reduce the production cost at a farm level and improve profitability by reducing environmental and economic damages.

3.3.3 Stress-tolerant crops: Stress-tolerant crops and varieties can improve productivity and save natural and financial resources. Farmers can cultivate stress-tolerant crops and varieties to optimise their production in changing climates and extreme weather events. Pakistan has experienced frequent drought, rising temperatures and unpredictable weather patterns, making stress-tolerant crops even more important (Asian Development Bank, 2017). CSA experts recommend stress-tolerant crops to fight changing climate due to their high tolerance against CO_2 levels, rising temperature, rain-fed conditions, drought and salinity levels. Similarly, some of the crops have unique traits that include resistance to water logging/flooding conditions; have the ability to mature faster when considered for rain-fed areas to avoid sensitive growth stages; can withstand higher insect pest populations; can resist existing and emerging diseases, and have adjustability to different cropping calendars (Burke & Lobell, 2010; Khan et al., 2022). These traits vary in different crops, depending on the area and weather conditions; these crops are indeed a solution against climate change and a key part of CSA.

3.3.4 Crop rotation: Crop rotation is an important adaptation tool at the farm level that positively impacts the whole ecosystem, water use efficiency, and higher yields. This helps in soil carbon sequestration, increasing soil organic matter

FIGURE 4. CSA knowledge products - Translated into local languages for farmers.

content, nutrient cycling, improving soil microbial activity and thus soil fertility, improving the water holding capacity of soils and suppressing weeds, insects and diseases, further leading to a healthy ecosystem. The crop rotations help in fulfilling the objectives of CSA through a well-planned and adapted pathway, which makes agricultural systems more resilient (Khan et al., 2022; Meyer-Aurich, Weersink, Janovicek, & Deen, 2006).

3.3.5 Crop diversification: Crop diversification refers to growing a mix of crops on a particular farm or a piece of land at the same time. These crops could be cereals, oil seeds, pulses, fodders, fibre crops, sugar crops, vegetables, fruits, etc., depending on the needs of farmers, market situation, or national preferences. Crop diversification is a cost-effective methodology that small landholders can also afford. Increasing genetic diversity, different varieties, or multiple species on a farm can reduce certain risks, such as adverse weather conditions, diseases and insects, market uncertainties, and risks related to mono-cropping. The genetic diversity of crops show resilience against temperature, precipitation, and other phenomenon related to climate change (Scherr, Shames, & Friedman, 2012; Khan et al., 2022)

Besides these prioritised five strategies, various other practices are recommended in the local context. Practices that increase soil organic carbon retain productive soils, need fewer chemical inputs, and support essential ecosystem services such as nitrogen cycling, all of which contribute to increased production, adaptation, mitigation, and resistance to climate change. The following measures should be implemented:

- Conservation tillage, reduced tillage, or zero tillage
- Integrated soil fertility management using inorganic and organic fertilisers; nitrogen fertiliser management; use of mulch, compost, manure, or green manure in place of inorganic fertilisers
- Erosion management, for example, lowering the slope's degree and length by progressive and bench terracing – protective soil cover from mulch, agricultural wastes, or cover crops
- Soil compaction control, restoring deteriorated soils and fallowing.

Reiterating the fact that CSA is not a specific technology or a tailored product to be implemented around the world, but is a holistic approach applied considering local agro-ecological conditions. Experts suggest these practices and technologies for capacity building and practical applications at

FIGURE 5. CSA knowledge products - Translated into the local language for farmers.

the field level. For that purpose, the CSA toolkit has effectively covered sustainable crop and livestock production to meet CSA objectives – adaptation, mitigation, and food security – and it is a key source of CSA knowledge in the local context for policymakers, agriculture officers, and farmers. A few prominent practices, technologies and approaches include crop and enterprise diversification, stress-tolerant crop varieties and livestock breeds, low water requiring crops, animal manure management, and utilisation of renewable energy sources to reduce fossil fuels dependence.

Each CSA practice and approach has multi-faceted benefits. For example, practices such as conservation tillage, residue management, utilisation of barren lands for food and feed production, improving water-holding capacity of soils, organic matter addition, crop rotations, crop diversification, manure management, and efficient irrigation systems, all are part of sustainable soil management. The potential benefits of these practices are very high, as they reduce soil degradation and erosion and improve soil fertility, structure and carbon sequestration. Considering conditions in agro-ecology, integration of various CSA practices and technologies reduces climate change impacts, leads to a reduction in GHG emissions, improves sustainable productivity and resilience, increases the compatibility of agriculture with ecosystems, and promotes rational use of natural resources.

3.4. CSA Capacity Building – a way forward

Despite advances in the agriculture industry over the years, productivity growth in the agriculture sector has been modest. The sector used to be dominant, contributing the most to the economy, but this has decreased over time. According to research, the agriculture sector has financed Pakistan's early industrialisation. This decrease in agricultural production is the result of various issues, including the absence of regulatory frameworks, the inadequacy of agricultural research, and the lesser capacity of agriculture extension services to meet developing difficulties. A study published by Oxford University Press states that agricultural institutes in Pakistan could not keep pace as required by the challenges and vulnerabilities of the sector. There is a lack of funds, lower integration and coordination in research, extension, and policy-making institutions. The organisational structure and strong research environment have not been fostered. Further, the extension system in Pakistan has been plagued with severe organisational problems coupled with lower funding and poor staff education and training (Husain, 2019). After the 18th amendment to the constitution, now agriculture sector is predominantly a provincial subject and it requires the attention of the provincial governments for reforms and capability development to meet the challenges (Shah, 2012).

Agricultural extension services are among the driving forces responsible for improved productivity by directly transferring the latest knowledge on agriculture to the farmers. This project has strengthened the capacity of agriculture extension services for adopting CSA and has contributed by developing a specialised resource kit on CSA practices and technologies in the country context (Khan et al., 2022). CSA experts have conducted professional learning sessions, have developed the capabilities of provincial agriculture extension officers, and focused on enabling extension officers to adopt the concept of CSA and relay their advisories in a manner that is compatible with climate change. Despite this project delivery, there is still not just a need but also a demand for capacity building of the institutions regularly and continuously throughout the country while utilising the resource kit, which covers greater knowledge and strategies for most local agro-ecological zones.

4. CONCLUSION

Agriculture is the foundation of food security and economic development in Pakistan, meets the livelihood needs of the majority of the rural population, and provides feed for livestock, raw materials for industry, and value-added products for both domestic consumption and international markets (Khan et al., 2022). However, the lack of capabilities to tackle the emerging challenges remain evident, and the development of knowledge products and capacity building was a much-needed intervention. The country's complex issues, such as alarming population growth and urbanisation trend, demand higher agricultural production. It needs agricultural diversification, switching to higher-value nutritious crops, and better management of natural resources, such as water, that can be achieved through the sector's transformation to CSA. This requires building institutional capacities on CSA and attuning the country's agriculture sector under a climate-compatible development (CCD) framework. To accomplish the agricultural growth ambitions and growing food demands, a lack of institutional capacities remains a major hindrance. It thus needs support through country-specific research and capabilities development. The adoption of CSA is one of the key interventions that can assist the country in enhancing its agricultural production, improving livelihoods, gaining economic growth, and achieving the larger goal of sustainable development.

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Review

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Assessment of the feasibility of applying payment for forest ecosystem services in Vietnamese mangrove forests

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ABSTRACT

Mangroves can play a major role in efforts to mitigate climate change through two pathways. These are (1) carbon sequestration following reforestation of areas where mangroves previously existed, and (2) protection of existing carbon stores in intact mangrove forests. There is considerable international interest in carbon mitigation by governments and businesses as a way of meeting emissions reduction targets, and this could result in significant investment in mangrove restoration and protection. This is likely to have positive benefits in terms of coastal protection, biodiversity protection and new economic activity. This project examined three aspects of mangroves related to the emerging carbon economy. There has been considerable (0.2 million hectares) mangrove restoration in Vietnam and this activity provides insights into the causes of project success or failure. A review of this restoration concluded that the failure of several past restoration projects in Vietnam could be attributed to poor species and site selection and lack of incentives to engage residents in long-term management. The economic, environmental and social aspects of mangrove-shrimp farming or aquaculture (MAS) systems in Ca Mau Province, Vietnam, were examined, and it was concluded that this approach allows the achievement of these multiple objectives. Whereas, most of the discussion around mangroves and their role in carbon management is at the international and national levels, implementation occurs at the local level. It was found that whereas local stakeholders had a reasonable understanding of climate change, they were less clear about carbon markets and the role that mangroves can play. This points to the need for new educational programmes. The study concluded that monitoring and verification systems for both carbon and biodiversity are essential to allow the resultant multiple benefits of carbon mitigation projects to be realised.

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KEYWORDS

Carbon mitigation, forest restoration, co-benefits, Vietnam, mangrove forests

HIGHLIGHTS

- Mangrove ecosystems are highly prospective for carbon mitigation.
- Carbon mitigation will also result in a range of environmental and societal co-benefits.
- Many landowners have a lack of understanding around mangrove carbon reforestation.
- Gaining payment for co-benefits requires clear metrics.

1. INTRODUCTION

Mangroves are the dominant vegetation in tidal, saline wetlands along tropical and subtropical coasts (Alongi, 2002) and provide several marine-based ecosystem services such as timber and food production, fish nursery maintenance, coastline protection, carbon storage and tourism (Barbier et al., 2011).

More than half of the global mangrove area has been lost (FAO, 2007) due to land conversion to aquaculture and agriculture, overharvesting and sea-level rise (Duke et al., 2007; Giri et al., 2015; Richards & Friess, 2015). The total global mangrove area was estimated in 2012 to be 14.7 million ha (Kauffman & Donato, 2012) compared to 19.8 million ha in 1980 (Valiela, Bowen, & York, 2001). The average annual rate of mangrove loss of 0.21%/year from 1996 to 2016 exceeds that of tropical and subtropical forests (IUCN, 2018).

This loss has important consequences, not only for the reduction in ecosystem services but also for overall carbon storage (Wylie, Sutton-Grier, & Moore, 2016). Mangrove loss has been calculated to contribute a substantial component (*c.* 3-19%) of the total global emissions from deforestation. However, investment in mangrove carbon projects may provide the capital for extensive restoration and protection efforts and thus reverse mangrove decline.

Mangrove restoration projects and programmes have been implemented in many countries, these including projects in the 1950s in China and India (Kodikara, Mukherjee, Jayatissa, Dahdouh-Guebas, & Koedam, 2017). More recent examples followed the 2004 Indian Ocean tsunami (Kodikara et al., 2017) and the 2013 Haiyan typhoon (Barnuevo, Asaeda, Sanjaya, Kanesaka, & Fortes, 2017; Wolanski & Elliott, 2015). Vietnamese mangrove restoration projects commenced in 1975 following the end of the Second Indochina War (Hong, 2008), with considerable subsequent activity (around 0.2 million hectares) funded through both state and international programmes.

Payment for ecosystem or environmental services (PES) schemes are a market-based approach to forest conservation with the aim of reducing forest loss by incentivising land managers (Locatelli et al., 2014; Wunder, 2015). As described above, mangroves can provide a wide range of ecosystem services and hence, the potential for mangrove PES has become the focus of current and critical debate (Thompson, Clubbe, Primavera, Curnick, & Koldewey, 2014). Additionally, there has been work to determine how mangrove ecosystems can be included within existing policy frameworks, including mechanisms such as Reducing Emission from Deforestation and Forest Degradation (REDD+) and United Nations Framework Convention for Climate Change (UNFCCC) mechanisms (Herr, Pidgeon, & Laffoley, 2012).

The majority of PES forestry projects, however, concern terrestrial ecosystems, with little known about how the PES approach can be applied to mangrove-dependent communities (Corbera, Brown, & Adger, 2007). Only 87 km^2 of mangrove forests worldwide are currently included in operational PES (Thompson, Primavera, & Friess, 2017), with this involving projects that focus on payment for carbon services (projects in Kenya and Madagascar and India (Wylie et al., 2016). Another mangrove PES in Thailand is related to tourism services (Jarungrattanapong, Mahasuweerachai, & Nabangchang, 2016). Twenty-nine countries, including Vietnam, formally pledged mangrove restoration activities as part of their response to the Paris Agreement of the UNFCCC (Herr & Landis, 2016).

Given the interest in incorporating mangroves into a PES framework and the considerable interest around carbon mitigation options using these ecosystems, this project centred on Vietnam, where there has been considerable activity related to mangrove restoration and the development of a PES framework. We considered that this work could provide insights into the implementation of mangrove carbon projects in the broader region. We thus examined the following:

1. The major insights gained from mangrove restoration projects in Vietnam, where over 0.2 million ha has been established through various funding mechanisms since 1975, and consideration of how the findings from this activity might relate to future carbon reforestation programmes;
2. The interplay between environmental, economic and social objectives for residents who participate in the protection of restored mangroves and engage in aquaculture (shrimp) production, and
3. The understanding of local communities around the carbon mitigation options from mangroves in the emerging carbon economy. This involved surveys in Ca Mau Province, Vietnam. Whereas much discussion is around international and national level treatment of carbon markets, mangrove carbon projects will be implemented locally, and this component directly examined the views from three stakeholder groups at the local level.

2. METHODOLOGY

The following are the main questions which were addressed. Each of these questions, and the methodology used, has been addressed in a formal publication.

1. How successful are mangrove restoration projects and programmes in Vietnam, and what are the main reasons for their success or failure (Hai, Dell, Phuong, & Harper, 2020)? This involved the examination of formal published outputs (50 papers), and also grey literature reports and project plans in English and Vietnamese.
2. To achieve sustainable management of mangroves in the long term, how can environmental, economic and social objectives be balanced for residents who participate in the protection of restored mangroves (Nguyen, Chu, Harper, Dell, & Hoang, 2022)? This involved a survey of 98 households in Ca Mau Province, with 3 contrasting systems involving shrimp farming and mangrove protection. The systems were (1) extensive shrimp farming without vegetation, (2) mangrove and shrimp (MAS) where the activities are integrated and (3) intensive shrimp farming.
3. Can payment for mangrove carbon service schemes be implemented as an incentive for local communities for mangrove protection (Nguyen, Dell, & Harper, 2023)? In this component, 73 interviews were undertaken across three stakeholder groups (potential sellers, potential buyers and intermediaries). The sellers included 40 households, five forest management boards, the buyers nine processing companies, eight intensive shrimp producers. and eight charcoal producers. The intermediaries comprised

three local authorities. Whereas much of the discussion is around international and national level treatment of carbon markets, mangrove carbon projects will be implemented locally, and this study directly examined the views from three stakeholder groups at the local level.

3. RESULTS AND DISCUSSION

Over the last three decades, there has been considerable investment in mangrove restoration programmes in Vietnam, resulting in 0.2 million hectares of mangroves being restored. For the first Project question, Hai et al. (2020) examined the effectiveness of mangrove restoration efforts and concluded that failure in some mangrove restoration programmes can be attributed to poor site and species selection and lack of incentives to engage local residents in the long-term management of restored areas. This review also suggests approaches to enhance mangrove restoration success, including improved matching of species with site types, having well-defined monitoring/reporting procedures, and instigating a co-management approach with local communities.

Examination of mangrove restoration project documents and discussions with local authorities revealed that there has been an acute lack of financial support for the management of restored areas after the initial establishment phase of 1 to 4 years. This is likely to have led to a decline in mangrove health and the failure of some mangrove restoration projects in Vietnam. One way to address this vexing problem is to empower local communities to be more engaged in long-term mangrove management. Therefore, for the second Project outcome, Nguyen et al. (2022) explored the development of the mangrove-shrimp farming system (MAS) in the Mekong Delta to protect mangroves by balancing economic, environmental and social objectives for local farmers who participate in mangrove protection. Ecosystem payment systems using shrimp rice systems had previously been explored in the Mekong Delta by Loc, Diep, Can, Irvine, and Shimizu (2017). Using household survey data in Ca Mau Province, it is concluded by Nguyen et al. (2022) that integrating mangroves with shrimp farming can support multiple objectives. This is because the mangrove-shrimp farming system provides the higher rate of economic return of all shrimp farming systems in south Vietnam; is inexpensive to implement and run; provides less risk for producers as shrimp production is less exposed to risks from natural disasters and shrimp diseases; helps to conserve mangrove cover and habitat; and women are more involved in the mangrove shrimp farming system than other shrimp production systems. Thus, due to these economic, environmental and social outcomes, Nguyen et al. (2022) described this as a "triple-win approach towards sustainable development".

A further strategy for the sustainable management of restored mangroves is to offer incentives for local communities (Nguyen, 2021). Payment for forest environmental services (PFES) is one way to support rural communities in managing forest reserves, and this scheme is well-known in Vietnam. However, payment for carbon forest services (C-PFES) is less known and, so far, has not been applied to mangroves in Vietnam. However, much of the discussion around mangroves and carbon is at the international and national levels. Simply put, the views of local communities where mangrove restoration projects are likely to occur have not been canvassed. Using interview data from potential sellers, potential buyers and intermediaries, Nguyen et al. (2023) investigated the feasibility of applying C-PFES for mangroves in Ca Mau province, Vietnam. Results for the third Project showed that farmers are generally aware of the impacts of climate change on their production and of how mangroves could help with environmental management. However, farmers had limited understanding of C-PFES or the carbon sequestration capacity of mangroves, and this presents a challenge in the future if C-PFES schemes are to be introduced. Only 29-56% of potential buyers were willing to participate in such a payment scheme. As carbon sequestration capacity of mangroves is an international ecosystem service, C-PFES for mangroves in Ca Mau and elsewhere should involve the participation of private companies, government agencies and international investors. We recommend policy revisions to allow stakeholders at national and international scales to participate in C-PFES investment.

Prior to implementing C-PFES projects, it is essential that the carbon budget for mangroves be accurately determined. However, the carbon budget of mangrove ecosystems is complicated by attributing carbon accumulation to mangrove primary production, oceans and terrestrial sources. Nguyen (2021) notes that there is often a misperception between carbon storage and carbon sequestration, leading to an exaggeration of the role of mangroves in climate change mitigation. Therefore, instead of focusing on the single role of mangroves in sequestering carbon, co-benefits generated from mangrove ecosystems should also be integrated into restoration projects and programmes. Hai et al. (2020) demonstrated the clear deficiencies in the long-term monitoring of mangrove projects and the need to develop inventory systems to verify rates of carbon sequestration. This will be crucial in the running of any future carbon market. Similarly, measuring, reporting and verification is required for other environmental markets (e.g. biodiversity and marine habitats).

4. CONCLUSIONS

Overall, mangrove restoration is important in Vietnam and across the Asia-Pacific region, where deforestation is a critical issue. Although there are some successful mangrove restoration projects, many programmes in Vietnam have failed with a low survival rate. Besides developing a provincial and national monitoring system, providing incentives to local residents may provide a solution for the long-term management of mangroves. One approach is to promote mangrove-shrimp farming, which can generate a triple-win solution in environmental, economic and social aspects. Promoting payment for mangrove carbon services (C-PFES) with the participation of multiple buyers, including the private sector, government and international investors, will increase livelihoods for local communities and protect mangroves. A key requirement, however, is for the different environmental services to be valued so that the benefits can be obtained by local landholders. Although carbon management is crucial in tackling climate change, mangrove preservation and restoration should be promoted in terms of carbon management and the delivery of co-benefits such as protection of biodiversity and marine habitats.

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Original article

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Historical drought and its trend in South Asia: Spatial and temporal analysis 2000-2020

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ABSTRACT

Every year, South Asian countries suffer from declining agricultural outputs due to climate extremes such as floods and droughts. Recurrent droughts have depressed rural economies and enhanced widespread hunger and human migration to South Asian cities (Miyan, 2015). Due to climatic changes, the region is projected to experience rising temperatures and more frequent extreme weather events in the long term (Trenberth et al., 2014). Accurate predictions of drought, its impact, and early detection facilities are not present in most South Asian countries due to a lack of sufficient hydro-meteorological datasets, poor access to satellite products, and shortages of well-trained staff. This study seeks to address these deficiencies scientifically by analysing historical drought conditions on a regional scale using open-access satellite products. The Drought Severity Index (DSI) has been employed to assess meteorological droughts from 2000 to 2020 and to prepare drought severity maps for the South Asian region. Results from DSI were further compared with the Standardised Precipitation Index (SPI) in Nepal and Bangladesh. The results identified pre-monsoon months as the driest period in South Asian countries experiencing severe to moderate drought.

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KEYWORDS

Drought Severity Index, meteorological drought, MODIS, longterm drought analysis

HIGHLIGHTS

- This research uses open-access satellite products to assess drought conditions in Nepal, Bangladesh, Pakistan, and selected regions of India from 2000 to 2020. Spatial and temporal drought maps are generated using DSI values, which are further utilised to assess the trends and severity of drought.
- Severe droughts are most common in the region during March, April, and May. During the winter months of December, January, and February, significant dryness was predominately observed in the northern and eastern side of South Asia, including Eastern India and Bangladesh.
- Satellite data-based Drought Severity Index calculations have been proven to be a reliable tool for drought monitoring at a regional scale, particularly for countries with insufficient hydro-meteorological datasets.

1. INTRODUCTION

Drought is a silent and pervasive hazard originating from the deficit of water availability, with devastating impacts on agriculture, water supply, and the environment (Popova et al., 2014; Yu et al., 2014), to cause economic losses (Below, Grover-Kopec, & Dilley, 2007; Wilhite, 2000; Wilhite, Svoboda, & Hayes, 2007). Unlike other natural hazards with a smaller geographic scope, these effects have a wider influence. The Intergovernmental Panel on Climate Change (IPCC) has identified South Asia as a global region most sensitive to drought, and consequently, water and food shortage events are expected to increase in frequency (IPCC, 2022). From 2046-2065, the region is expected to experience a rise in temperature of 2-4 degrees Celsius (Walsh et al., 2017). The Sixth Assessment Report of the IPCC has found South Asia as the most food-insecure population in the warming scenario (IPCC, 2022). Therefore, understanding drought to minimise its adverse impacts and to secure food production in South Asia has become more relevant than ever.

A recent study has found that a proper drought monitoring system on a regional scale is unavailable in most South Asian countries (Aadhar & Mishra, 2017). Despite this, individual efforts to assessing drought in South Asia (Sigdel & Ikeda, 2010; Shakya & Yamaguchi, 2010; Kafle, 2014; Dahal et al., 2016; Masud, Khaliq, & Wheater, 2015; Abuzar et al., 2017; Carabine et al., 2014; Miyan, 2015; Aadhar & Mishra, 2017) using different drought indices have taken place. From these previous studies, the most frequent droughts evidenced across South Asian nations are attributed to variations in rainfall volume (i.e., absence), onset, and distribution pattern during the main monsoon season (Hore, Werner, & Maskey, 2019; Meshram, Gautam, & Kahya, 2018; Miyan, 2015; Regmi, 2010; Imbulana, 2010). In India, the 2014–2015 drought, which has a return duration of 542 years (Mishra, Aadhar, Asoka, Pai, & Kumar, 2016), impacted 330 million people and resulted in a severe water shortage. One of the worst occurrences was the 2002-2003 drought, in terms of magnitude, spacing, dispersion, and duration, affecting almost 300 million people in India (Patel, Parida, Venus, Saha, & Dadhwal, 2012; Dutta, Kundu, & Patel, 2013; Bhat, 2006). Pakistan has also endured numerous droughts; the 1999–2000 droughts, which persisted until 2002, impacted an estimated 3.3 million people and caused the national agriculture sector to decline at a -

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2.6% rate (Ahmad, Hussain, Qureshi, Majeed, & Saleem, 2004). As such, the Pakistani government declared emergency conditions because of severe droughts (Tariq, 2012). In Bangladesh, 19 droughts were recorded between the period of 1960 and 1991. According to (Dey et al., 2011), a severe drought in Bangladesh occurs every 2.5 years on average, impacting 40% of crop production and affecting 53% of the population. In Nepal, the spatial distribution of drought varies; far-western and western regions experience winter drought, whereas pre-monsoon droughts are felt more acutely in the eastern and central regions in comparison (Kafle, 2014). The worst winter drought was experienced in 2008–2009, when the country received less than 50% of its average precipitation (Wang, Yoon, Gillies, & Cho, 2013). Due to this, a 14.5% decline in wheat production and a 17.3% decline in barley production was reported (Joint Assessment Report, 2009).

Detecting historical drought patterns will allow researchers to identify the drought-prone areas and quantify the indicators of vulnerability. Drought can be detected, monitored, and evaluated using drought indices that have been developed in the past (Niemeyer, 2008). Drought indices were developed for different objectives, applications, and the spatial coverage of geographical locations (Zargar, Sadiq, Naser, & Khan, 2011). Basic meteorological data, such as precipitation and temperature, were originally used to develop drought indices (Wu et al., 2013), including the Standardised Precipitation Index (SPI) (Mckee, Doesken, & Kleist, 1993), the Palmer Drought Severity Index (PDSI) (Palmer, 1965), and the Moisture Anomaly Index (Z index) (ibid). These indices work successfully at the scale of individual meteorological stations or across geographical regions of homogeneous land cover and similar climatic conditions. However, in places with scattered or absent meteorological data, these indices are insufficient for timely drought detection, monitoring, and decision-making (Son, Chen, Chen, Chang, & Minh, 2012; Brown, Wardlow, Tadesse, Hayes, & Reed, 2008; Unganai & Kogan, 1998).

Satellite remote sensing has been proven to be a capable and reliable tool for monitoring drought in countries with a scarcity of meteorological datasets (Abbas, Nichol, Qamer, & Xu, 2014; Wu et al., 2013), a valuable alternative to station-based data. They are critical to ascertain spatial and temporal drought patterns and trends due to the availability of time-series datasets, the low cost of access, the synoptic view, and the repetition and reliability of data acquisition (Mao, Ma, Xia, Tang, & Han, 2012). Various remotely-sensed drought indices using different satellite products have been developed and used for various applications and purposes (Peng, Deng, Di, & Han, 2015). Recently, regional drought monitoring tools in South Asia have been developed using remote sensing data sets (Aadhar & Mishra, 2017) . However, these applications have only utilised precipitation related data products, or only vegetation indices-related data products (Aboelghar et al., 2010; Kundu & Dutta, 2011; Mondal et al., 2014), which does not predict drought accurately across different land cover situations. Topographical complexity and scarcity of meteorological data are significant factors affecting the proper delineation of drought-prone areas in the South Asian region, therefore, integrating multiple variables from remotely sensed platforms and in-situ climate data is necessary to improve current drought assessment and monitoring systems. In this study, we have used the Drought Severity Index (DSI) (Mu, Zhao, Kimball, Mcdowell, & Running, 2013; Zhang & Yamaguchi, 2014), a remote sensing-based method applying evapotranspiration, potential-evapotranspiration, and vegetation index products to detect historical drought conditions at a regional scale. The main objective of our research is to examine the characteristics of long-term meteorological drought to understand its severity, frequency, and trends in South Asia under various climatic conditions and seasonal fluctuations. The timing and duration of drought have been studied, and outcomes from satellite datasets have been examined with field-based drought indices in Nepal and Bangladesh. The government agencies and other parties involved in designing drought mitigation initiatives would benefit from this knowledge. Furthermore, stakeholders can better prepare for regional shifts in actual and realised crop output under the stress of future climatic changes by understanding the spatial and temporal patterns of drought sensitivity for crops systems.

1.1. Study area

The study area comprises of Nepal, and selected regions of India, Pakistan, and Bangladesh, as shown in Figure 1. The land cover type data was obtained from MODIS Combined Terra+Aqua products, specifically MCD12Q1 data (collection v005, 500m) retrieved from the open-access National Aeronautics and Space Administration (NASA) Earth Data repository (https://earthdata.nasa.gov) for the 2000-2020. According to the International Geosphere-Biosphere Programme (IGBP) land cover classes (IGBP, 2017), including forests, croplands, wetlands, open shrublands, closed shrublands, grasslands, urban and built-up areas, bare soil, and roads, as shown in Figure 2. Altitudinal and climatic differences also exist in the study area.

2. METHODOLOGY

2.1. Remotely sensed data

In the study, eight days of composited reflectance data from the MODIS sensor has been retrieved from NASA and the United States Geological Survey (USGS), via the Earth Resources Observation and Science (EROS) centre (Justice et al., 1998). MODIS products of Landcover, Normalised Difference Vegetation Index (NDVI), and evapotranspiration/potential evapotranspiration (ET/PET) have been used for this study. The use of NDVI in this study is due to the potential of this product to link climate changes with vegetation responses (Xu et al., 2011).

2.1.1. MODIS Landcover Data

The land cover type data was derived from time series 2000-2020 MCD12Q1 data (collection v005, 500m), obtained from the MODIS Combined Terra+Aqua products on the open-access NASA Earth Data repository (https://earthdata.nasa.gov). Land cover was classified into 17 categories and later merged into eight categories: forests, savannas, grasslands, cropland, urban and built-up lands, barren, and water bodies (IGBP, 2017). Cropland was identified by at least 60% coverage of cultivated land and a mosaic of 40-60% small-scale cultivation with natural trees, shrubs, or herbaceous vegetation (IGBP, 2017).

2.1.2. MODIS ET, PET, and NDVI Data

The initial remote sensing data set included 8-day MOD16A2 Gap-Filled ET, PET, and MOD13A1 NDVI products at 500m spatial resolution for twenty-one years (2000-2020). The ET, PET, and NDVI datasets were obtained from the NASA Earth Data repository (https://earthdata.nasa.gov/), and the NASA Land Processes Distributed Active Archive Centre (LP DAAC, https://lpdaac.usgs.gov/).

2.2. Drought Severity Index (DSI)

According to Mu et al. (2013), the DSI Index, which combines the NDVI and ET/PET, is calculated as shown in Equation (1) to Equation (4). Incorporating transpiration and vegetation indicator data in DSI has been regarded as an improvement over other drought indices. To study historical drought in South Asia, monthly DSI values were calculated over twenty-one years (2000–2020). To identify the spatial distributions of drought, the mean monthly DSI values of South Asia and a few countries of South Asia were calculated separately. Following are the equation systems that were used:

$$Z_{Ratio} = \frac{ET/PET - \overline{\overline{ET/PET}}}{\sigma_{ET/PET}} \tag{1}$$

$$Z_{NDVI} = \frac{NDVI - \overline{\overline{NDVI}}}{\sigma_{NDVI}} \tag{2}$$

$$Z = Z_{Ratio} + Z_{NDVI} \tag{3}$$

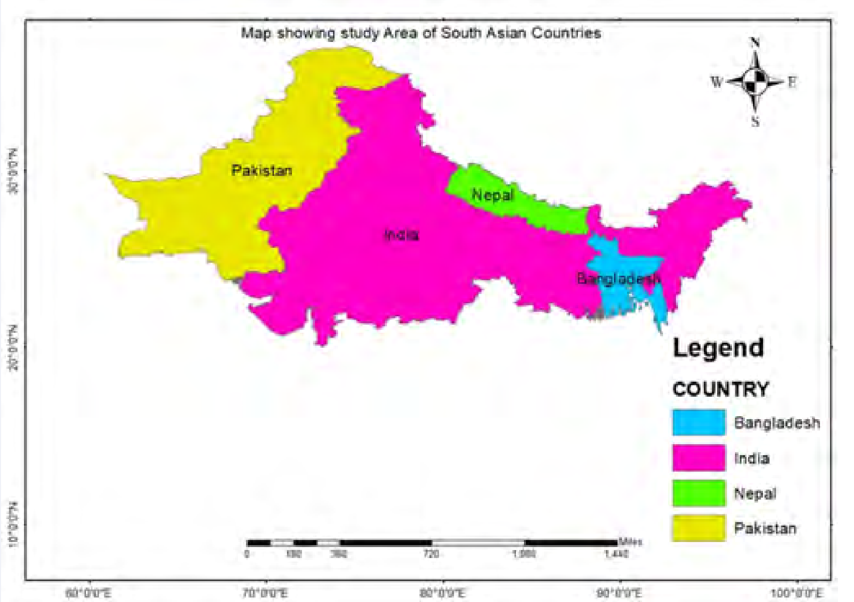

FIGURE 1. Map showing the study area of South Asia.

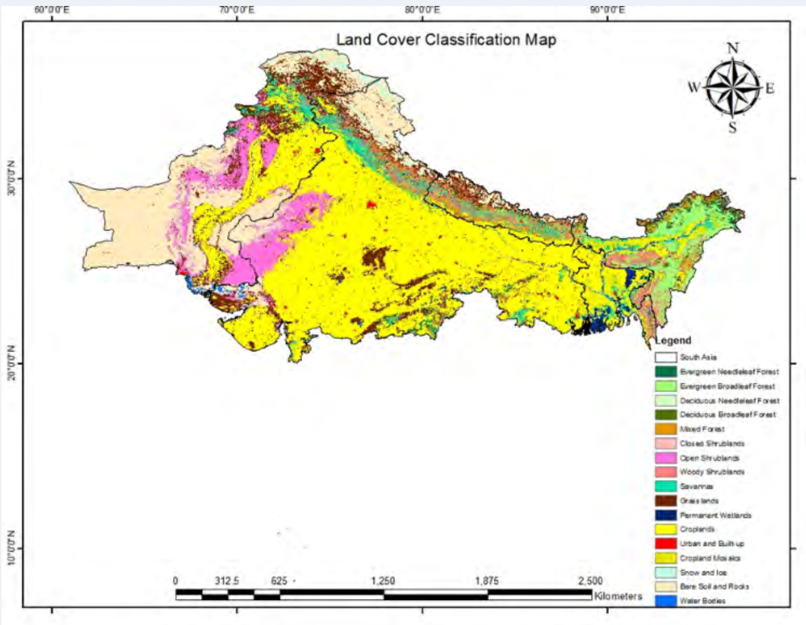

FIGURE 2. Land cover classification of South Asia of 2020.

$$DSI = \frac{Z - \underline{Z}}{\sigma_Z} \tag{4}$$

Where Z_{Ratio} and Z_{NDVI} is the standardized value of ET/PET ratio and NDVI, respectively. $\underline{ET/PET}$ and $\underline{NDVI}$ is the mean, and σ_{Ratio} and σ_{NDVI} is the standard deviation of ET/PET ratio and NDVI, respectively. $\underline{Z}$ and σ_Z represents the mean and standard deviation of the sum of Z_{Ratio} and Z_{NDVI} respectively. The Drought Severity Index is represented by the DSI calculated in Equation (4). The positive value of DSI represents wet conditions, while the negative value of DSI shows dry conditions. Mu et al. (2013) classified the values of DSI into categories of drought severity, as shown in Table 1.

Detailed calculation steps of DSI with the process of satellite data product download and processing has been shown in Figure 3.

Category	DSI Value
Extremely wet	1.5 or greater
Very wet	1.2 to 1.49
Moderately wet	0.9 to 1.19
Slightly wet	0.6 to 0.89
Incipient wet spell	0.3 to 0.59
Near normal	0.29 to -0.29
Incipient drought	-0.3 to -0.59
Mild drought	-0.6 to -0.89
Moderate drought	-0.9 to -1.19
Severe drought	-1.2 to -1.49
Extreme drought	-1.5 or less

TABLE 1. Drought Severity Index Classes.

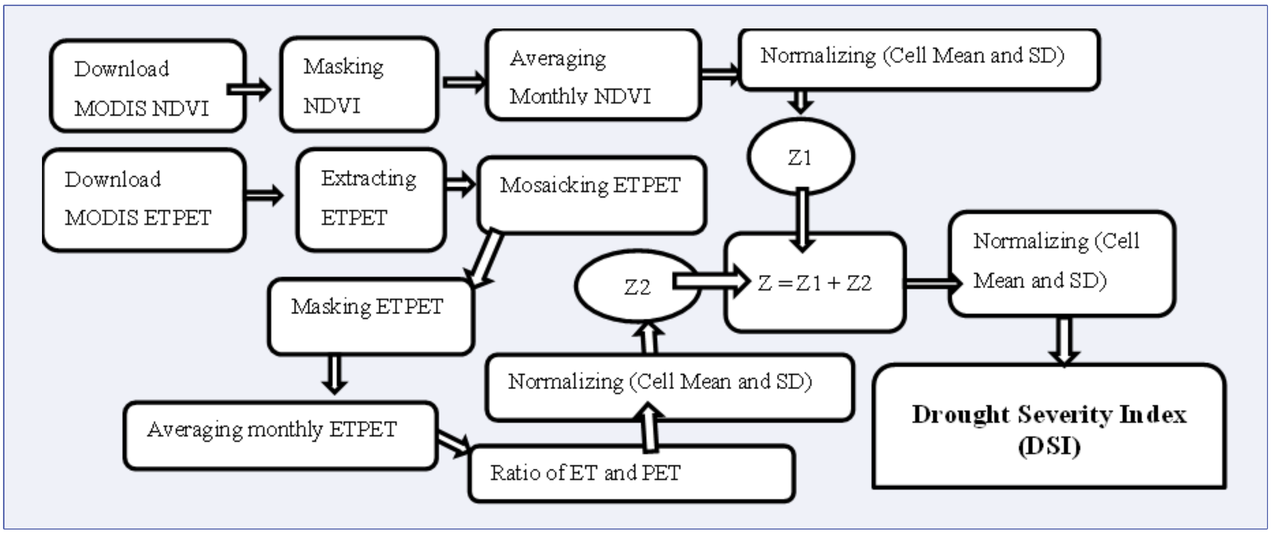

FIGURE 3. Chart showing process to calculate DSI.

2.3. Standardised Precipitation Index (SPI)

SPI is the measure of standard deviations that the observed mean precipitation deviates from the long-term mean precipitation (Mckee et al., 1993), as defined in Equation (5). The input parameter is monthly precipitation data, and the index can be calculated for multiple timescales (1, 3, 4, 6, 9, 12, and 24 months). SPI was endorsed as a primary meteorological drought index by the World Meteorological Organisation (WMO) in 2009 (Hayes, 2011) and is widely used for early drought detection.

$$SPI = \frac{P - P*}{\sigma} \tag{5}$$

In which P is the total precipitation, $P*$ is the mean precipitation, and σ is the standard deviation. Monthly SPI (SPI1) and three-monthly SPI (SPI3) have been calculated for the available meteorological data of Nepal and Bangladesh.

3. RESULTS AND DISCUSSION

3.1. Mean monthly DSI values of South Asia

The long-term average monthly DSI values for South Asia from 2000 to 2020 have been shown in Figure 4. The X-axis shows the time period, while DSI values are shown on the Y-axis. Positive DSI levels indicate wet conditions, whereas negative values denote drought conditions (Mu et al., 2013). The lowest mean monthly DSI value of -1.01 was reported in April 2001, suggesting severe drought conditions during the studied period (2000-2020). The lowest DSI values in the winter months were in January 2001, with a mean monthly DSI value of -0.63, showing a mild drought condition. We have also found long-term drought episodes for a continuous five-month period in 2000, 2001, and 2012. Most drought occurrences were in the pre-monsoon season (March, April, and May) in each year of the studied period except 2003, 2006, 2013, and 2019. There were no drought episodes in any month of 2020. The least drought-affected years were determined to be 2007, 2014, 2015, and 2019 with no instances of extremely dry circumstances, in reference to DSI values.

According to the average DSI values of South Asia, the summer months of March to May appear to be drought-prone. This may occasionally stretch into June. However, compared to the summer months, the winter months were less affected by the drought except during January 2001 and February 2000, 2001, 2012, 2016, and 2018. Compared to other years, 2007, 2019, and 2020 had relatively more precipitation, indicating wet conditions across South Asia.

3.2. Mean monthly DSI values of drought months in South Asia

Mean monthly DSI values of the drought months in each year were analysed to study the characteristics of the historical drought in South Asia (Figure 5). The X-axis represents the drought months each year from 2000 to 2019, as 2020 was the wettest year in the past 20 years. Y-axis represents the mean DSI values across South Asia. According to our results, the onset of drought is often observed from March. On occasion, during drier years, the onset of drought conditions may be observed from February. The severity of drought is observed to peak in April, and the cessation of drought is often observed in June. However, in some years, it has been recorded in the month of July. This phenomenon is spatially variable across different parts of South Asia. Drought onset is seen mainly from the eastern part of South Asia, and gradually moving towards the western part. Similarly, the cessation of drought is attributed to the monsoonal rain, originating from the eastern part of South Asia.

3.3. Spatial and temporal distribution of drought

Drought maps of the studied area from the months of January to December in different drought years, as explained above, are shown in Figure 6. These maps represent the characteristics and severity of drought in different locations in South Asia. In the month of March (Figure 6c), the eastern region of South Asia had severe to moderate drought for most of the research period. After that, the drought moved to the west, creating severe to moderate drought in April (Figure 6d) in southern Nepal and northern India. In May (Figure 6e), the location of the drought struck once more, this time in the west, impacting southern Nepal, northern India, and the south-eastern region of Pakistan. While the north-western region of South Asia continues to experience a moderate to mild drought, the eastern region receives rain in June (Figure 6f).

As the monsoon continues, the study area becomes moist, except for Pakistan's western region, which experiences an early drought. Almost all of South Asia experienced rain in August (Figure 6h) and September (Figure 6i). The post-monsoon months of October (Figure 6j) and November (Figure 6k) are primarily moist in the east. In contrast, the north-western section of the research region is found to be in severe to impending categories of drought. Meanwhile, moderate to mild drought conditions persisted throughout South Asia in December (Figure 6l). The eastern portion of the continent saw severe to mild drought conditions in January (Figure 6a) and February (Figure 6b), mostly in eastern India and Bangladesh. The most notable drought in the investigated era, affecting all South Asian countries, occurred in April (Figure 6d) and May (Figure 6e). In these months, both people and the environment were affected by drought.

3.4. Seasonal drought variation in South Asia

For the seasonal analysis of drought, the DSI was averaged to DJF (December-January-February) as shown in Figure 7d for winter, MAM (March-April-May) (Figure 7a) for pre-monsoon, JJA (June-July-August) (Figure 7b) for monsoon, and SON (September-October-November) (Figure 7c) for post-monsoon seasons.

Pre-monsoon season (MAM) is when droughts are most prevalent, ranging from severe to moderate. As rainfall becomes more readily available

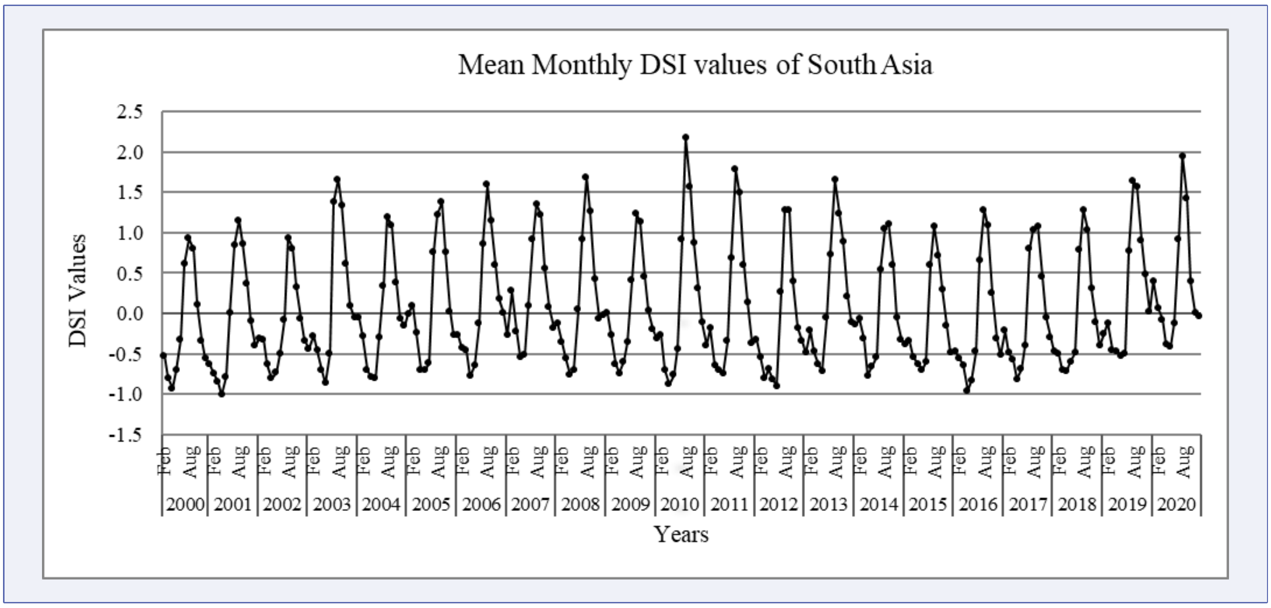

FIGURE 4. Mean monthly DSI values of South Asia during 2000-2020.

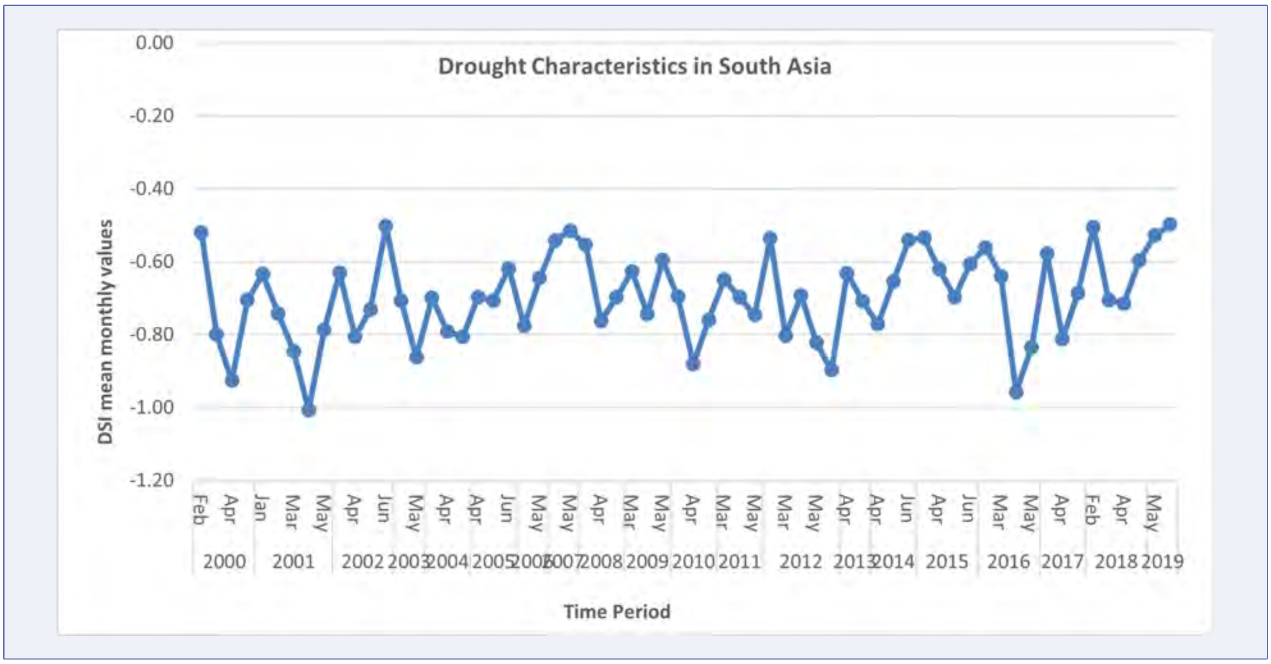

FIGURE 5. Long-term drought characteristics in South Asia.

during monsoon season (JJA), the severity of the droughts gradually decreases. Similar to the post-monsoon SON season, eastern part of South Asia is remains moist, with a developing drought in the northwest of the study region. Most of the eastern part of South Asia, including eastern India and Bangladesh, and certain regions of the northern belt of South Asia, experience considerable dryness during the DJF cold season. In MAM, severe signs of drought dominated, which often impacted water sources and farmlands. In comparison to the classification of land cover, South Asia's farmland is more affected by droughts in MAM. Long-term farmland dryness during the pre-monsoon season can impact the nation's agricultural growth and productivity.

The results indicate longer drought episodes during December 2000 to May 2001 in Nepal, April, May, June, and July 2002 in Pakistan, and December 2000 to April 2001 in Bangladesh. These types of drought occurrences could impact the region's agriculture, thereby seriously reducing crop yield and threatening food security for people. Similar results

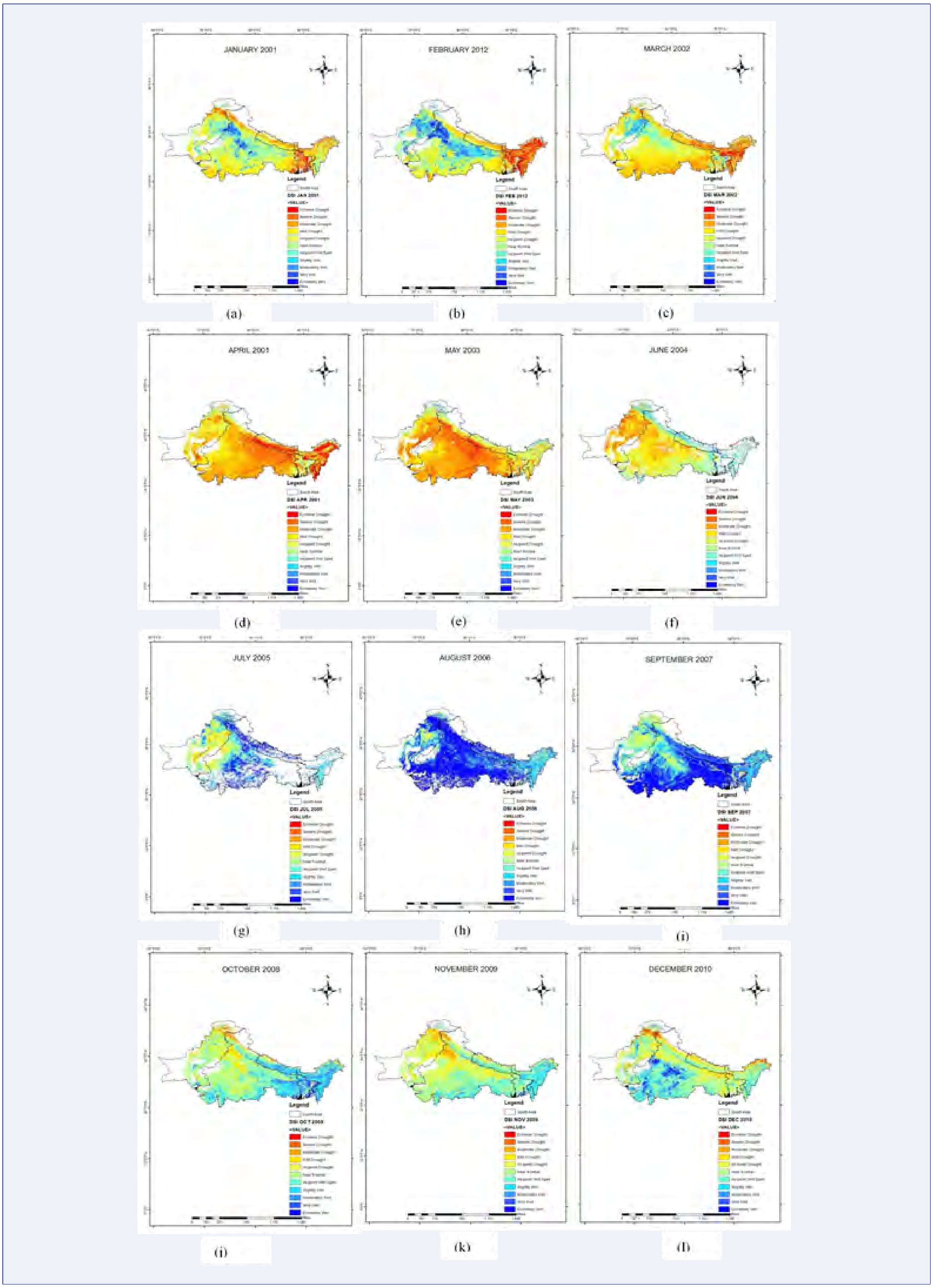

FIGURE 6. Spatial maps of drought in studied areas in different months.

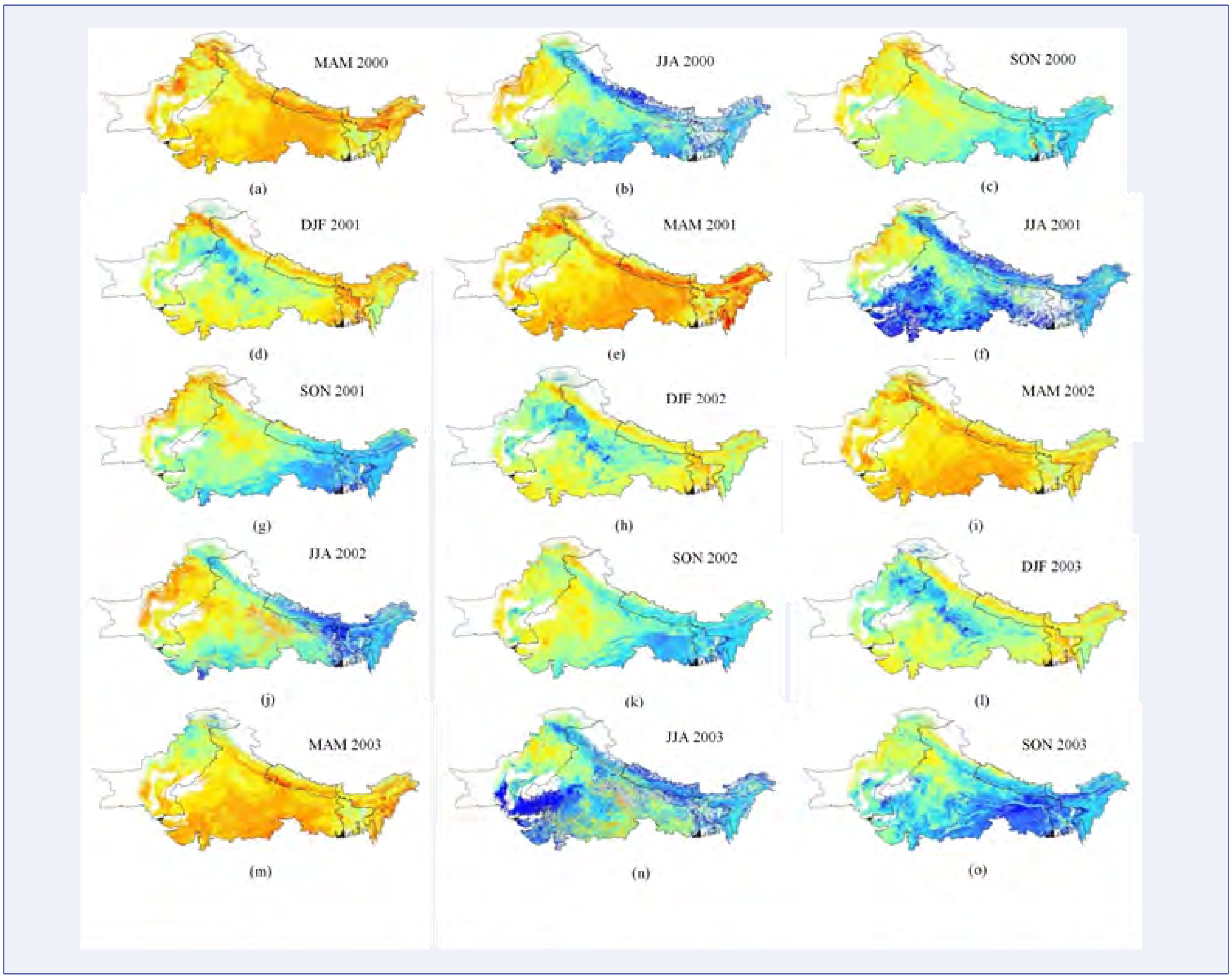

FIGURE 7. Drought events showed by seasonal maps from 2000 to 2003.

were shown in a study from Ahmad et al. (2004), which reports that a severe drought episode during 2000–2001 had a substantial impact on the growth rate of crop plants, declining by 2.6%, compared to a positive growth rate of 1.4% during 2001–2002 in Pakistan. Adnan, Ullah, and Shouting (2016) also identified severe drought in south-central Asia in 2000, including Pakistan. According to previous research (Ramamasy & Baas, 2007; Shahid & Behrawan, 2008), droughts affected around 2.3 million hectares of Bangladesh's agricultural land from April to September 2001, and 1.2 million ha of cropland from October to March 2001, resulting in an annual production loss of 1.5 million tons. The severe drought occurrences in Bangladesh from December 2000 to April 2001 are consistent with studies from Raghib et al. (2010). Our findings on drought using the DSI index in Nepal were also consistent with the study by Adhikari (2018), which shows the impact of drought on the agriculture and hil farming system in various areas of Nepal in the years 2002, 2008, 2009, 2012, 2013, and 2015.

3.5. Comparison of DSI values with SPI in Nepal and Bangladesh

Monthly SPI values of 24 meteorological stations in Bangladesh and 59 meteorological stations in Nepal were compared with DSI values from the same latitude/longitude of each meteorological station. The line graphs of SPI and DSI values of four stations in Bangladesh (Figure 8a, b, c, d) and four stations in Nepal (Figure 8e, f, g, h) are shown below.

As indicated from the graphs, we found a similar trend of SPI and DSI values in some stations. However, there were different trends and values in some years. These could be due to the different land cover designations of the geographical area. It can also be assumed that each DSI value is the

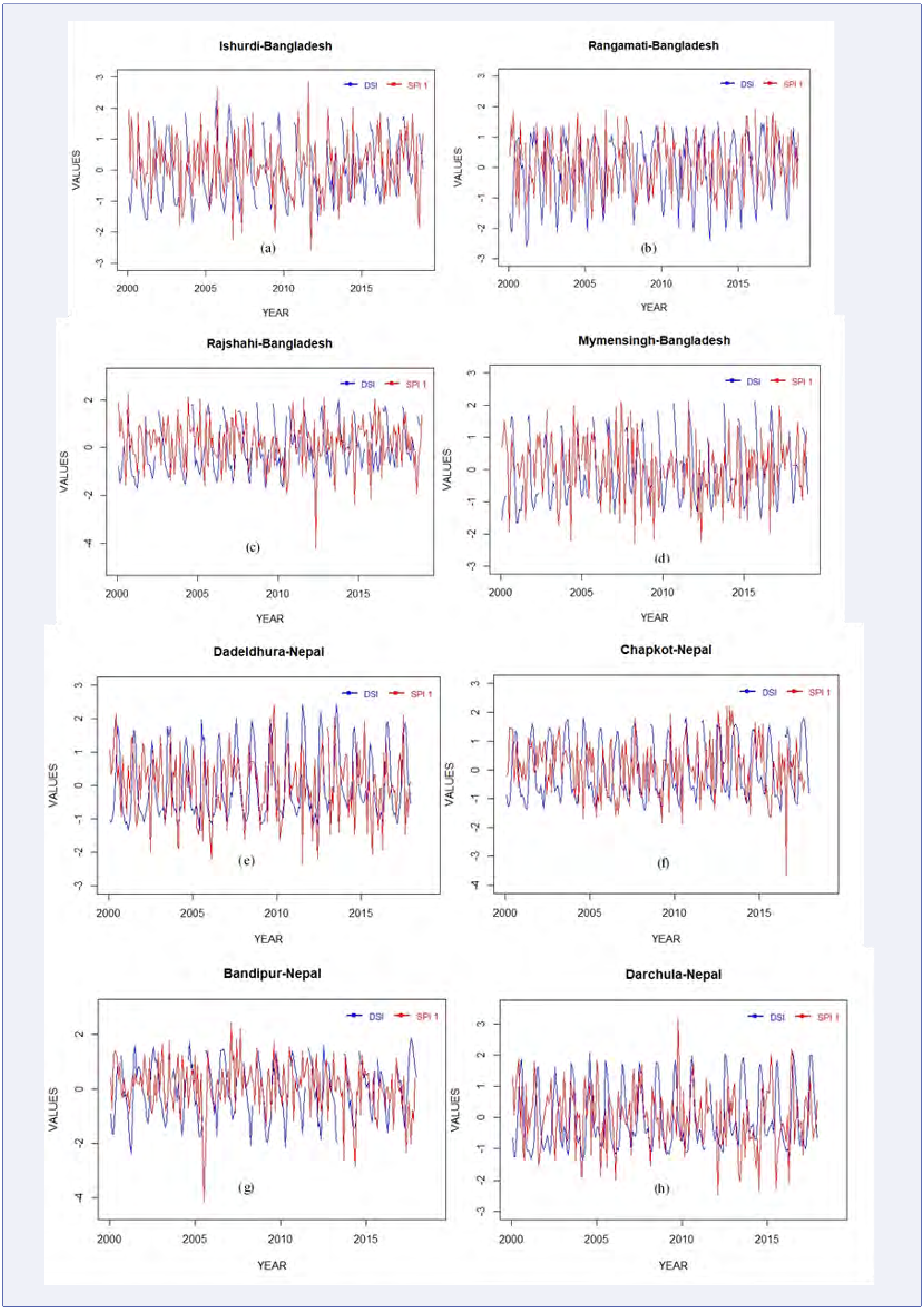

FIGURE 8. Comparison between DSI and SPI in Nepal and Bangladesh.

average value of each land cover within the MODIS 500m*500m data tile. Conversely, the SPI value of each station indicates the point location where the meteorological station was situated, whereby SPI values could be influenced by irrigation facilities on the field. As DSI calculations do not utilise precipitation value, the area with an irrigation facility will be moist, although the precipitation value of that location is very minimal. In this case, we can identify severe drought from SPI calculation. Therefore, the occurrence of drought due to anthropogenic causes will not be captured by SPI values.

4. CONCLUSION

One of the key elements influencing the nation's agricultural growth is found to be drought, as shown in this study of historical drought of South Asia from 2000-2020 using open-access satellite data products. Drought severity maps of each month and season in drought periods demonstrate that past drought experiences substantially influenced South Asia. The most severe drought events investigated, affecting all South Asian countries, occurred in 2000, 2001, 2004, 2010, 2012, and 2016. These years had notable drought occurrences that affected people and the environment for several months. Severity of drought in these years could also be due to the El Nino-Southern Oscillation (ENSO), since the occurence of ENSO was found to be in the years 2002, 2004, 2006, 2010, and 2016.

In most of the selected study areas, severe to moderate drought was identified from March to May in the years 2000, 2001, 2002, 2004, 2009, 2010, 2011, 2012, 2016, and 2018. DSI value characterisation of different countries resulted in significant drought events in different periods; for instance, in Bangladesh, the extreme drought events took place in February, in Nepal, it was during March-April-May, and in Pakistan, during April-May-June. Moreover, severe to moderate drought occurrences were most prevalent during South Asia's pre-monsoon season (MAM). During the monsoon season (JJA), when rainfall is more frequent, the severity of the droughts gradually diminishes. Similar to the post-monsoon SON season, eastern parts of South Asia was still damp, with a small area that may soon see dryness. During the DJF cold season, the majority of the eastern parts of South Asia, including eastern India and Bangladesh, and some areas of the northern belt of South Asia experienced significant dryness. Furthermore, western and north-western regions of Nepal, eastern and central-southern parts of India, the south-eastern region of Bangladesh, and southern parts of Pakistan were likely to have long-term drought risk.

A comparison between the monthly DSI values and the monthly SPI values in Nepal and Bangladesh showed a similar trend in some places. Varied values and trends among SPI and DSI values were attributed to differing land cover types, irrigation facilities, and the presence of vegetation. This result demonstrates that SPI captures the occurrence of drought due to natural causes or precipitation. On the other hand, drought caused by anthropogenic factors and also natural factors are captured by DSI. The results demonstrate that the monitoring of past and present drought is possible using DSI on a regional scale, with no availability of meteorological stations.

Mitigating drought is essential, and investigating historical drought experiences can be quite helpful in this regard. The economic effects of droughts have not been adequately quantified, and policymakers frequently fail to take preventive measures to prepare for them. Additionally, population growth, urbanisation, water consumption trends, governmental policy, social behaviour, and environmental factors affect society's susceptibility to drought. The vulnerability of society to drought may increase or decrease as a result of these components. An assessment of likely corrective actions to prevent the negative impact of drought should be produced.

This study's analysis of the historical drought episodes between 2000 and 2020 can aid in monitoring droughts in South Asia. Future research may concentrate on the interaction between other climatic and topographic variables influencing drought. Moreover, various insitu data-gathering methods might be used for field validation.

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Editorial

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Climate science communication in Pakistan: A compulsive need

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Science to policy communication is an important aspect of climate science due to the presence of uncertainty, varied viewpoints and complexities of the climate system. The manner in which climate scientists convey their research to politicians will determine how much of an impact their work has on a government's policies and actions about the effects of climate change. A lack of effective communication between scientists and policymakers leads to ineffective policies, which ultimately exacerbate the damage caused by the impacts of climate change. This lack of communication is either a result of scientists' and researchers' limited ability to communicate their research to decision-makers - ultimately leading to their confusion about the uncertainties and complexity of the climate system - or is a result of policymakers' inability to communicate their priorities to researchers, which prevents them from conducting research that is focused on producing results. In such scenarios of communication gaps, the media is recognised as having the role of "intermediaries between researchers and decision-makers, representing the information into usable form" (Howlett, 2011). In recent years, to prevent climate change from developing into a crisis, there has been a noticeable increase in emphasising effective communication of climate change to policymakers. Every region of the world is being impacted by climate change, which is on the verge of becoming one of the largest disasters the world has ever seen. Unfortunately, Pakistan, which contributes less than 1% of global greenhouse gas (GHG) emissions, has been among the most vulnerable nations for past decades, according to the Germanwatch Climate Risk Index published yearly. The problem is that the effects are anticipated to worsen, increasing the vulnerability of the nation's livelihood and economy. Rehman, Adnan, & Ali (2018) reveal that Pakistan has experienced greater warming than the world as a whole, as measured by an increase in average temperature. Due to this increased warming, the Paris Agreement targets of 1.5°C and 2°C may appear earlier in Pakistan (Kiani et al., 2021). As a result of this temperature increase, climate and weather patterns alter in a variety of ways, resulting in unanticipated changes in precipitation, increases in the frequency and severity of extreme weather events, changes in the monsoon patterns, and an increase in heatwaves (Ali et al., 2019; 2020). These changes negatively impact people's livelihoods and well-being, as recurring floods, glacial lake outburst floods (GLOFs), droughts, and heatwaves of greater intensity affect many people every year, making the country one of the top ten vulnerable regions in the world. Recent floods in Pakistan are also attributed to unexpected precipitation during the monsoon season and increased glacier and snowmelt flow downstream. The main problem, however, is that while climate scientists and researchers are well aware of the underlying causes of such catastrophes, they are unable to convey this knowledge to decision-makers in order for them to devise policies that can help to minimise the loss caused by such climate change-induced events. Regarding this, the term "Science to Policy Communication" has gained prominence in many parts of the world; nevertheless, the phrase is less well-known in Pakistan. Realising the climate change adversity in the country and the communication gap between researchers and policymakers, a project was conducted under APN's Early Career Science Communicators programme. The project's primary goal was to communicate scientific research on climate change to various stakeholders. The project included various activities aimed at translating scientific research into understandable information and communicating it to the general public to raise awareness of the real-time challenges of climate change. Media has emerged as an essential means of communicating climate research to policymakers and the general public worldwide (Ahchong & Dodds, 1988; Aram, 2011; Boykoff, 2011; and Schäfer, 2012). However, media in developing countries such as Pakistan lacks the capacity to translate scientific information and connect it to everyday life, resulting in widespread neglect of the issue. Against this backdrop, a one-day media training workshop on "Climate Change with Emphasis on Health Impacts" was organised in collaboration with the Health Services Academy (HSA), Islamabad, Pakistan. The workshop's primary goals were to provide training and capacity building for Pakistani journalists and media professionals to improve their efficacy of climate change communication and raise awareness among students and the general public. The media training workshop was attended by renowned media persons and journalists, climate scientists, members of the Health Services Academy, health professionals, and several students to acquire knowledge on the health impacts of climate change and effective climate change communication. The training workshop provided a forum for the media to interact with climate scientists and health professionals, and helped journalists and reporters understand the complexities of climate science and its associated uncertainties. During technical sessions, renowned journalists, including Farid Raees (Neo News), Khalid Jamil (Media Communications) and Hina Chaudhary (PTV news), working in the field of climate change communication, educated participants on the importance of science to policy communication and how to bring the issue of climate change to the forefront of media. Furthermore, they discussed the challenges associated with climate change communication in Pakistan. Climate scientists and health professionals also discussed the country's vulnerability to climate change and the consequences for human health. The representatives of the newly formed 'Environmental Journalists Association,' a group of journalists working on environmental and climate issues, also attended the workshop and invited other journalists to join them to call the media's attention towards climate change. The event was covered by one of Pakistan's leading news channels SAMAA TV and received remarkable appreciation from the participants. Such activities not only help to build capacity but also help to pave the way for cross-sectoral cooperation. The workshop also served to encourage students and researchers to play their part and participate in communication efforts.

In addition to the capacity building of media in effective climate change communication, public awareness of environmental issues is critical, as they are the ones who face the consequences of the changing climate in their daily lives, such as heatwaves that cause illness and death, failing crops and flooded land. It is perceived that developing-country communities do not need to be convinced of climate change; rather, all they need is to 'make sense' of what they are witnessing, to understand it in the context of science, and to recognise future vulnerabilities and how to deal with them. In order to accomplish this, it is critical to effectively communicate to them their future vulnerability and potential solutions in an understandable manner. With this in mind, the project involved the use of multiple modes of communication to raise local community awareness, including dedicated radio programmes in the national language Urdu and TV interviews in the local language, i.e. Pashto. Through such non-scientific science communication, communities could better relate to and connect the information to their vulnerability and possible ways to cope.

Finally, given the formidable climate-induced challenges to society and the economy, climate change communication is a compelling necessity in countries such as Pakistan. Projects like the one described can contribute to enhancing the capacity of media to better communicate climate change while allowing researchers to get involved in science communication efforts. Regarding this, it is widely acknowledged that APN plays a remarkable role in leading regional efforts to support climate change communication projects. The persistence of such science communication efforts will eventually push the issue of climate change to the top of policy priorities, enabling more informed decision-making.

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