Received: 13 May 2022 | Revised: 3 October 2022 | Accepted: 14 October 2022

DOI: 10.1002/aqc.3897

RESEARCH ARTICLE

WILEY

What is the ecological footprint of aquaculture after 5 decades of competition between mangrove conservation and shrimp farm development?

Samuel A. Ofori[1,2] | Sunanda K. A. Kodikara[3] | Loku P. Jayatissa[3] | Sanduni K. Madarasinghe[4] | T. W. G. F. Mafaziya Nijamdeen[1,5] | Farid Dahdouh-Guebas[1,2,6]

[1]Systems Ecology and Resource Management, Department of Organism Biology, Faculty of Science, Université Libre de Bruxelles (ULB), Brussels, Belgium

[2]Ecology & Biodiversity, Department of Biology, Faculty of Science and Bioengineering Sciences, Vrije Universiteit Brussel, Brussels, Belgium

[3]Department of Botany, Faculty of Science, University of Ruhuna, Matara, Sri Lanka

[4]Department of Physics, Faculty of Science, University of Ruhuna, Matara, Sri Lanka

[5]Department of Biological Sciences, Faculty of Applied Sciences, South Eastern University of Sri Lanka, Sammanthurei, Sri Lanka

[6]Interfaculty Institute of Social-Ecological Transitions, Université Libre de Bruxelles - ULB, Brussels, Belgium

Correspondence
Samuel Appiah Ofori, Systems Ecology and Resource Management, Department of Organism Biology, Faculty of Science, Université Libre de Bruxelles (ULB), Brussels, Belgium.
Email: ofori496@gmail.com

Abstract

1. Among the several threats to the conservation of mangrove ecosystems in most South Asian countries, shrimp farming is predominant. Since the introduction of shrimp farming in Sri Lanka in the 1980s, mangroves on the island's north-western coast have been continually cleared to create new shrimp farms, leading to a decline in the social-ecological services provided by the mangrove ecosystems.
2. Using aerial (1973) and satellite (1996–2020) images, this study assessed areal changes in mangroves and shrimp farms in the Pambala-Chilaw lagoon complex and Ihala Mahawewa, as well as the ecological footprint of shrimp farming in the study area.
3. Mangroves around the Chilaw lagoon had decreased in areal extent by 45% from 1973 to 2020 of which 92% of this change was attributed to shrimp farming. There was, however, a decrease in the areal extent of shrimp farms from 2001 to 2020, and a corresponding increase in mangroves from 2006 to 2020.
4. The ecological footprint of shrimp farming was assessed by comparing the expected surface ratios with those recorded for shrimp farms with mangroves and surface water bodies in the study area from 1973 to 2020. The results showed that the current shrimp farming was unsustainable (i.e. high ecological footprint).
5. While the results support the current view that there is cause for cautious optimism with mangrove conservation (as evidenced by an increase in mangrove areal extent), it also reveals that semi-intensive shrimp farming in Sri Lanka and probably other similar tropical countries is unsustainable.
6. If immediate actions such as effective regulation of shrimp farming activities and mangrove restoration are not taken, the mangrove ecosystem will continue to decline.

KEYWORDS

ecological footprint, mangrove conservation, on-screen digitization, quantity and allocation disagreement, shrimp farming, Sri Lanka

1 | INTRODUCTION

Mangroves are plant communities which are present in more than 120 countries in the tropical, subtropical and warm temperate latitudes, where they grow at the land–sea interface, in bays, estuaries, lagoons and backwaters (Dahdouh-Guebas et al., 2021). Generally, mangroves are represented by woody trees and shrubs, with some non-woody (e.g. *Nypa fruticans*) or herbaceous (e.g. *Acrostichum* spp. and *Acanthus* spp.) species (Dahdouh-Guebas et al., 2021). Mangroves serve as highly productive areas and provide spawning and nursery grounds for migratory species, play a significant role in the global carbon cycle (Donato et al., 2011; Cooray et al., 2021), promote sustainability of fishing communities (Madarasinghe et al., 2020a; Madarasinghe et al., 2020b; zu Ermgassen et al., 2021) with high primary productivity, and protect the coastal zone, preventing erosion and reducing the impact of natural hazards such as tsunamis (Dahdouh-Guebas et al., 2005).

Mangroves also serve as a source of wood products which are useful for construction, fuelwood and charcoal production, as well as non-timber vegetation products such as food and drinks, and chemical substances of medicinal interest to local communities (Nfotabong-Atheull et al., 2011; Dahdouh-Guebas et al., 2021). They also have a scenic beauty, which promotes tourism and generates local and international revenues for local communities and countries possessing mangroves (Spalding & Parrett, 2019; Dahdouh-Guebas et al., 2020).

Studies conducted on the changes in the global mangrove extent have reported a decline in the rate of loss from 2.07% between 1980 and 2000 (Valiela, Bowen & York, 2001) to 0.13% between 2000 and 2016 (Friess et al., 2020; Goldberg et al., 2020). Despite such positive reports, some key unsustainable activities have still not been adequately addressed. These activities include shrimp aquaculture, agriculture, urban expansion, firewood collection, and timber and charcoal production (Duke et al., 2007; Lee et al., 2014; Goldberg et al., 2020). In many South and South-East Asian countries such as Sri Lanka, India, Bangladesh, Indonesia, Vietnam, the Philippines and Thailand, shrimp farming is known to be one of the major contributing factors causing mangrove loss (Dahdouh-Guebas et al., 2002; Dahdouh-Guebas et al., 2006a; Van et al., 2015; Abdullah et al., 2016; Richards & Friess, 2016).

Since the early 1980s, the expansion of shrimp farming on Sri Lanka's north-western coast has remained the greatest threat to mangrove ecosystems (Dahdouh-Guebas et al., 2002; Leslie, 2011; Bournazel et al., 2015). The increase in shrimp farming activities over time could lead to a gradual decrease in mangrove forests until the forest is completely converted into shrimp farms (Gunawardena & Rowan, 2005). Most shrimp farmers believe that areas occupied by mangroves, particularly the intertidal zones, are most suitable for shrimp farming since the soil there possesses high salinity, and saltwater from the sea, lagoon, or canals is continually accessible (Cattermoul & Devendra, 2002; Munasinghe et al., 2010).

Since the 1990s, shrimp farming in the North-western Province of Sri Lanka has experienced declines and improvements due to environmental issues and political interference such as unresolved legal issues associated with land tenure (Foell, Harrison & Stirrat, 1999; Dahdouh-Guebas et al., 2002; Galappaththi & Berkes, 2014). The occurrence and spread of the white spot disease (WSD) on shrimps in both shrimp farms and natural waters of Sri Lanka from 1994 to 1995 promoted the abandonment of infested ponds and the clearing of mangrove vegetation to create new shrimp farms (Dahdouh-Guebas et al., 2002; Bournazel et al., 2015). In the Pambala-Chilaw lagoon complex (P-CLC), which is located in the North-western Province of Sri Lanka (Figure 1), Dahdouh-Guebas et al. (2002) reported a decline (6.1%) in mangrove area from 209.29 ha to 196.53 ha and an increase (48.4%) in shrimp farm area from 51.87 ha to 76.99 ha between 1994 to 1998.

The reported decline in mangrove extent caused by shrimp farming and their strict dependence on coastal water resources highlights the need for an assessment of the ecological footprint of shrimp farming on mangrove ecosystems. The ecological footprint method, which was first described by Larsson, Folke & Kautsky (1994) and Folke et al. (1998), explains the pressures on ecosystems from human activities (including resource consumption and waste discharge) and the surface area required to support these activities. Several studies have been conducted to assess different types of footprints attributed to aquaculture; these include carbon footprint (Kauffman et al., 2017), water, energy and land footprint (Guzmán-Luna, Gerbens-Leenes & Vaca-Jiménez, 2020), seafood consumption footprint (Guillen et al., 2019), and marine ecological footprint (de Leo, Miglietta & Pavlinović, 2014), among others.

Larsson, Folke & Kautsky (1994) recommended that a semi-intensive shrimp farm requires support from an ecosystem with a surface area 35–190 times larger than the shrimp farm. In P-CLC, most of the shrimp farms occurring around Chilaw lagoon are semi-intensive or small-scale in their shrimp production; they use mud banks in pond construction, shrimp feeds are formulated with required nutrients and not all the ponds are aerated. Additionally, the surrounding lagoon or the creeks in the area, or canal water, serve as a source of clean pond water and also for washing wastewater through the ponds out into Chilaw lagoon or Dutch canal (Cattermoul & Devendra, 2002).

Apart from the study conducted by Dahdouh-Guebas et al. (2002) on how shrimp farming has led to the decline of mangrove forests in P-CLC between 1994 and 1998, no study has been conducted to investigate the subsequent changes in the areal extent of mangroves and shrimp farms in P-CLC and its connected mangrove vegetation in Ihala Mahawewa, as well as the associated ecological footprint of shrimp farming in the entire area.

Therefore, the objectives of this study were to:

i. Quantify, the changes in areal extent of mangrove vegetation and shrimp farms in P-CLC and Ihala Mahawewa from 1973 to 2020 using high spatial resolution images.
ii. Understand the factors leading to the changes in areal extent of mangrove vegetation and shrimp farms in P-CLC and Ihala Mahawewa from 1973 to 2020.
iii. Assess the ecological footprint of shrimp farming in P-CLC and Ihala Mahawewa from 1973 to 2020.

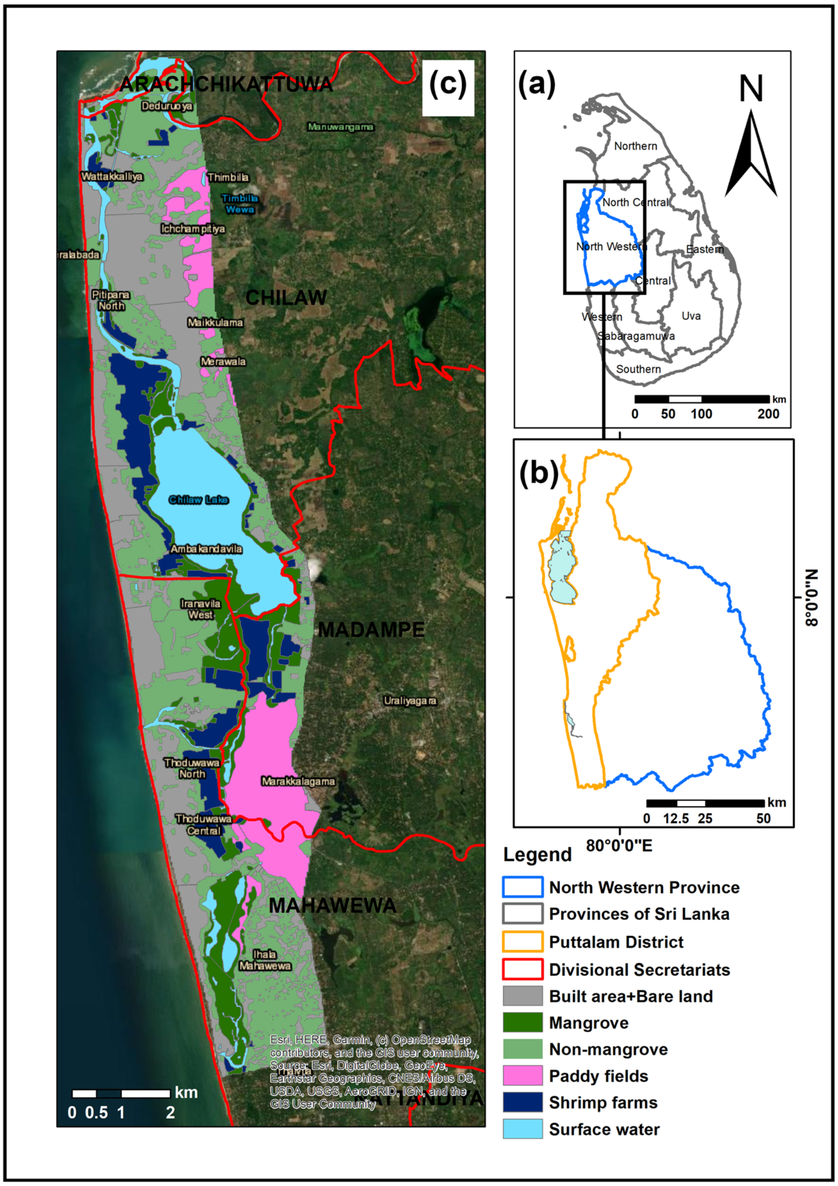


FIGURE 1 Map showing the study area. (a) Provinces of Sri Lanka; (b) North-western Province, Puttalam District; (c) the study area (Pambala-Chilaw lagoon complex and Ihala Mahawewa) and the available land uses/covers: Chilaw lagoon, creeks, rivers, mangrove vegetation, non-mangrove vegetation, paddy fields, sea, shrimp farms, built area and bare lands. The Sri Lanka – Subnational Administrative Boundaries and Lagoons were accessed from https://data.humdata.org/dataset/cod-ab-lka and https://data.humdata.org/dataset/sri-lanka-water-bodies-0, respectively. Data source: Survey Department of Sri Lanka. Data contributor: OCHA Regional Office for Asia and the Pacific (ROAP).

2 | METHODS

2.1 | Study area

The study was conducted in P-CLC and Ihala Mahawewa of the Puttalam district in the North-western Province of Sri Lanka. The landmarks defining the northern, western, eastern and southern boundaries of the P-CLC are the Daduru Oya river, the seashore, the road between the Puttalam district and the Kurunegala district, and Kakkapalliya, respectively. Ihala Mahawewa is located at the southernmost point of P-CLC. The P-CLC consists of 49 Grama Niladhari divisions with a total population of 63,188 and it is identified as one of the regions where local people are involved in shrimp farming inside and around the Chilaw lagoon (Ministry of Home Affairs, 2021).

The study area is located in the intermediate climate zone of Sri Lanka with a geographical location of 07°35′48″ N, 79°47′25″ E (Di Nitto et al., 2013). The major land uses/covers (LU/LCs) are mangroves, surface water bodies (lagoon, creeks and dams), shrimp farms, built area, bare lands, coconut plantations, croplands and paddy fields (Figure 1). The mangrove community in the area has 17 true mangrove species and 13 mangrove associates (Jayatissa, Dahdouh-Guebas & Koedam, 2002), which are distributed along the Chilaw lagoon and a complex of creeks, i.e. Marambettiya Ela, Bate Ela, Pol Ela and Dutch Channel (Di Nitto et al., 2013).

2.2 | Remote sensing and GIS

2.2.1 | Acquisition and processing of remote sensing and GIS data

The extent of the study area was delineated from the northern mouth of Chilaw lagoon towards the mangrove vegetation occurring in Ihala

Mahawewa, covering an area of about 20 km in length and about 4 km wide. Aerial images of the P-CLC for the year 1973 were acquired from the Survey Department of Sri Lanka. Cloud-free Landsat 5 and 8 satellite images covering the study area were also acquired for the years 1996, 2001, 2006, 2011, 2015 and 2020 from the US Geological Survey (USGS) Earth Explorer website (Table 1).

Image processing was done using ArcMap 10.5 and Google Earth Pro 7.3. All images were projected to the Universal Transverse Mercator coordinate system; Datum WGS 1984, zone 44 N. The study area polygon for GIS analysis was created using Google Earth Pro 7.3. The polygon was then used to clip the Landsat satellite images to the extent of the study area (P-CLC and Ihala Mahawewa) using ArcMap 10.5. For the aerial images, georeferencing was done by overlaying them onto the oldest image scene (2002) of the study area available in Google Earth Pro 7.3. The georeferenced images were then mosaicked and clipped to the extent of P-CLC using ArcMap 10.5.

For Landsat 5 and 8 satellite images, a composite raster was created for each year using a combination of the green, red and infrared bands. For each of the composite images, a false colour composite raster was further generated using 4–3–2 (infrared–red–green) and 5–4–3 (infrared–red–green) band combinations for Landsat 5 and 8 satellite images, respectively. In some instances, a false colour composite of 5–6–7 (infrared–midinfrared1–midinfrared2) was used for Landsat 8 satellite images to improve classification accuracy (Pagkalinawan, 2015). The false colour composite images were then clipped to the study area extent.

2.2.2 | Image classification

LU/LC classes of interest for image classification included: surface water bodies, mangrove vegetation, non-mangrove vegetation (i.e. coconut plantations and croplands), paddy fields, shrimp farms and built area+bare lands. Built area and bare lands were combined as a single class because of the high similarities in their spectral features. LU/LC classification of processed images was conducted using the on-screen digitization method, allowing the researcher to visually interpret LU/LC classes using image attributes (Dahdouh-Guebas et al., 2006a; Madarasinghe, Yapa & Jayatissa, 2020). This method was deemed better since abandoned shrimp farms that were either filled with water or dried-up could not be correctly classified as shrimp farms when a pixel-based classification is used. Since the extent of the 1973 aerial image was limited to the P-CLC, its classified map was compared with the 2020 classified map of the same extent. The set of satellite images was used to assess the LU/LC changes in the study area (P-CLC and Ihala Mahawewa) from 1996 to 2020.

To increase classification accuracy, Google Earth Pro 7.3 was used as a ground-truthing resource to validate the existing LU/LCs in the study area during and after each classification process. In the ArcMap 10.5 interface, corrections were done for both positional (overshoots and undershoots) and topological (dangles and overlaps) errors that may have occurred during the on-screen digitization process. A list of identification keys, which included tonality, texture, structure and position, was used for LU/LC classification (Table 2).

2.2.3 | Classification accuracy assessment and change detection

Classification accuracy assessment was done only for images from the years 2006, 2011, 2015 and 2020, since accurate reference images were not available for images from the years 1973, 1996 and 2001. The Quantity and Allocation Disagreement method which was developed by Pontius & Millones (2011) was used for assessing the classification accuracy. This works as a more efficient method without bias when compared to the popular Kappa indices of agreement. Quantity disagreement describes the amount of difference between the reference map and a classified comparison map that is due to the less than perfect match in the proportions of the LU/LC categories. For quantity errors, a 'miss' of category X is a place that is category X on the ground and not category X on the map while a 'false alarm' of category X is a place that is category X on the map and not category X on the ground.

Allocation disagreement, by contrast, refers to the amount of difference between the reference map and a classified comparison map that is due to the less than optimal match in the spatial allocation of the LU/LC classes, given the proportions of the LU/LC classes in the reference and comparison maps (Pontius & Millones, 2011). The allocation difference, which is divided into two components, called 'exchange' and 'shift', is used by considering a reference map and the classified comparison map. 'Exchange' represents the errors caused

TABLE 1 Characteristics of selected images

Image source	Acquisition date	Spatial extent	Spatial resolution (m)
Landsat 8 OLI/TIRS C2 L1	13/01/2020	P-CLC and Ihala Mahawewa	30
Landsat 8 OLI/TIRS C2 L1	16/02/2015	P-CLC and Ihala Mahawewa	30
Landsat 5 TM C2 L1	20/01/2011	P-CLC and Ihala Mahawewa	30
Landsat 5 TM C2 L1	07/02/2006	P-CLC and Ihala Mahawewa	30
Landsat 5 TM C2 L1	09/02/2001	P-CLC and Ihala Mahawewa	30
Landsat 5 TM C2 L1	16/04/1996	P-CLC and Ihala Mahawewa	30
Aerial image	1973	P-CLC	1.8

TABLE 2 Identification keys for land use/cover (LU/LC) classification for the false colour composites of Landsat 5 and 8 images (Dahdouh-Guebas et al., 2006b)

LU/LC	Tonality	Texture	Shape	Structure	Position
Surface water bodies	Dark and very dark grey	NA	Irregular and elongated	NA	NA
Mangrove vegetation	Dark red	Coarse	Irregular	Continuous canopy	Near surface water bodies
Non-mangrove vegetation	Light red	Fine	Irregular	Discontinuous canopy	Not near surface water bodies
Shrimp farm	Blue and dark grey	NA	Rectangular	Grouped with separating lines	Near surface water bodies and mangrove
Built area+bare land	White	NA	Rectangular/irregular	NA	NA
Paddy field	Dark brown	NA	Irregular	NA	NA

Abbreviation: NA, not applicable.

by a pairwise confusion between LU/LC classes, while 'shift' represents the errors caused by non-pairwise confusions (Pontius & Santacruz, 2014). A 'shift' will only occur when there are three or more LU/LCs. This method unlike, the Kappa indices of agreement, works by converting the sample matrix into a matrix that represents the entire area under study to compute unbiased summary statistics in a contingency table.

After image classification, specific codes (0,1,2,3,4,5) were respectively assigned to the six LU/LC classes (non-mangrove vegetation, mangrove vegetation, surface water bodies, shrimp farms, paddy fields and built area+bare lands). Depending on each LU/LC feature, 120 GCPs were created with each GCP being assigned a specific code (0,1,2,3,4,5) using the reference map and the classified comparison map. A frequency table and a contingency table (pivot table in ArcMap 10.5) were computed and exported into the Pontius Matrix version 42. which is an Excel® workbook for assessing classification accuracy.

After on-screen digitization of all images, the merge, dissolve and intersect tools in ArcMap 10.5 were used to create new attribute tables for change detection. The area statistics of individual LU/LCs were estimated in ArcMap and their changes were calculated and transferred into MS Excel® for further analysis.

2.3 | Ecological footprint of shrimp farming

To assess the ecological footprint of shrimp farming in the study area, the ecological footprint methods developed by Larsson, Folke & Kautsky (1994) and Robertson & Phillips (1995) were adapted to estimate the ecosystem support (in terms of area) required for a sustainable shrimp farming industry. To this end, it was estimated by Larsson, Folke & Kautsky (1994) that a semi-intensive shrimp farm in Sri Lanka will require spatial ecosystem services that are 35–190 times larger than the surface area of the shrimp farm. Considering the study area, the ecosystem services may include seed shrimp and clean water sourced from the Chilaw lagoon and creeks, mangrove vegetation serving as nursery grounds for wild-caught adult shrimps during their juvenile stage, and sequestration of carbon directly or indirectly released from shrimp farms, as well as providing mangrove support area (i.e. the average area required to reduce nutrients before they reach the lagoon, and to produce sufficient leaf litter that comprises 30% of shrimp feed).

Since hatcheries in the study area are abundant and only 10% of post-larvae are caught wild (Cattermoul & Devendra, 2002), the current study estimated that 10 ha of mangrove nurseries will be required for a 1 ha shrimp farm. It is further proposed that a lagoon area (including creeks) of 7 ha is required as a water source for a 1-ha shrimp farm. Considering the pollution control mechanism of mangroves; it was estimated that a 1 ha shrimp farm would require a 2–3-times larger *Rhizophora*-dominated mangrove area (Robertson & Phillips, 1995) to reduce the levels of nitrogen and phosphorus in effluents reaching adjacent and successive ecosystems such as lagoons, tidal flats, salt marshes, the sea and coral reefs. The chosen *Rhizophora*-dominated mangrove area is based on the estimates of the nitrogen and phosphorus required for primary production in an average, humid tropical *Rhizophora* forest; that is nitrogen and phosphorus budgets for a semi-intensive shrimp farm (Robertson & Phillips, 1995).

Hence, the current study uses surface area ratios of 1: 10 and 1: 7, respectively, as the recommended ratios in this study for 'shrimp farm: mangrove' and 'shrimp farm: surface water' across all the years (1973 to 2020). In the surface area ratio calculations, ratios that were nearing the recommended ratios were classified as relatively lower ratios and the ratios that were further below the recommended ratios were classified as relatively higher ratios.

3 | RESULTS

3.1 | Classification accuracy assessment

Classification errors for the years 2006, 2011, 2015 and 2020 were calculated and compared with each other. The years 2011 and 2015 recorded the highest number of errors ($n = 14$) while the year 2020 recorded the lowest error ($n = 4$). Three components (quantity, exchange and shift) of error for each LU/LC category or class in the four different years were also computed (Figure 2). Quantity errors were recorded in all four different years, with the highest recorded in 2015 (n = 14), and the lowest recorded in 2006 and 2020 (n = 4). Unlike the other years, the errors recorded in 2015 and 2020 were only quantity errors. Shift errors were only recorded in 2006 and 2011, and exchange errors were only recorded in 2006.

Considering the LU/LC categories across 2006, 2011, 2015 and 2020, shrimp farms recorded the lowest number of errors (n = 1), which was due to quantity disagreement for 2020 (Figure 2). Shrimp farms recorded the least classification error because they were easy to identify using their shape, unlike other LU/LC categories which required a combination of multiple identification keys. Non-mangrove vegetation recorded the highest number of errors (n = 16) across all years and all errors were due to quantity and allocation disagreement (Figure 2). Such errors occurred as a result of arising confusion between the spectral features of non-mangrove vegetation and other vegetation such as mangrove vegetation and paddy fields. In other instances, since non-mangrove vegetation types were adjacent to mangrove vegetation, paddy fields and built area+bare lands, this resulted in digitization errors due to overlaps during classification.

The number of errors (n = 5) recorded by mangrove vegetation across 2006, 2011, 2015 and 2020, were all due to quantity disagreement (3 misses and 2 false alarms). The two 'false alarms' were recorded for 2011 where non-mangrove vegetation was recorded as mangrove vegetation, whereas the three 'misses' were recorded for 2006, 2015 and 2020 where mangrove vegetation was overlapping with surface water (2006) and shrimp farms (2015 and 2020).

3.2 | Changes in LU/LC areal extent

The recorded changes in the areal extent of LU/LCs varied depending on the type of LU/LC and the assessment year. Considering the period 1996 to 2020, the surface water and non-mangrove vegetation experienced a decreasing trend in areal extent while built area+bare lands and paddy fields experienced an increasing trend in areal extent (Figure 3 and Figure 4). Mangrove vegetation experienced a decreasing trend in areal extent from the period 1996 (608.40 ha) to 2006 (536.56 ha), and an increasing trend from the period 2006 (536.56 ha) to 2020 (678.87 ha). For shrimp farms, an increase in areal extent was first seen from 1996 (636.18 ha) to 2001 (702.09 ha) and then a decreasing trend from 2001 (702.09 ha) to 2020 (529.74 ha). The individual gains and losses in the areal extent of the LU/LCs from 1973 to 2020 are provided in Table 3.

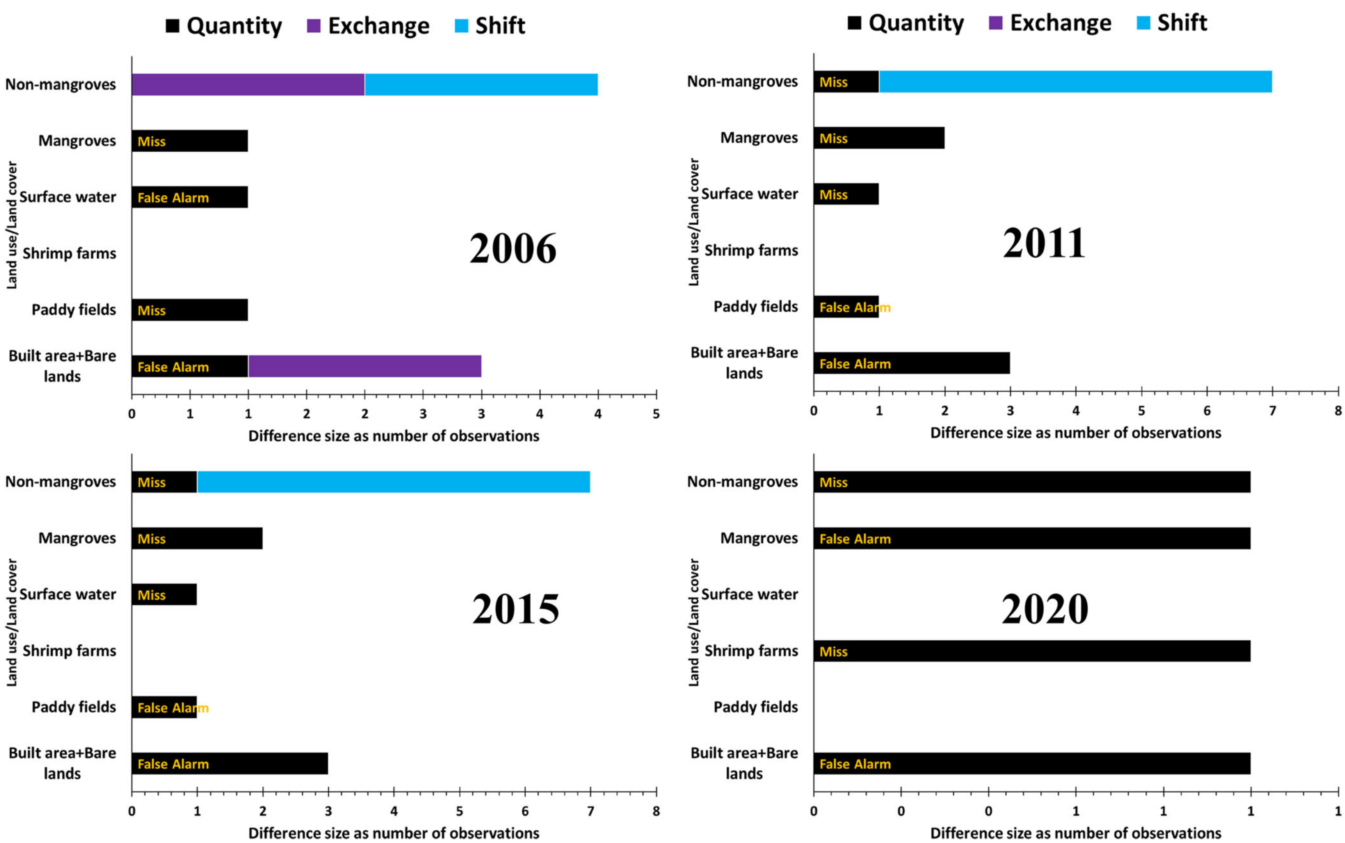


FIGURE 2 Quantity, exchange and shift errors recorded for each land use/cover in the years 2006, 2011, 2015 and 2020. In each figure, the magnitude of each type of error (quantity, exchange and shift) recorded during the classification of each land use/cover (y-axis) is indicated on the x-axis as difference size as number of observations.

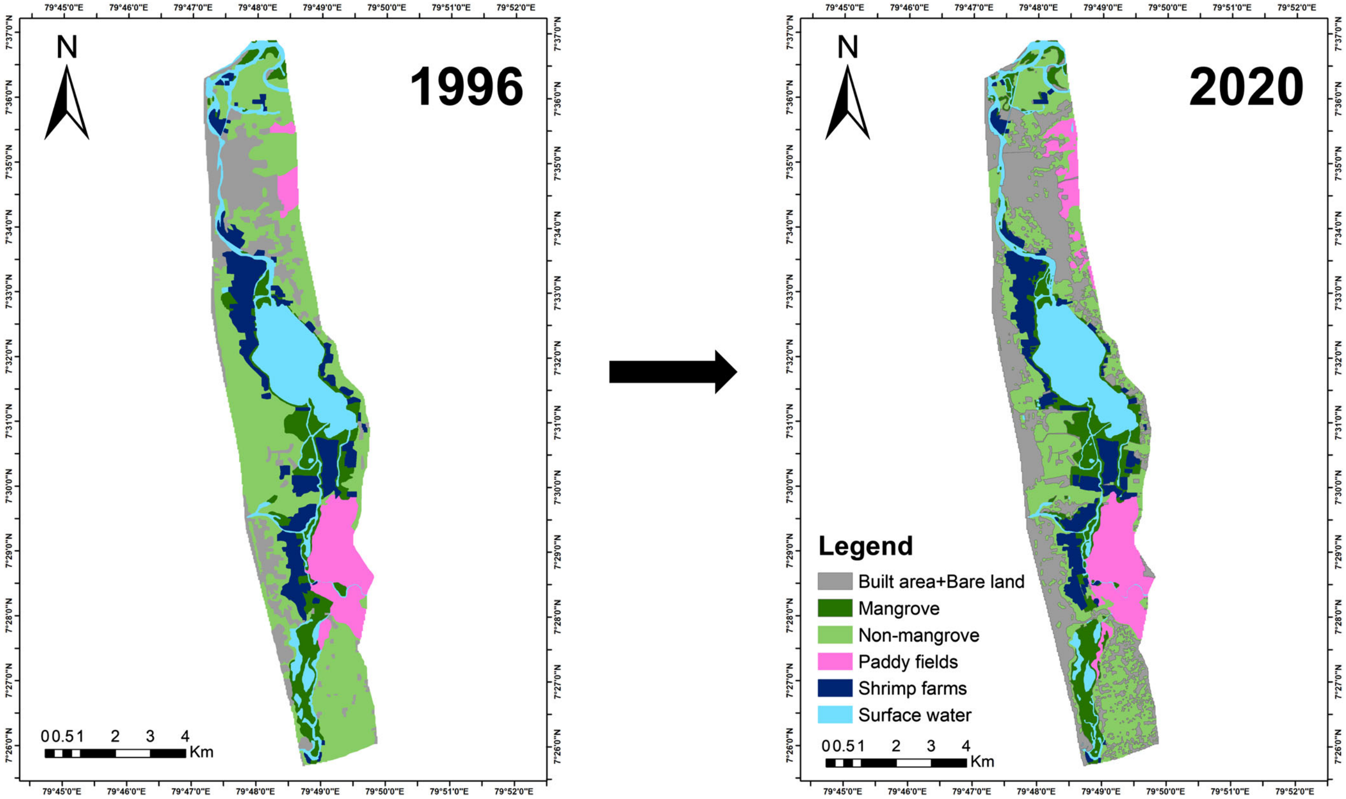
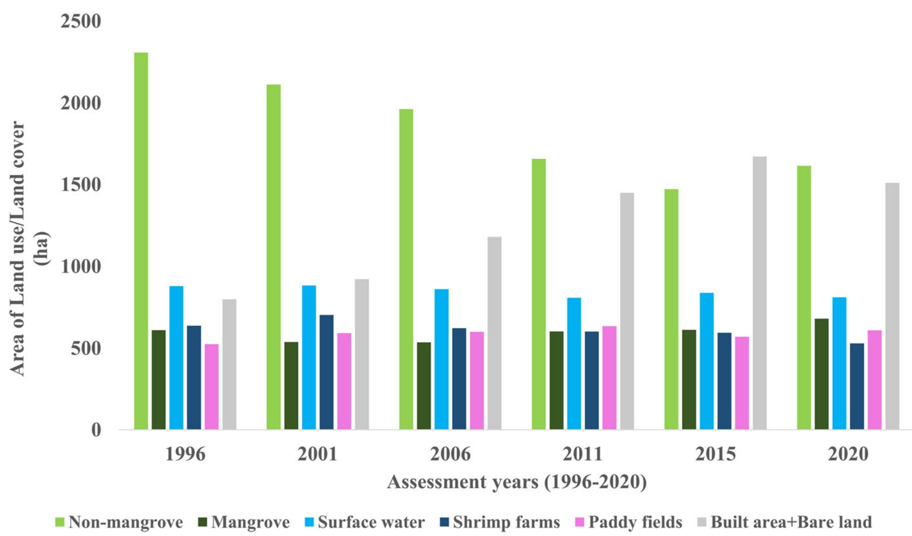


FIGURE 3 Land use/cover maps of study area in 1996 and 2020. The land use/cover includes built area+bare land (grey), mangrove vegetation (dark green), non-mangrove vegetation (light green), paddy fields (pink), shrimp farms (navy blue) and surface water (light blue). Full set of maps is provided as Supplementary Figure 1.

FIGURE 4 Changes in land use/cover areal extent in study area from 1996 to 2020. Mangrove vegetation area (in dark green) increases from 2006 to 2020, while shrimp farm area (in navy blue) decreases from 2001 to 2020.



Mangrove vegetation, non-mangrove vegetation, and surface water underwent a decrease in their areal extents by 45% (from 736.66 to 409.06 ha), 49% (from 1,435.41 to 733.05 ha), and 1.23% (from 616.67 to 609.07 ha) respectively. Paddy fields and built area+bare lands also experienced an increase in their areal extents by 2% (from 297.51 to 304.04 ha) and 1027% (from 57.73 to 650.43 ha), respectively. Whilst there were no shrimp farms in 1973, their areal extent in 2020 was 438.71 ha (Figure 5 and Figure 6).

3.3 | Ecological footprint of shrimp farming

The surface area ratios (area in hectares) of shrimp farms with mangrove vegetation and surface water recorded in P-CLC (from 1973 to 2020) and the study area (from 1996 to 2020) were used to assess the ecological footprint of shrimp farming. The calculated surface area ratios for 'shrimp farm: mangrove vegetation' and 'shrimp farm: surface water' across all the years (1973 to 2020) were

TABLE 3 Land use/cover (LU/LC) changes in Pambala-Chilaw lagoon complex from 1973 to 2020

LU/LC change	Area (ha)	LU/LC change	Area (ha)
Built area+Bare land to Mangrove	1.24	Non-mangrove to Shrimp farms	126.01
Built area+Bare land to Non-mangrove	8.70	Non-mangrove to Surface water	8.88
Built area+Bare land to Shrimp farms	0.18	Paddy fields to Built area+Bare land	3.02
Built area+Bare land to Surface water	2.35	Paddy fields to Mangrove	6.54
Mangrove to Built area+Bare land	20.90	Paddy fields to Non-mangrove	3.98
Mangrove to Non-mangrove	58.34	Paddy fields to Shrimp farms	0.19
Mangrove to Paddy fields	3.77	Paddy fields to Surface water	0.76
Mangrove to Shrimp farms	302.73	Surface water to Built area+Bare land	2.69
Mangrove to Surface water	62.29	Surface water to Mangrove	56.90
Non-mangrove to Built area+Bare land	576.47	Surface water to Non-mangrove	11.01
Non-mangrove to Mangrove	55.68	Surface water to Paddy fields	2.45
Non-mangrove to Paddy fields	15.04	Surface water to Shrimp farms	8.64

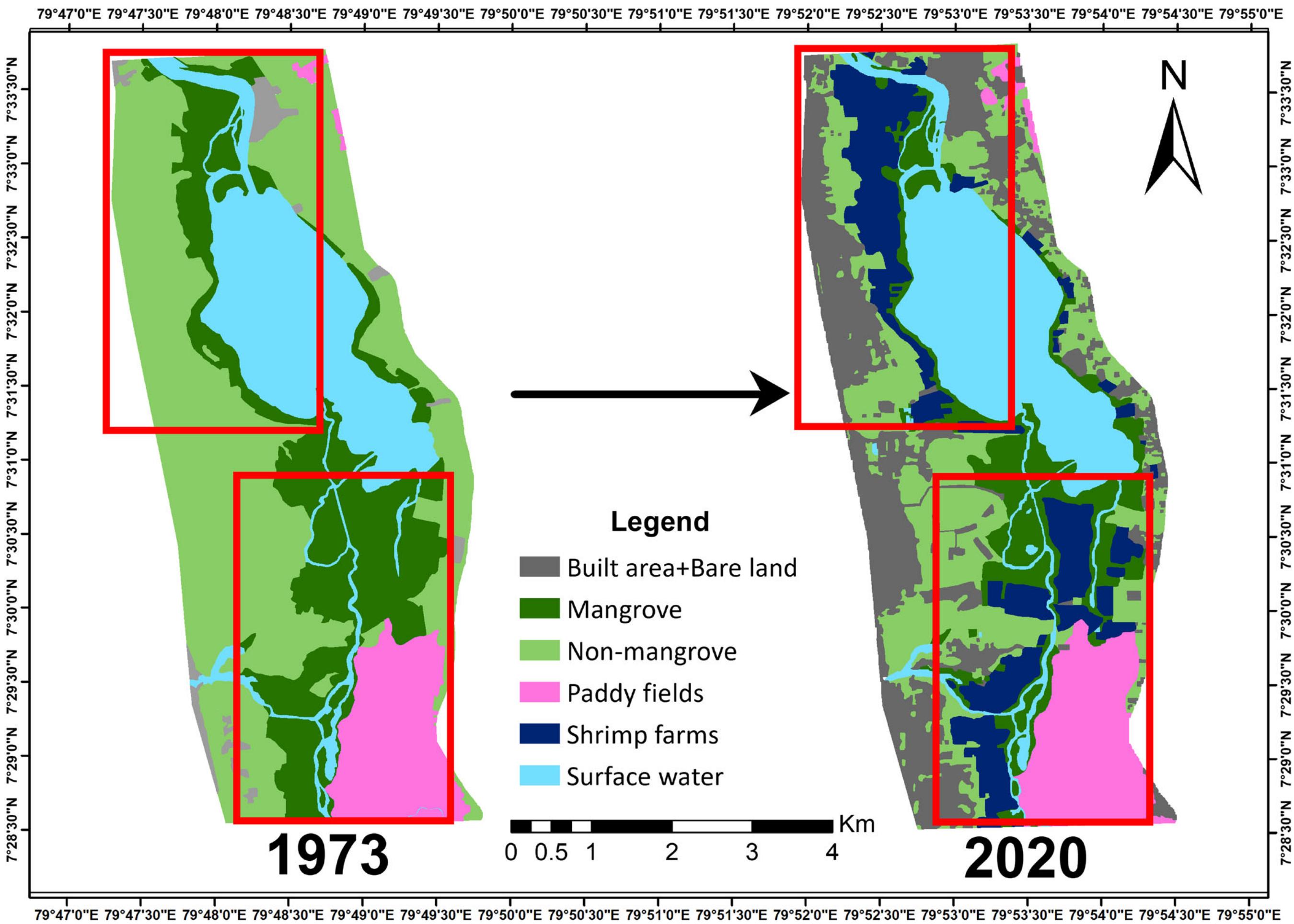


FIGURE 5 A visualization of land use/cover changes of Pambala-Chilaw lagoon complex in 1973 and 2020. The land uses/covers include built area+bare land (grey), mangrove vegetation (dark green), non-mangrove vegetation (light green), paddy fields (pink), shrimp farms (navy blue) and surface water (light blue). It can be seen (as highlighted with red rectangle shapes) that mangrove vegetation in 1973 was converted into shrimp farms in 2020.

lower than the recommended ratios in this study, i.e. 1: 10 and 1: 7, respectively (Table 4 and Figure 7). Considering the surface area ratios recorded in the period 1973 to 2020 for the P-CLC, the highest 'shrimp farm: mangrove vegetation' surface area ratios were recorded in 2001 (1: 0.6) and 2006 (1: 0.6), while the lowest ratio was recorded in 1973 (0: 7.3). Similarly, the highest 'shrimp farm: surface water'

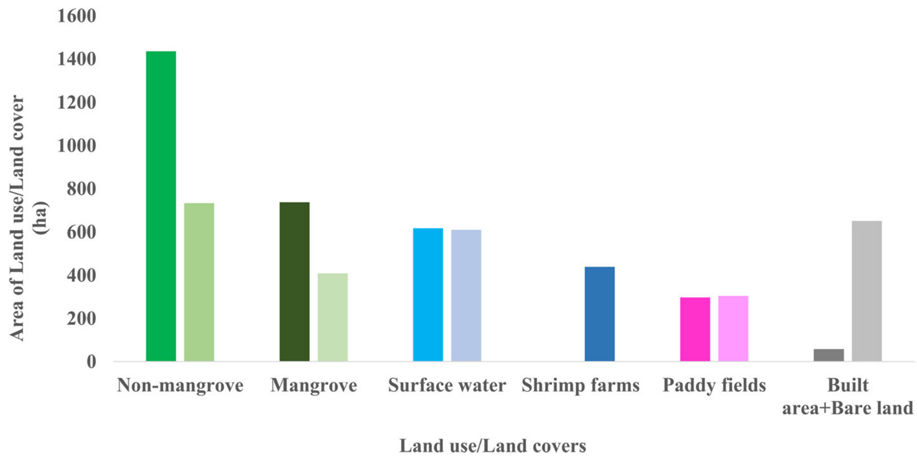


FIGURE 6 Comparison of areal extents of same land uses/covers in Pambala-Chilaw lagoon complex between 1973 and 2020. Darker colours represent areas (ha) in 1973 while lighter colours represent areas (ha) in 2020.

TABLE 4 Surface area ratios of shrimp farms with mangrove vegetation and surface water from 1973 to 2020. NA, not applicable, indicating that the 1973 image only captures Pambala-Chilaw lagoon complex (P-CLC)

	Shrimp farm: Mangrove vegetation		Shrimp farm: Surface water	
Year	P-CLC	P-CLC & Ihala Mahawewa	P-CLC	P-CLC & Ihala Mahawewa
1973	0: 7.3	NA	0: 6.1	NA
1996	1: 0.7	1: 1	1: 1.2	1: 1.4
2001	1: 0.6	1: 0.8	1: 1.1	1: 1.3
2006	1: 0.6	1: 0.9	1: 1.2	1: 1.4
2011	1: 0.8	1: 1	1: 1.2	1: 1.3
2015	1: 0.7	1: 1	1: 1.3	1: 1.4
2020	1: 0.9	1: 1.3	1: 1.4	1: 1.5

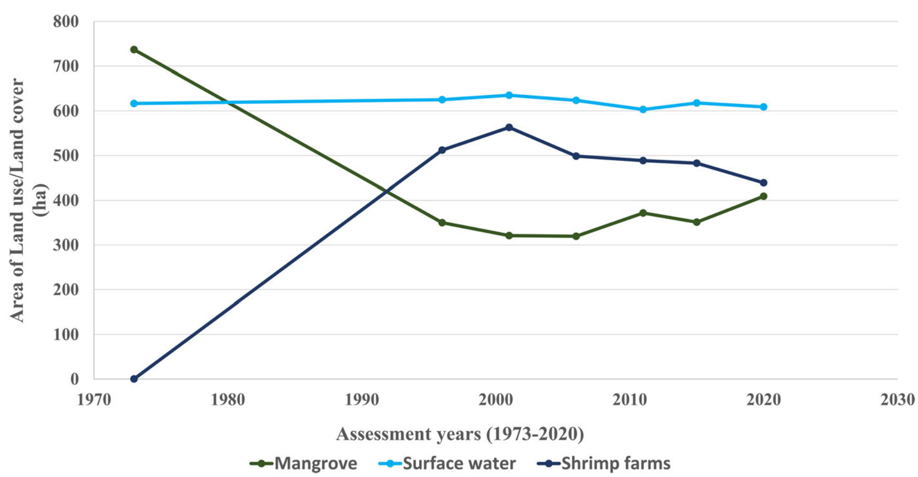


FIGURE 7 Changes in the areal extent (in hectares) of land uses/covers (mangrove, surface water, and shrimp farms) present in Pambala-Chilaw lagoon complex from 1973 to 2020. Note that the high(est) mangrove area, which was recorded in 1973, is still underestimated because it occurs in a subsection of the study area.

surface area ratios of the same period was recorded in 2001 (1: 1.1), while the lowest ratio was recorded in 1973 (0: 6.1).

Considering the surface area ratios recorded in the period 1973 to 2020 for the study area, the highest 'shrimp farm: mangrove vegetation' surface area ratio was recorded in 2001 (1: 0.8), while the lowest ratio was recorded in 2020 (1: 1.3). Similarly, the highest 'shrimp farm: surface water' surface area ratios for the same period were recorded in 2001 (1: 1.3) and 2011 (1: 1.3), while the lowest ratio was recorded in 2020 (1: 1.5).

4 | DISCUSSION

4.1 | LU/LC changes in the P-CLC and Ihala Mahawewa

Since the introduction of shrimp farming on Sri Lanka's north-western coast during the early 1980s, several studies have reported on the extent of mangrove destruction caused by shrimp farm development. The use of historical aerial images serves as a key source of historical information that reveals the LU/LCs that existed in an area of interest, complementing data from open-source satellite imagery which may not go as far back in time. In this study, the use of the 1973 aerial image, which is almost 50 years old, served as a baseline to uncover changes that have occurred in the extent of mangroves and the other LU/LCs present in the study area, as well as the potential activities contributing to these changes. For instance, mangroves that were present at the southern end of Chilaw lagoon in 1973 were identified as having been converted into shrimp farms between 1996 to 2020 (Figure 8). While there exists a gap of 23 years from 1973 to 1996, it can be assumed that the potential LU/LCs that could have contributed to the loss of the mangrove vegetation are shrimp farms and non-mangrove vegetation. Since shrimp farming in the Puttalam district only started in the early 1980s, the gap of 23 years can be reduced to about 10 years, when major activities such as clearing of land, digging and construction of ponds, and development of hatcheries, among others, would have taken place, meaning that shrimp farming is the most likely cause of mangrove destruction before 1996.

Dahdouh-Guebas et al. (2002) identified a 48% increase in shrimp farms against a 6.1% decrease in mangrove vegetation between 1994 and 1998 in the P-CLC but suggested that long-term change assessments were needed to draw effective conclusions. In this study, it was revealed that out of the 327.60 ha (45%) net loss of mangrove vegetation in P-CLC from 1973 to 2020, 92% (302.73 ha) was a result of their conversion into shrimp farms (Table 3). So far, this is the highest value of percentage loss of mangrove cover in Sri Lanka as a result of their conversion into shrimp farms. A study by Bournazel et al. (2015) which was also conducted in the Puttalam district, showed that 34% of mangrove cover in the Puttalam lagoon area (about 44 km north of P-CLC) was also converted into shrimp farms between 1992 and 2012. An 18% decrease in non-mangrove vegetation in P-CLC between 1973 and 2020 was also identified to be a result of their conversion into shrimp farms (Table 3). Both

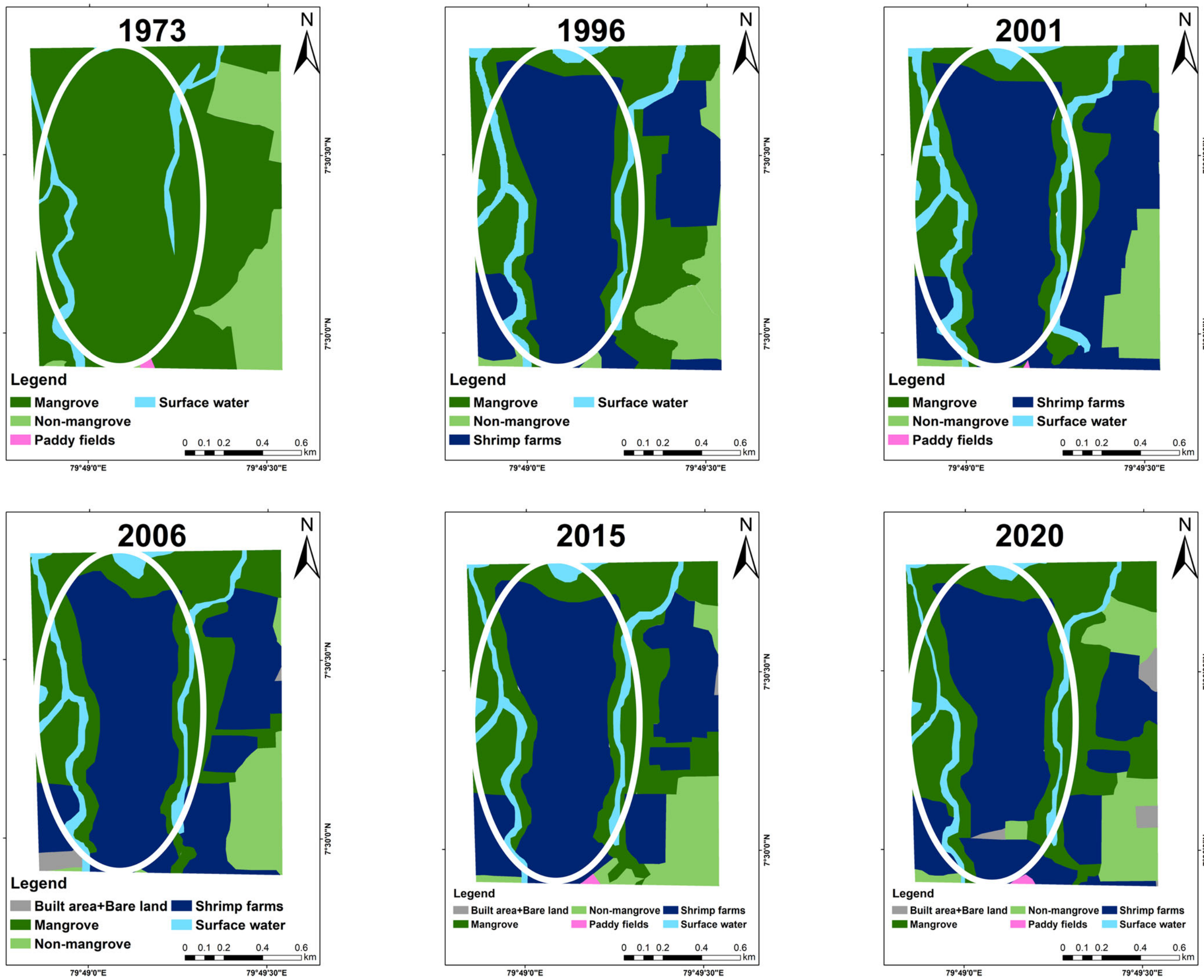


FIGURE 8 Maps showing the conversion of mangroves to shrimp farms from 1973 to 2020 at the southern end of Chilaw lagoon. The area of interest is delineated using a white oval shape.

LU/LCs are noted to have suffered the most from the development of shrimp farming on Sri Lanka's western coast.

Although the findings of this study support those of Goldberg et al. (2020) who estimated that 62% of global mangrove losses between 2000 and 2016 primarily resulted from their conversion to aquaculture and agriculture, it is important to note that such estimates could be higher when such global assessments involved historical archives revealing the extent of mangroves before the major period (the 1970s) when commercial shrimp farming started, especially in countries in South America, and South and South-East Asia (Hamilton, 2013).

Based on the use of satellite images from 1996 to 2020 to study LU/LC changes in the study area, two major observations were made: a decrease in shrimp farm area from 2001 to 2020, and an increase in mangrove vegetation, especially from 2006 to 2020. The latter finding could be explained by three major events that took place in the 1990s. Firstly, the Small Fisher Federation of Lanka in the 1990s started the planting of about 50,000 seedlings of *Rhizophora* spp. as part of a mangrove restoration project in Pambala (Dahdouh-Guebas et al., 2002) with a percentage survival of 78% after 17–20 years of planting (Kodikara et al., 2017). Secondly, as projected by Di Nitto et al. (2013), there was natural regeneration of mangroves occurring at some abandoned shrimp farms. Thirdly, in 2015, the Sri Lanka government pledged to protect all of its mangroves, making it the first country in the world to do so (Priyashantha & Taufikurahman, 2020; Dahdouh-Guebas et al., 2021).

Factors such as the outbreak of the WSD in shrimp farms, financial constraints and illegal operations of some farmers rendered some shrimp farms in the study area inactive, explaining the decline in the area of shrimp farms from 2001 to 2020. Some of these shrimp farms were identified to be either naturally recolonized by mangrove vegetation while others were left with pools of rain- or inundated water. While one can expect natural recolonization of mangroves in some of these inactive ponds after 15–30 years (de Lacerda et al., 2021), it is difficult to envisage this phenomenon in other ponds due to the absence of tidal flooding events and adjacent mangrove stands around these ponds.

4.2 | Ecological footprint of shrimp farming

Considering the recommended surface area ratios of ‘shrimp farm: surface water’ (1: 7) and ‘shrimp farm: mangrove vegetation’ (1: 10), the existing total area of shrimp farms (529.74 ha) in the study area would require a surface water area of 3,708.17 ha and a mangrove vegetation area of 5,297.40 ha for ecosystem support. The required mangrove surface area for existing shrimp farms is about the same surface area as the whole study area, which is 5,217 ha (excluding the area occupied by shrimp farms). Moreover, following the current study's estimation that 1 ha of semi-intensive shrimp farm would require a 2–3 times larger mangrove (dominated by *Rhizophora* spp.) area than the shrimp farm to remove nitrogen and phosphorus in the effluents released from the shrimp farm, it is thus expected that the existing total area of shrimp farms (529.74 ha) in the study area would require from 1,059.48 to 1,589.22 ha of mangrove vegetation (dominated by *Rhizophora* spp.).

In this study, the current (as of 2020) surface area ratio of ‘shrimp farm: surface water’ is 1: 1.5, and that of ‘shrimp farm: mangrove vegetation’ is 1: 1.3 for the study area (Table 4). While these ratios are the best ratios recorded from the year 1996, they are, however, about 4.5 times (for ‘shrimp farm: surface water’) and 7.8 times (for ‘shrimp farm: mangrove vegetation’) smaller than their expected surface ratios of 1: 7 and 1: 10, respectively. This exposes the current shrimp farming activity in the study area as highly unsustainable. Moreover, the Chilaw lagoon is described as gradually becoming a ‘dead’ lagoon due to the increased continual input of nutrients and other pollutants and the formation of high berms in the channel area. If the polluting activities reported by Ofori et al. (2022) from the shrimp farms and other potential sources continue, and the mangroves and lagoon ecosystems that serve as support areas are subsequently destroyed, it can be projected that the shrimp farm industry will collapse in the next few years.

Realizing the potential of mangrove ecosystems in climate change mitigation and adaptation, through their ability to sequester carbon, serve as barriers to coastal communities, promote biodiversity and their socio-economic benefits to coastal communities, there is a need to promote their protection and restoration. If the global mangroves continue to be destroyed, it could negatively affect connected ecosystems such as seagrass beds, tidal flats and coral reefs, further resulting in the emission of 2,391 Tg $CO_{2\ eq}$ by the end of the century (Adame et al., 2021).

5 | CONCLUSION

The study presents the spatio-temporal changes in LU/LCs and further assessed the factors leading to such changes in mangroves and shrimp farms during the last 5 decades (1973 to 2020). It revealed that shrimp farming caused a major decline in mangroves between 1973 and 2020. There was, however, an increase in the area of mangroves between 2006 and 2020.

However, the ecological footprint assessment of shrimp farming in the study area from 1973 to 2020 showed that shrimp farming is highly unsustainable. There is no sustainable future for the shrimp farming industry, and local people and biodiversity will face negative impacts if crucial actions are not undertaken. Moreover, shrimp farms would face the risk of similar disease outbreaks like the WSD, with higher and unexpected costs in shrimp disease management. The following actions are therefore recommended:

i. Pollution from shrimp ponds should be reduced by installing wastewater treatment systems and sedimentation tanks in shrimp farms. The careful planting of mangroves (especially *Rhizophora* spp.) in the water channels of shrimp farms in such a way that it does not prevent water flow in the channels will be required to reduce pollution reaching the Chilaw lagoon and nearby ecosystems. Abandoned shrimp farms should be used to restore lost mangroves. However, as these shrimp ponds tend to be very deep, varied ecological engineering activities, which may involve the opening of tidal channels, flattening of pond walls or building up of islands inside the ponds should first be undertaken to make the area suitable for mangrove restoration (Zimmer et al., 2022).

ii. More effective regulation and supervision of sustainable shrimp farming by the National Aquaculture Development Authority of Sri Lanka and other related institutions should be practised, with shrimp farmers adopting integrated mangrove–shrimp farming to prevent mangrove destruction and promote the restoration of 50% or more of deforested mangroves (now converted into shrimp farms) within the next 5 years. Although the implementation of the integrated mangrove–shrimp farming comes with its challenges, if it is effectively practised, it will enhance environmental conditions, reduce production costs and promote eco-friendly shrimp farming with positive social implications.

iii. The existing policies, such as the Sri Lankan Coastal Zone and Coastal Resource Management Plan of 2018 and the National Policy on Conservation and Sustainable Utilization of Mangrove Ecosystems in Sri Lanka, that seek to promote mangrove conservation should be revisited and effectively implemented in line with the global agenda of restoring half of the global mangroves, halting mangrove loss and doubling global mangrove protection efforts (Leal & Spalding, 2022).

iv. Harkes et al. (2015) assessed the sustainability of shrimp farming in Puttalam lagoon area and proposed a Climate Compatible Development policy framework that focuses on shrimp farming actions required to enhance climate change mitigation and adaptation. The technical and management interventions of the policy framework (Harkes et al., 2015) when implemented in Sri Lanka and other countries facing similar socio-ecological challenges will promote a sustainable shrimp farming industry.

v. Further studies should assess other impacts of shrimp farming on organisms such as fish and other crustaceans in lagoon and mangrove ecosystems. Countries such as Brazil, India, Bangladesh, Indonesia, Vietnam, the Philippines and Thailand, among others, that are also facing similar challenges from shrimp farming as Sri Lanka should also undertake similar studies and implement the recommendations mentioned in this study. This will go a long way to increase the reduction in the global rate of mangrove loss and promote the socio-ecological benefits provided by mangrove ecosystems.

ACKNOWLEDGEMENTS

This project was funded by the European Commission through the Erasmus Mundus Joint Master Degree in Tropical Biodiversity and Ecosystems – TROPIMUNDO, and the University Grants Commission of Sri Lanka (UGC/VC/DRIC/PG2019(1)/SEUSL/01). All Landsat satellite images are courtesy of the U.S. Geological Survey. The authors extend their gratitude to Douglas Thisera and Anuradha Wickramasinghe of the Small Fishers Federation of Lanka (SFFL/Sudeesa), Saminda Lakmal of the National Aquaculture Development Authority (NAQDA) of Sri Lanka, as well as Udara V. Gunathilaka and Isuru Wijesundara of the University of Ruhuna for their support in carrying out this research. To the editor and the anonymous reviewers of this paper, the authors are very thankful for your constructive reviews.

CONFLICT OF INTEREST

Authors declare that there is no existing conflict of interest.

AUTHOR CONTRIBUTIONS

Samuel Ofori: conceptualization (equal); investigation (equal); methodology (equal); software (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Sunanda Kodikara:** conceptualization (equal); supervision (equal). **Loku Jayatissa:** conceptualization (equal); supervision (equal); writing – review and editing (equal). **Sanduni Madarasinghe:** methodology (equal); validation (equal); writing – review and editing (equal). **T. W. G. F. Mafaziya Nijamdeen:** supervision (equal); writing – review and editing (equal). **Farid Dahdouh-Guebas:** conceptualization (equal); formal analysis (equal); supervision (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

Data are available upon request.

ORCID

Samuel A. Ofori https://orcid.org/0000-0002-8462-5264

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ofori, S.A., Kodikara, S.K.A., Jayatissa, L.P., Madarasinghe, S.K., Nijamdeen, T.W.G.F.M. & Dahdouh-Guebas, F. (2023). What is the ecological footprint of aquaculture after 5 decades of competition between mangrove conservation and shrimp farm development? *Aquatic Conservation: Marine and Freshwater Ecosystems*, 33(1), 15–28. https://doi.org/10.1002/aqc.3897