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The impacts of shrimp farming on land-use and carbon storage around Puttalam Lagoon, Sri Lanka

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Abstract

The expansion of shrimp aquaculture in Sri Lanka over the past three decades has dramatically changed the coastal landscape, in particular by converting mangrove forests. The current study quantified these impacts in the Puttalam lagoon, an area of the country that has experienced some of the most destructive development. Land use change was analysed using a multi-temporal set of aerial and satellite images taken in 1992/1994 (aerial photographs), 2007 (SPOT 5) and 2012 (Pleiades). The area of shrimp farms increased by 2 777% over this 19-year period, with salt pans expanding by 60%. Mangroves declined in area by 34% and coconut groves increased by 17%. Because of problems with disease many intensive shrimp farms are abandoned after a few years, leaving denuded and unproductive landscapes; here a large majority of farms (90% of the total area of shrimp aquaculture) were found to be abandoned. The loss of carbon sequestration and storage services caused by this unsustainable recent history of shrimp farming was calculated as one measure of environmental impact. The documented land use changes in Puttalam lagoon resulted in an estimated net carbon loss of 191 584 tC. This was mainly due to conversion of mangroves to shrimp farms, making up 75.5% of the total carbon loss. These results demonstrate the scale of environmental degradation caused by intensive shrimp farming in the study area, and highlight the need for an entirely new aquaculture model in Sri Lanka.

Keywords: shrimp aquaculture; ecosystem carbon stock changes; land-cover changes; mangrove; Sri-Lanka

1. Introduction

Although shrimp production in coastal pond systems is a traditional practice in Asia (Dierberg and Kiattsimkul, 1996; Bergquist, 2007), recent decades have seen a huge increase in the extent and intensity of shrimp aquaculture activities, driven by consumer demand from Japan, North America and Europe (Primavera, 1997; Thornton *et al.*, 2003; Bergquist, 2007; Bosma and Verdegem 2011). Sri Lankan shrimp farming became one of the fastest growing industries in the 1980s, most likely inspired by the profits seen in established shrimp farming practices in countries such as Thailand, Ecuador, Indonesia, China and Vietnam (Cattermoul and Devendra, 2002; Munasinghe *et al.*, 2010).

Sri Lanka has 1700 km of coastline comprising lagoons and sheltered bays that are prime sites for aquaculture development (Dayananda, 2004; Drengstig, 2013). Shrimp farming started in the north western coast of the country, with pioneer farms established around Chilaw Lake (Fig.1; Senerath and Visvanathan, 2001), which were followed by rapid expansion particularly concentrated along the coast from Chilaw to Puttalam lagoon in the northwestern province (NWP) (Dahdouh-Guebas *et al.*, 2001; Munasinghe *et al.*, 2010).

The major shrimp species cultured in Sri Lanka is *Panaeus monodon* (Fabricius), commonly known as black tiger shrimp, which is naturally found along the Sri Lankan coast (Cattermoul and Devendra, 2002). During its peak period, shrimp farming was an important source of employment in Sri Lanka and shrimp exports represented one of the main sources of foreign exchange for the country, accounting for 40-50% of total aquaculture exports (Senerath and Visvanathan, 2001; Dayananda, 2004; Munasinghe *et al.*, 2010). Although there is significant potential for the industry to contribute to national economic growth and to reduce poverty, unsustainable shrimp culture causes environmental as well as socio-economic harm due to the exploitation of coastal natural resources (Bergquist, 2007; Rajitha *et al.*, 2007). The major environmental impacts of unsustainable shrimp farming have been well documented. The main problems are caused by direct conversion of natural habitats to shrimp ponds, which leads to drastic loss of mangrove forests, salt marshes, seagrass beds and mudflats, along with many of their associated ecosystem services (Senerath and Visvanathan, 2001). Other environmental impacts are caused by the disposal of untreated wastewater, rich in nutrients and often laden with pesticides and antibiotics, directly into lagoon waters (EJF, 2004; Primavera, 2006). Furthermore, excessive use of antibiotics encourages the emergence of antibiotic-resistant strains whilst chemical discharges damage off-target populations and pollute aquifers (Primavera, 2006; Bosma and Verdegem 2011). Other environmental impacts may include declines in wild capture of fish and shrimp (Cattermoul and Devendra, 2002) and the spread of diseases such as the White Spot Syndrome Virus (WSSV), which is considered the most serious pathogen of shrimp, causing 100% mortality within 7-10 days in infected shrimp farms (Witteveldt *et al.*, 2004; Primavera, 2006). In the NWP of Sri Lanka, which includes Puttalam lagoon, the Dutch Canal is the main source of water for shrimp farms. This semi-enclosed coastal water system has a low flushing rate, which exacerbates these problems, with hydrological changes, salinization of soil and water and siltation now also recorded in the area (EJF, 2004; Weerakoon, 2007).

Because of disease and other problems, the productivity of intensive shrimp ponds often declines after 4-10 years. Ponds may then be abandoned and new areas cleared during the establishment of new ponds (Bosma and Verdegem, 2011). There are socio-economic as well as environmental costs of intensive shrimp cultivation. The poorest people on the coast are usually highly dependent on coastal ecosystems such as mangroves (Dayananda, 2004). In Thailand, it has been estimated that intact mangrove forests have a total economic value 70% higher than shrimp farms, largely because of the range of ecosystem services that are destroyed by conversion of mangroves to ponds (Primavera, 2006). The expansion of aquaculture despite these economic losses is testament to differences in power between those who benefit and lose rather than any economic logic. A pattern of rapid expansion followed by abandonment and local collapse of the industry, with resultant coastal unemployment, is a sadly familiar story (Primavera, 2006).

Extensive mangrove destruction leads to loss of goods and services for local populations including loss of coastal protection, decreased availability of timber and firewood and loss of breeding and nursery grounds for fish (Alongi, 2002; Satyanarayana *et al.*, 2013). Mangroves provide important habitat for a wide range of species hence their removal also reduces local biodiversity (Pathirana *et al.*, 2008). One of the most important regulating ecosystem services of mangroves is their ability to sequester carbon. In fact, they are amongst the most carbon dense of all ecosystems and are thus globally important carbon sinks (Alongi, 2012). If disturbed by land-use change, the carbon buried in mangroves has the potential to become a significant source of greenhouse gas (Donato *et al.,* 2011). Carbon storage in mangroves is also a factor for economic opportunities. A recent study valued carbon sequestration in southern Kenya to be 251 USD/ha, measured from 2014 estimates, which makes this ecosystem service the 2nd most valuable after protection against coastal erosion (Huxham *et al.*, in press).

By providing a description of the actual shrimp farming situation and the coastal ecosystem losses of services in Puttalam, this paper aimed to aid in the management and conservation of mangroves as well as highlighted the need for more sustainable aquaculture practices around the lagoon. There is indeed an important gap in Sri Lankan policies response to deforestation as well as a need for stronger land use policies (Government of Sri Lanka, 2000; Bandaratillake and Sarath Fernando, 2003). The current study had two objectives. First it aimed to provide an up-to-date assessment of land-use changes driven by aquaculture in Puttalam lagoon region during the period early 1990s to 2012. The second and final objective of the current work was to assess the loss of carbon sequestration and storage ecosystem services as one measure of environmental impacts of farm expansion in Puttalam.

Indeed, the latest available Sri Lankan national forest inventory dates from 1992-1996 (Mattsson *et al.*, 2012). Recording the presence of aquaculture ponds does not reveal their economic viability; all authors recognise that many ponds are permanently or temporarily abandoned (Di Nitto *et al.*, 2013). However, estimates of the degree of abandonment vary widely. Hence this study also assessed the proportion of all ponds that are still productive, which is essential information in considering the current state of the aquaculture industry in Sri Lanka and how improvements can be made.

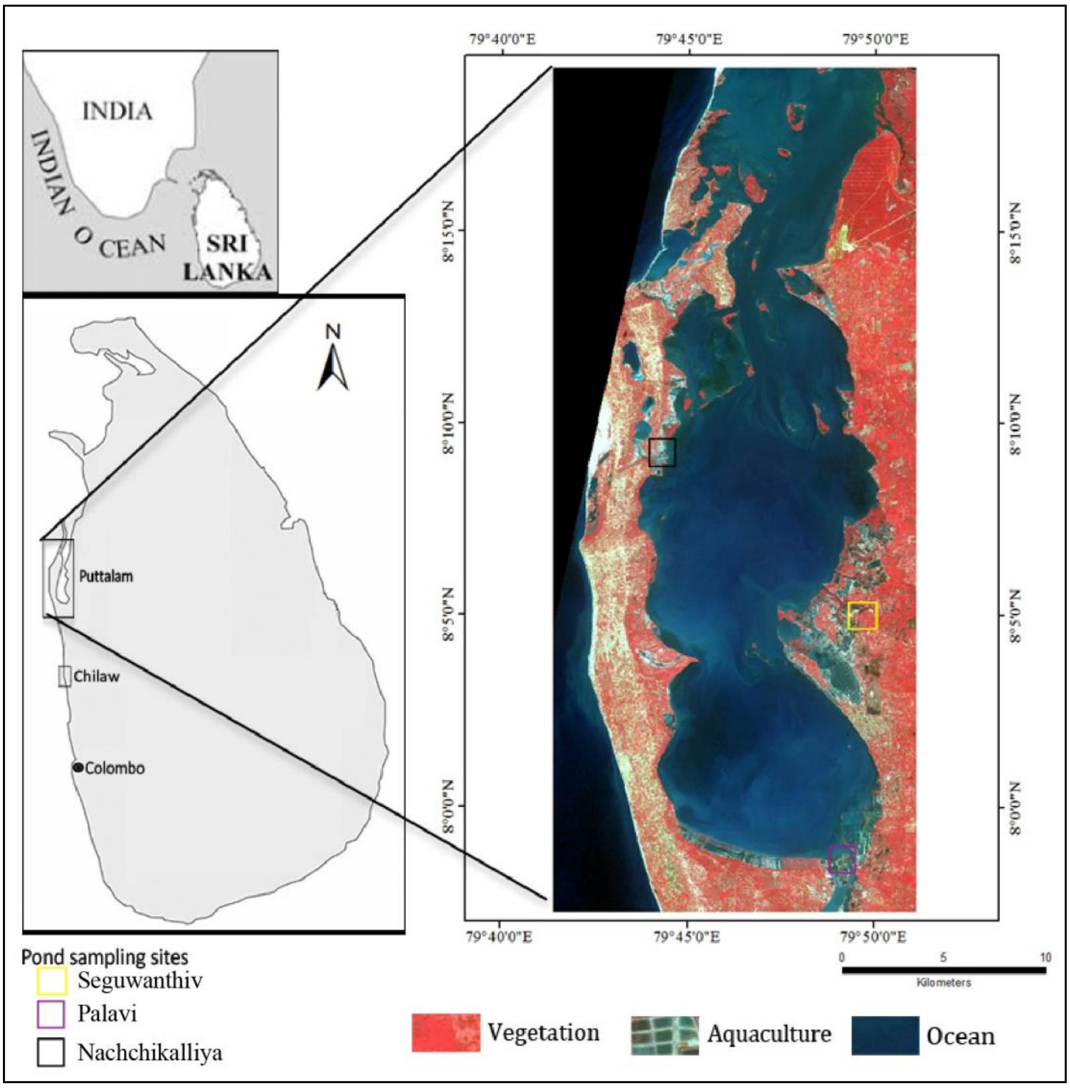
Finally, one of the key ecosystem services provided by mangroves is carbon sequestration and storage. Removal of mangrove forests by shrimp farmers certainly causes the loss of future sequestration potential and may lead to the partial or total loss of stored carbon. However, there are no published reports on the impacts of shrimp ponds on carbon stores. A final objective of the current work was therefore to assess the impacts of aquaculture in Puttalam on the carbon balance of the landscape and to represent the spatial distribution of carbon dynamics.

2. Methods

2.1 Study site

This study was conducted in the Puttalam lagoon situated in the NWP of Sri Lanka (Fig. 1). The lagoon has a surface area of 32 700ha and the surface temperature of the water ranges from 28 °C to 32 °C (Pathirana *et al.*, 2008). The area is subject to a micro-tidal regime that limits the tides to within 1m range. The Puttalam lagoon is connected to the open ocean through the Dutch Bay located at the northern end of the lagoon. Seasonal precipitation levels are driven by monsoon winds and show a bimodal pattern. The long rains fall between mid May and early October and the short and weaker rains fall from December to early March (Di Nitto *et al.*, 2013). The population density in Puttalam was 431/km^2 in 2010 (Ranasinghe, 2010) and most people in the area rely directly or indirectly on fisheries (Pathirana *et al.*, 2008). The west of the lagoon consists of sand dunes and long sandy beaches, while the east and south are cultivated land and forest (Ranasinghe, 2010). Coconut plantations are the main agricultural crop grown around the lagoon, as well as some banana, cashew, vegetables and home garden areas. Shrimp ponds, salt pans and irrigation canals also commonly occur (Ranasinghe, 2010). This coastal area presents ideal characteristics for the installation of shrimp ponds such as protected coastal lagoons, easy access by road to and from the international airport of Colombo as well as being located away from zones of political conflict (Munasinghe *et al.*, 2010). The shrimp farms in Puttalam are mainly small-scale, with 73% of them covering an area of less than 2 ha (Munasinghe *et al.*, 2010). A major proportion of the total extent of mangroves in Sri Lanka is found in the Puttalam lagoon area, especially in sheltered estuaries (Pernetta, 1993). These forests exhibit high floral diversity and thus belong to the most valued mangrove forests in Sri Lanka (Amarasinghe, 1988; Jayatissa *et al.*, 2002; Ranasinghe, 2010).

***Figure 1** Overview of the study area: Puttalam lagoon in the north western province in Sri Lanka (SPOT5 data acquired in 2007, RGB=NIR-red-green).*



2.2 Land use change detection

2.2.1 Time series data

The earliest remote sensing data available for this study consisted of thirty-six aerial photographs, acquired between 1992 and 1994, covering Puttalam lagoon (Survey Department of Sri Lanka).

The data set available for 2007 consisted of one SPOT 5 image covering the area of the lagoon. SPOT 5 images have a spatial resolution of 10 m in multispectral mode.

Finally, two overlapping Pleiades images were available from 2012, with a high spatial resolution of 50 cm and four bands (blue, green, red and NIR).

2.2.2 Images processing

The aerial photographs were geo-referenced using ArcGIS 9.3 (The Environmental Systems Research Institute, USA) (UTM map projection: WGS_1984datum, UTM_Zone_44N), resulting in an average root mean square error of 8.95m. They were then compiled together with the mosaic tool in ArcGIS.

Then the photographs and the SPOT 5 image were classified using an Object-Based Image Analysis (OBIA) within eCognition 8.7 (Definiens-Imaging, Germany). All scenes were featured in a UTM map projection (WGS_1984 datum, UTM_Zone_44N). The OBIA creates "objects" by segmenting an image into groups of pixels showing similar characteristics based on spectral properties such as spectral band or index (e.g. NDVI) means, and on spatial properties such as image texture.

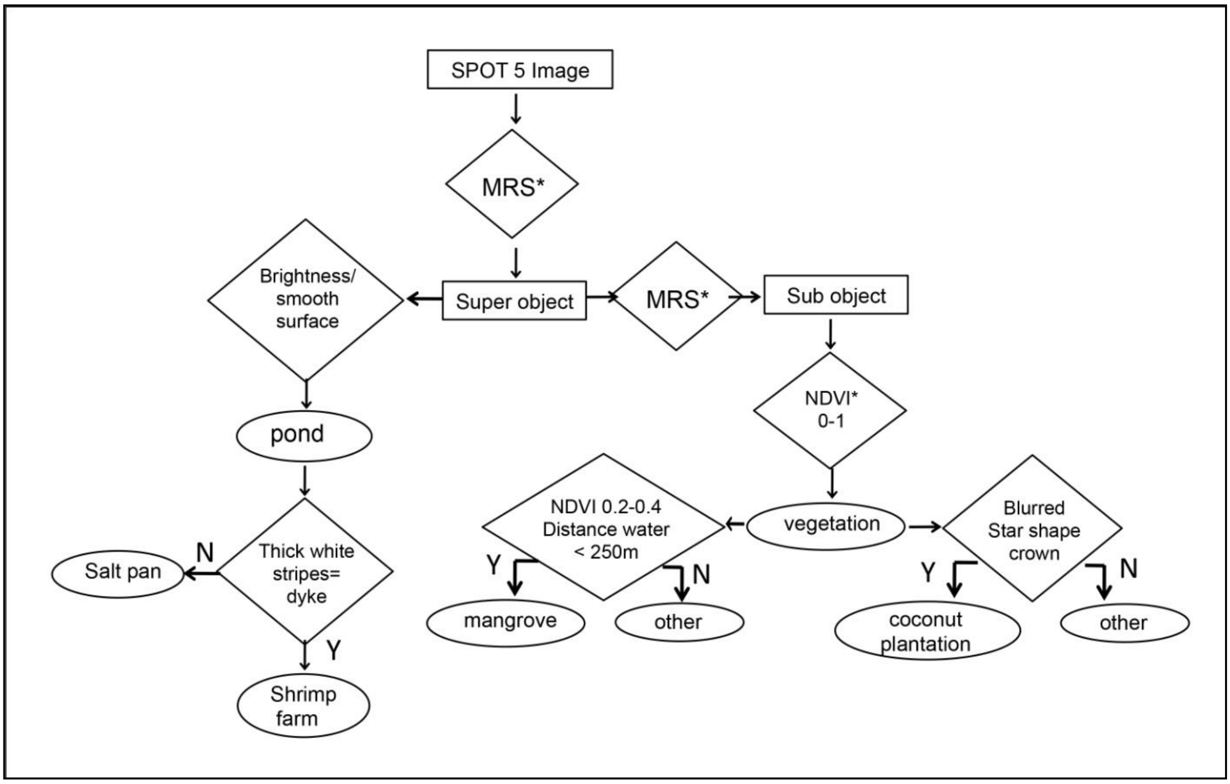
The segmented object properties were then used for image classification (Robin *et al*., 2010; Heumann, 2011). Two multi-resolution segmentations were applied within eCognition software to the SPOT 5 image with the same weight for each of the three bands. The first segmentation (scale parameter=30, shape=0.05, compactness=0.5) was used to extract aquaculture ponds (shrimp farms and salt pans). As pond areas are clearly demarcated by dykes, they exhibit a good structure for segmentation. A second segmentation was performed in order to detect mangrove forest patches (scale parameter=10, shape=0.05, compactness=0.5). A multi-resolution segmentation was also applied to the aerial photographs (scale parameter=50, shape=0.5, compactness=0.5).

2.2.3 Image classifications

A visual classification of different land uses in Puttalam lagoon (four classes: shrimp farm, salt pan, mangrove, coconut plantation) was performed at the object level resulting from multi-resolution segmentation of the aerial photographs. The classification was based on visual analysis of the aerial photographs using features such as tonality or texture. Some areas of the lagoon could not be classified for 1992-1994 as photographs were not available, resulting in 4% of the study area not covered by these data.

The classification of the SPOT 5 image was carried out following the multi-resolution segmentation using the same land use classes mentioned above. The classes were derived within eCognition software using a decision tree (Fig. 2). When confusion between objects occurred, they were manually edited using visual interpretation and existing maps of the area when available.

Figure 2 *OBIA decision tree (rectangle=image, diamond = rule, oval = class) used to classify the SPOT 5 image from 2007. * MRS = Muti-Resolution Segmentation, NDVI = Normalized Difference Vegetation Index, Y= Yes, N=No.*



Finally, the Pleiades images from 2012 were also classified with the same use classes using the Iso cluster tool within ArcGIS 10. The Maximum Likelihood Classification (MLC, in ArcGIS 10) was then applied to the image. MLC is an unsupervised classification based on an automated routine. The results were then refined manually to reduce error.

2.2.4 Validation

A total of 360 reference points were used within Google Earth images (Google Earth, 2011) to assess the accuracy of the land-use/cover classification produced for the 2012 data set. A confusion matrix with descriptive statistics (Table 1) was computed as per Carney *et al.*

(2014). An overall classification accuracy of 79% was achieved for the 2012 Puttalam lagoon land-use/cover classification using the MLC method. The largest classification error occurred for the class 'Other' (with 62% accuracy, Table 1), while Coconut plantations was the most accurate class (92% accuracy, Table 1). Accuracy of classifications from aerial photographs and SPOT5 image could not be assessed due to the lack of reference data at that time. However, as the aerial photography classification was based on visual assessment and only four classes were used, the chance of misclassification was minimised.

Table 1 *The accuracy confusion matrix of Pleiade classification image.*

Categories	***Mangroves***	***Shrimp farms***	***Salt pans***	***Coconut plantations***	***Other***	***Total***	***User's accuracy***
Mangroves	**56**	0	0	0	13	69	81%
Shrimp farms	0	**77**	0	0	7	84	92%
Salt pans	1	0	**31**	8	3	43	72%
Coconut plantations	0	0	0	**59**	5	64	92%
Other	0	8	7	23	**62**	100	62%
Total	57	85	38	90	90	**360**	
Producers's accuracy	98%	91%	82%	66%	69%		

Overall Classification Accuracy = 79.17 %

2.3 Carbon stocks

2.3.1 Belowground carbon stocks in mangrove forests and coconut plantations

For this study, three abandoned shrimp ponds (*Nachchikalliya*: abandoned for 5 years, *Palavi*: abandoned for 7 years and *Seguwanthiv*: abandoned for 13 years, Fig. 1), resulting from the conversion of mangroves, as well as intact mangroves adjacent to them, were sampled in January 2014. Samples (n=9) were collected from mangrove sites using a deep soil corer. Subsamples were taken for the determination of sediment bulk density and carbon concentration at the following depths (cm): 0-5, 5-10, 10-20, 20-50, 50-100, 100-150, 150-200 and 200-250. The Loss On Ignition (LOI) method was applied to the sediments (Kauffman and Donato, 2012). Dry biomass was converted into carbon mass using carbon:biomass ratios of 45% (IPCC, 2014) and soil carbon storage was calculated as described by Donato *et al.* (2012).

Using the pond surface area, depth and the soil bulk density at each depth interval, the amount of soil removed (in kg) due to conversion into ponds was estimated. The carbon soil storage patterns prior to pond excavation were assumed to be similar to the adjacent mangrove forests. Thus, the amount of carbon lost with the removed soil for each depth interval of the ponds was obtained as the product of soil carbon content in mangroves and the total soil weight removed at the same depth in ponds.

Coconut soil carbon content was measured using the same method. Samples (n=7) were taken each time at two depths (cm): 0-15 and 15-50. A LOI: CN ratio of 31% was determined by analysing sediments for C:N ratio (Kauffman and Donato, 2012). Soil carbon storage was then calculated.

2.3.2 Spatial distribution

To estimate carbon (C) vegetation stock balance related to land cover/use changes detected in the study area between 1992/1994 and 2012, C vegetation stocks ($t.ha^{-1}$) were taken either from the literature or from new field measurements (Table 2). Carbon gained or lost between 1992/1994-2007 and 2007-2012 for transitions between the land use categories was determined using GIS. Parameters queried for each possible combination of land-use/cover change were as follows: belowground carbon (BGC), aboveground carbon (AGC), Net Primary Production rates (NPP) and belowground storage rates (BS) (Table 2). Time since conversion was used to calculate the sums of annual carbon increments gained or lost in conversions involving mangroves. Information about the exact year of change from one land cover to another was taken from the literature when available. If a conversion from vegetation cover (mangroves or coconut plantations) to aquaculture ponds was detected between 1992/1994 and 2007, the year of conversion was estimated to be 1995 since this is recorded as the peak year in this time envelope for new aquaculture developments (IUCN 2009). On the contrary, when a return from aquaculture to vegetation cover was observed, the estimated year of conversion was 2004 as a major WSSV outbreak caused waves of decline in the industry in 2004-2005 (Munasinghe *et al.*, 2010). No literature related to the changes in coconut plantations along the lagoon was found. Thus conversion from either coconut plantation to mangrove or mangrove to coconut plantation was estimated to take place at the mid-point of the time series (in 2000 for 1992/1994-2007, or in 2009 for the 2007-2012 series). These assumptions were made in the absence of remote-sensed data for each year between 1992-2012. Carbon stock changes induced by conversion into salt pans were assumed to be the same as for a conversion into shrimp ponds, as deforestation techniques used to clear the ponds are identical.

Table 2 *Carbon stock and flow values for each vegetation cover as well as gain or loss applied to each land cover changes detected in the study area. BGC=belowground carbon; AGC=aboveground carbon; NPP=net primary production; BS=belowground storage rate from trapped sediment. M=mangrove; SF=shrimp farms; SP=salt pan; C=coconut plantations. Other= land use other than mangroves, aquaculture or coconut groves. Carbon stocks are expressed in t.ha^{-1}±SD. If SD does not figure in the table this means the value was not given in the literature.*

	BGC		AGC		NPP		BS	
	tC.ha^{-1}	*Source*	*tC.ha^{-1}*	*Source*	*tC.ha^{-1}.yr*	*Source*	*tC.ha^{-1}.yr*	*Source*
Mangrove	199.18± 19.02	*Field measurement*	159	Donato *et al.* (2011)	5.3	Alongi, (2009)	1.74±0.23	Alongi, (2014)
Coconut plantation	34.15 ±31.01	*Field measurement*	194.4	Mattsson *et al.* (2009)	n/a		n/a	
Land-use change queries	BGC		AGC		NPP		BS	
M → SF / SP	-186.64±26.49		- 159		- 5.3		-1.74±0.23	
SF/SP → M	n/a		n/a		+ 5.3		+1.74±0.23	
C→SF/SP	-34.15 ±31.01		-194.4		n/a		n/a	
SF/SP → C	+34.15 ±31.01		+ 194.4		n/a		n/a	
M→C	-199.18± 19.02 +34.15 ±31.01		-159 + 194.4		n/a		n/a	
C→ M	n/a		-194.4		+ 5.3		+1.74	
M-No change	n/a		n/a		+5.3		+1.74	
M→ other	n/a		- 159		- 5.3		- 1.74	

2.4 Establishing the number of working shrimp ponds

In order to understand the degree of abandonment of shrimp ponds in Puttalam lagoon, high-resolution images from 2011 on Google Earth were manually analysed. Shrimp ponds were distinguished from salt pans based on their size: ponds exceeding 50x50m size were always classified as shrimp ponds.

Functioning and non-functioning ponds were distinguished using various features. When the boundaries of ponds were even and well shaped, the ponds and/or dykes were free from any type of vegetation (*i.e.* herbs, bushes or trees) and not submerged by water; if they were full of homogeneous water and some aerators were present then it was classified as a functioning pond.

The dimensions of functioning/non-functioning ponds were measured using Google Earth tools, allowing calculations of their areas. The first three of the abovementioned factors were compulsory in categorising a pond as functioning. In order to ground truth the results, field visits and interviews (n=20) with local people were carried out.

3. Results

3.1 Land use changes between 1992/1994 and 2012

The outlines of the land use classification varied depending on the type of image (aerial photograph, SPOT 5 or Pleiades). In order to compare patterns of land use/cover between 1992/1994, 2007 and 2012, images were extracted by mask within ArcGIS to show the same area and thus be comparable. The quantifications of change in land use between 1992/1994 and 2012 are shown in table 3. There was a dramatic expansion of shrimp farms during this period (+ 2777%, Table 3). Highlighted in Fig. 3 is the Mee-Oya estuary on the east of the lagoon that represents these patterns of change.

The rate of growth in the area of shrimp farms was higher between 1992/1994 and 2007, with an increase of 71 ha year^{-1}, compared with a slower rate of 23 ha year^{-1} between 2007 and 2012 (Table 4). On the contrary, the area of salt pans increased faster between 2007 and 2012 than between the early 1990s and 2007, +32 ha year^{-1} and +12 ha year^{-1} respectively (Table 4). The area of coconut plantations increased more between 1992/1994 and 2007 than between 2007-2012, +27 ha year^{-1} and +10 ha year^{-1} respectively (Table 4). Mangroves were lost at a rate of 27 ha $year^{-1}$ between 1992/1994 and 2007, while they increased by 3 ha $year^{-1}$ between 2007 and 2012.

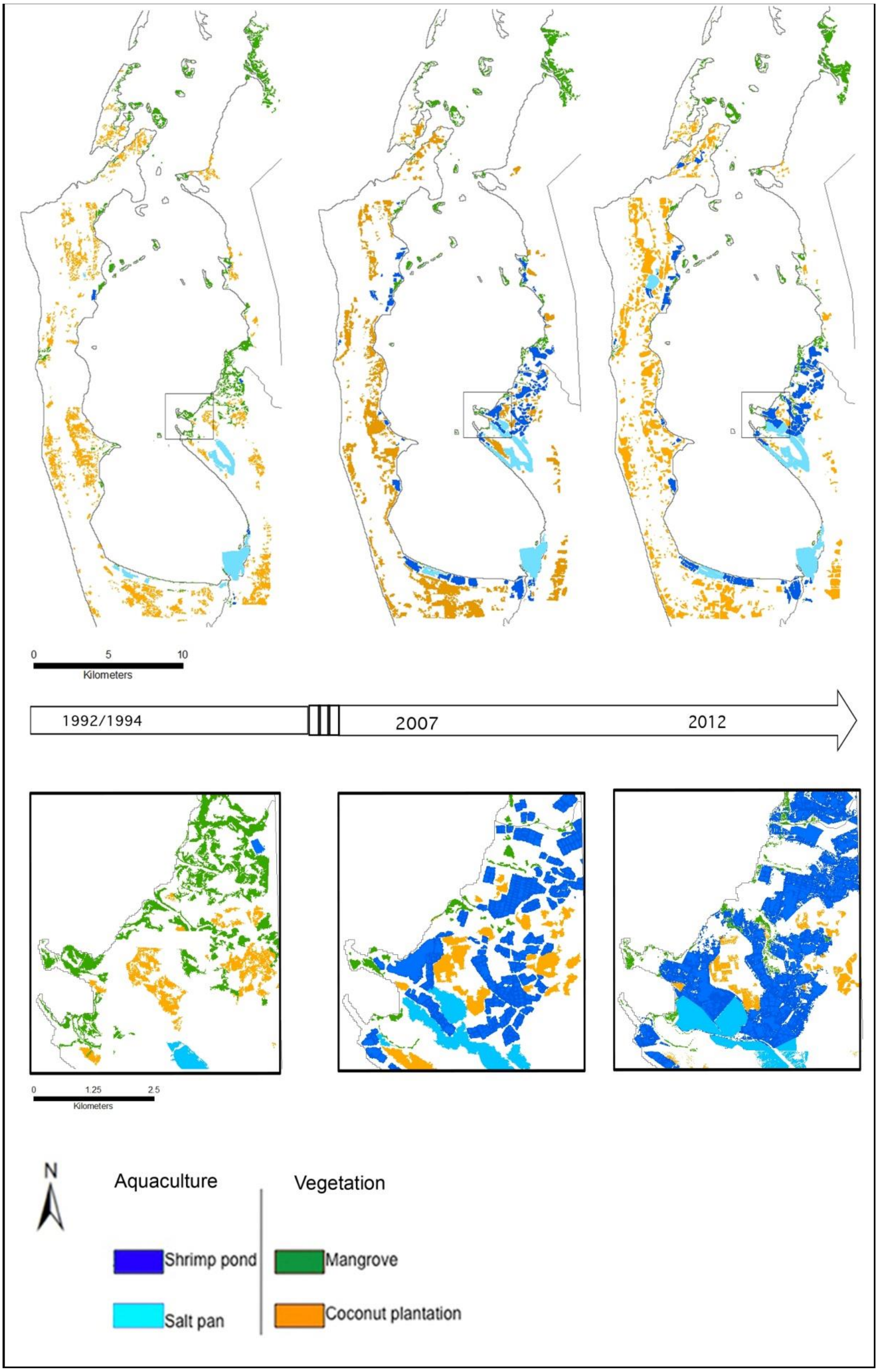
Table 3 *Land use areas in 1992/1994 and 2012 in Puttalam lagoon. Ratios of the area of shrimp farm (SF) to mangrove (M), and of shrimp farm (SF) to coconut plantation (CP) are indicated in the table, as well as the changes in land use areas between the beginning of the 90s and 2012. Percentages in brackets represent the percentage of total land areas.*

Land use	1992/1994 (ha)	2012 (ha)	Net Change (%)
Shrimp farms	39.63 (1%)	1 140.3 (20%)	+2 777.3
Salt pans	539.3 (13%)	862.1 (15%)	+59.8
Mangroves	1 093.7 (26%)	726 (13%)	- 33.6
Coconut plantations	2 535 (60%)	2 963.6 (52%)	+16.9
SF: M ratio	1: 28	1: 0.6	
SF: CP ratio	1: 64	1: 2.6	

Table 4 *Hectares of each land use lost or gained per year for the Puttalam lagoon, based on the analysis of image classification between 1992/1994-2007 and 2007-2012.*

Land use	1992/1994-2007 (ha yr^{-1})	2007-2012 (ha yr^{-1})
Shrimp farms	+ 71	+23
Salt pans	+ 12	+32
Mangroves	- 27	+3
Coconut plantations	+27	+9.9

Figure 3 *Time series for the four land uses classified in this study in Puttalam lagoon, with a zoom in the Mee-Oya estuary, clearly showing expansion of shrimp farms and salt pans and loss of the coastal mangrove ecosystem between 1992/4 and 2012.*



3.2 Impacts of shrimp farming on carbon dynamics between 1992/1994-2012

Figure 4 shows changes in carbon stocks between the early 1990s and 2012; it was obtained by superimposing carbon gain/loss in 1992/1994-2007 and 2007-2012 (Supplementary material table S1). The important areas of carbon accumulation are mostly located at the NE of the lagoon, which is an area of mangrove forest with no aquaculture infrastructure. Therefore, this area represents the capacity of mangroves as carbon stores when they are not subject to intense deforestation. Losses of >2 000 tC have taken place mainly in areas where mangroves were replaced by aquaculture ponds. The conversion from mangroves to shrimp farms represents 24% all land cover changes to aquaculture observed between 1990s-2007, which is the second largest proportion of land use changes due to aquaculture observed around the lagoon (Fig. 5). The largest proportion of change is the conversion of 'Other' to aquaculture, which includes mainly coastal vegetation (Fig. 5). A decrease of the conversion from mangroves to shrimp farms can be observed between 2007-2012 (Fig. 5). During the first time period of the study, 34% of mangroves were converted to shrimp ponds, and 23% to other land use, which includes agricultural uses and housing areas (Table 5). Between 2007-2012 this conversion from mangroves to other land uses increased, with 32% of mangroves present in 2007 lost in 2012 to 'Other' (Table 5). 41% and 59% of the mangroves present in 1990s and 2007 respectively have not changed and have accumulated a total of 52 892 tC in 1990s-2012 (Table 5, S1), which represents by itself the major carbon accumulation along the lagoon for the study period. The conversion of mangroves to ponds (shrimp farms and salt ponds) led to a loss of 186 359 tC between 1990s-2012, whilst the conversion of coconut plantations into ponds accounted for 2 502 tC lost in Puttalam (S1). Therefore, the conversion of mangrove into aquaculture ponds represents the most significant carbon loss. The overall carbon loss in the study area for the time period 1990s-2012 was 191 584 tC (S1).

Table 5 *Combinations of land-use and their proportion of loss. M=mangroves; SF=shrimp farms; SP=salt pans; C=coconut plantations; other= other land-use. No change represents unchanged areas.*

	Area converted (ha)		**Loss as % of original LC**	
	1992/1994-2007	2007-12	1992/1994-2007	2007-12
C → M	1.12	1.38	0.04	0.05
C→ SF	3.73	4.83	0.15	0.17
C → SP	0.21	2.17	0.01	0.07
C- no change	1 279.72	1 647.91	50.48	56.54
C → other	1 250.27	1 258.08	49.32	43.17
M → C	15.57	0.48	1.42	0.07
M → SF	374.67	64.34	34.26	9.05
M → SP	2.28	1.71	0.21	0.24
M- no change	446.92	418.73	40.86	58.90
M → other	252.9	226.36	23.12	31.84
SF → C	0.002	0.25	0.01	0.02
SF → M	0.28	1.02	0.71	0.10
SF → SP	0	23.69	0	2.31
SF- no change	26.48	775.13	66.82	75.54
SF → other	12.87	225.91	32.48	22.02
SP → M	0.52	0.001	0.10	0
SP → C	0	0.02	0	0
SP → SF	32.14	19.83	5.96	2.82
SP – no change	458.53	631.09	85.02	89.75
SP → other	48.63	52.25	9.02	7.43

Figure 4 *Carbon dynamics in Puttalam lagoon between 1992/1994 and 2012, with a zoom in the Mee-Oya estuary, which equates to a carbon loss of > 2 000tC with mangrove conversion to aquaculture.*

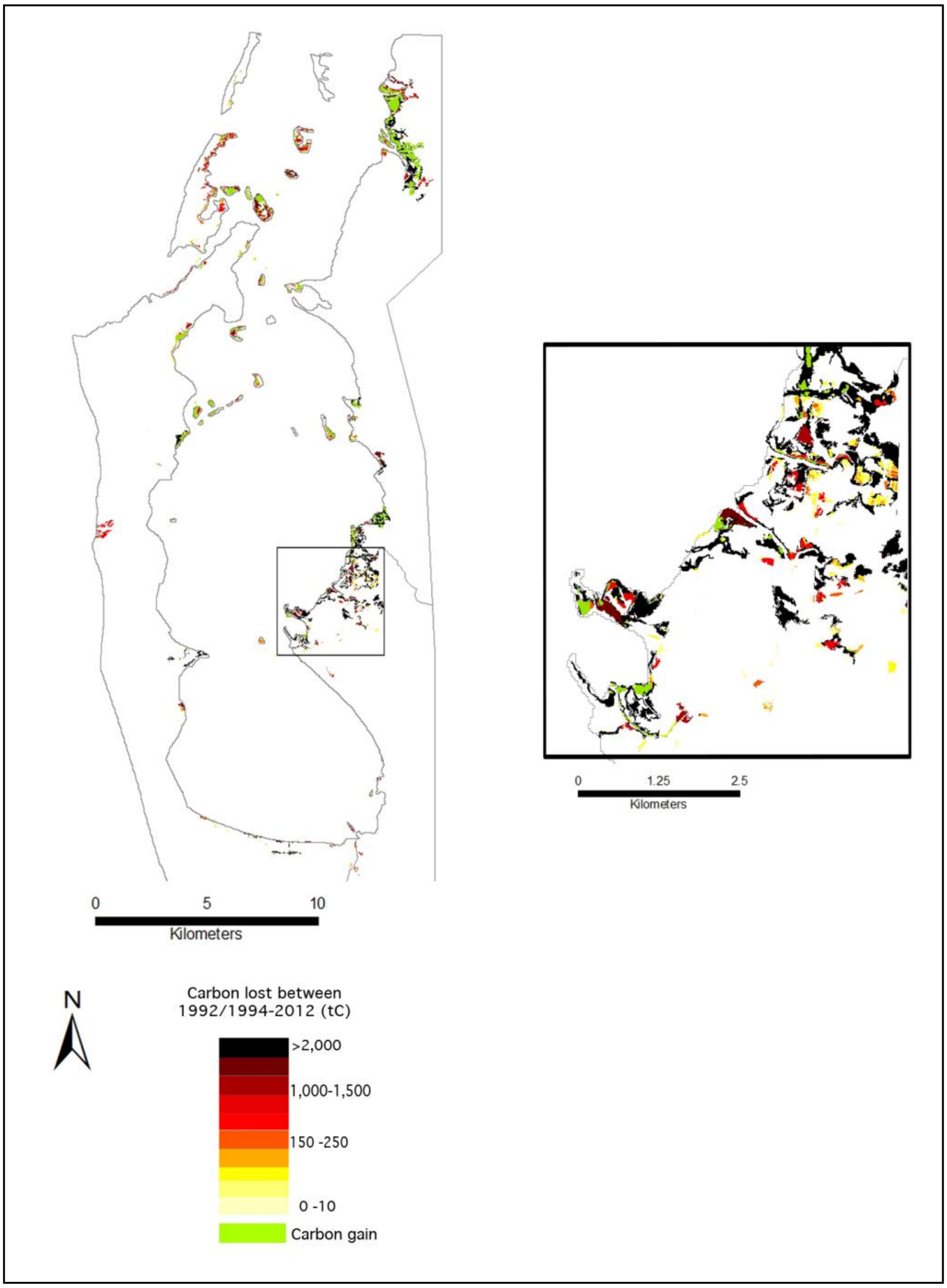
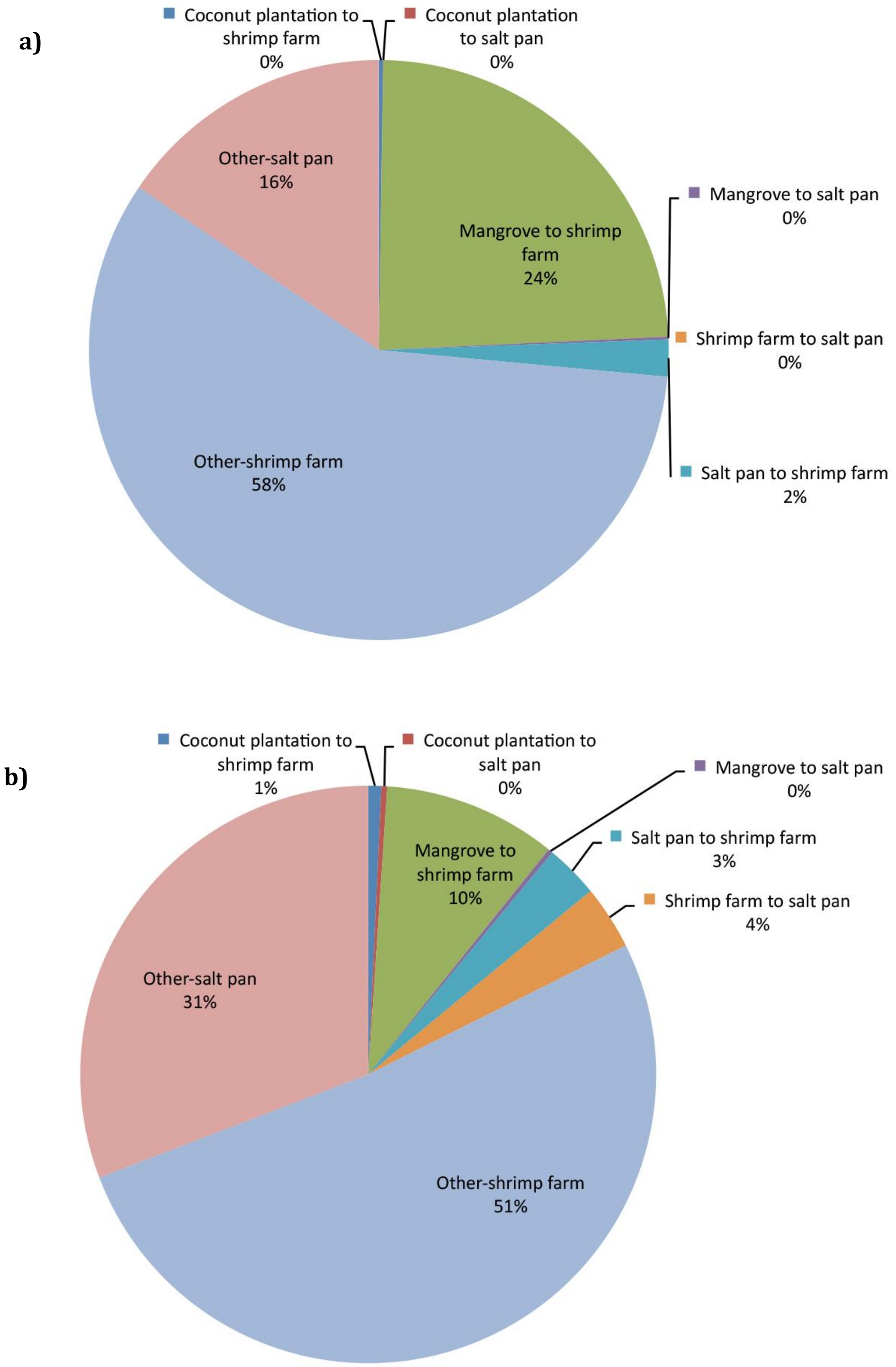


Figure 5 *The proportion of land cover/land use types converted to aquaculture around Puttalam lagoon between **a)** 1990s-2007 and **b)** 2007-2012.*



3.3 Estimate of the current functioning shrimp farms area

Only 10% of the shrimp ponds in Puttalam lagoon were classified as currently productive, leaving a large area of ponds unused. This number suggests a continuing decline in shrimp farming viability around the lagoon, as 75 % of farms were estimated to be non-operational in 2008 (Pathirana *et al.*, 2008).

4. Discussion

4.1 The extent of shrimp farming in the Puttalam lagoon: impacts on land use/cover change since 1992-1994.

GIS and remote sensing techniques are potentially powerful tools to support the sustainable management of shrimp aquaculture. Studies in India (Hossain *et al.*, 2003; Kumaran *et al.*, 2003), Brazil (Cavalcanti Maia Santos *et al.*, 2014), Mexico (Sanchez *et al.*, 2003), Bangladesh (Salam and Ross, 2000; Quader *et al.*, 2004), Thailand (Tripathi *et al*., 2000) and Vietnam (Tong *et al.*, 2004; Giap *et al*., 2005) give different case studies on how GIS and remote sensing can be used to inform the management of shrimp culture. The present study adds to the literature on this matter.

Previous studies of land use change caused by shrimp farming in the Puttalam lagoon used aerial surveys conducted in the Puttalam district between 1981 and 1992 (Senarath and Visvanathan, 2001; Pathirana *et al.*, 2008). The latest national forest inventory data available for Sri Lanka are from 1992-1996 (Mattsson *et al.* 2012). Therefore, the time series presented here provides a more recent and comprehensive picture of the impacts of aquaculture development in the Puttalam lagoon.

The ratio of mangrove forests to shrimp farms changed from 28:1 at the beginning of the 1990s to 0.6:1 in 2012 (Table 3). These observations concur with studies of other sites on the west Sri Lankan coast. In Chilaw, Dahdouh-Gubeas *et al.* (2001) recorded a ratio of mangroves to shrimp farms of 2.6:1 in 1998 and noticed a historical trend towards 1:1, with increasingly fewer mangroves and more shrimp ponds. The current results suggest that shrimp farming dynamics are likely to be similar among lagoons in the NWP of Sri Lanka.

Between 1981 and 1992, 64% of the mangrove area in Puttalam was lost (Senarath and Visvanathan, 2001). Approximately 34% of the remaining mangrove area has been lost between 1992/1994 and 2012 in Puttalam (Table 3). Hence it appears that the rate of mangrove destruction around the lagoon has decreased in recent decades, with a slight increase in mangrove coverage in the final five years of our study. Mangrove loss observed during the 1980s and 1990s was mostly caused by the initiation of shrimp farming in the NWP, but could also be partly attributed to increased pressure from local populations; about 55% of house-holds used mangrove as firewood in the mid-1980s, and this consumption further increased with an influx of political refugees in the west of the country (Senarath and Visvanathan, 2001; Pathirana *et al.*, 2008; Ranasinghe, 2010).

Of the various types of land-use considered in the present study, 41% and 59% is represented by mangrove area that remained forested between 1990s-2007 and 2007-2012 respectively (Table 5). When considering only land use changes over the studied period, 34% of mangroves were converted to shrimp farms between 1990s-2007, which is by far the largest category of land-use change concerning mangroves (Table 5). This trend has changed more recently, with 9% of mangroves that were converted to shrimp ponds between 2007 and 2012, leaving their conversion to other land uses becoming the major conversion occurring around the lagoon (32%, Table 5). The land uses included in this miscellaneous category were not classified using GIS. Our knowledge of the field site suggests that they include conversion to other agricultural land uses (including paddy fields), loss to buildings, to scrub or other coastal vegetation and to water.

Shrimp farms around Puttalam lagoon were mainly constructed on areas previously occupied by coastal vegetation (classified as 'other' in this study). Nevertheless, a significant proportion of these ponds also replaced mangrove areas, especially between 1992/1994-2007, with 24% of land-use conversion to aquaculture attributed to the change from mangrove to shrimp ponds (Fig. 5). This result shows that the impact of shrimp farms on mangroves in Puttalam follows the dramatic trend of other countries where land cover changes related to shrimp culture have recently been studied. For instance, 23.9% of mangrove cover has been converted to shrimp farms between 1999 and 2008 in Ha Long, Vietnam (Bui *et al.*, 2014).

Only two salt ponds were present in the Puttalam area at the beginning of the 1990s (Fig. 3). The salt industry also contributed, albeit to a lesser extent, to the loss of mangroves; in 1992/1994 only 13% of the lagoon was used for this purpose compared to 15% in 2012 (Table 3). Finally, conversion of mangroves to coconut plantations accounted for only a small percentage of total land changes (1.42% and 0.07% in 1990s-2007 and 2007-2012 respectively, Table 5). However, the high carbon density of mangroves means this still resulted in a loss of some 2 081 tC between the early 1990s and 2012.

Whilst large areas of valuable mangrove forest have been lost, this has not resulted in permanent (or even extended) economic benefits for local people. Intensive shrimp farms have a relatively short initial productive life, with problems of disease and pollution often leading to permanent or temporary abandonment after 5 to 10 years. Stevenson (1997) described this problem in Thailand and estimated that 'up to 70%' of all farms in the study area were abandoned. Our data show that the situation in Puttalam is worse than this, with 90% of farms abandoned; because of the criteria used to identify abandonment, which included the growth of vegetation which will take many years to establish, this estimate may be conservative. Pond abandonment results in large areas of unoccupied land unsuitable for most uses because of the unfavourable chemical and physical properties of the soil, which include low pH and loss of organic structure (Towatana *et al*., 2003).

Between the early 1990s and 2012, shrimp farms in Puttalam have been converted into coconut plantations at a constant rate of 0.02% (Table 5). Some natural mangrove regeneration can be observed in abandoned ponds, with 0.71% and 0.010% of shrimp farm area classified as returning to mangroves during 19902/1994-2007 and 2007-2012 respectively (Table 5). However natural recovery of these ponds is likely to remain very slow, due to limits on the dispersal ability of propagules (Di Nitto *et al.*, 2013) as well as the chemical and physical unsuitability of the sediments.

Most shrimp farms in Puttalam were constructed illegally, thus appropriate site selection was not performed (Cattermoul and Devendra, 2002; Dahdouh-Guebas *et al.*, 2001). Mangrove areas are able to buffer the impacts of effluents from ponds in surrounding areas hence retaining mangroves is one way of helping to ensure sustainability and avoiding collapse. The low ratio of mangrove to shrimp farms (abandoned or operational) in Puttalam estimated in the current study (0.6:1 in 2012, Table 3) will have contributed to the high rate of abandonment and the slow rates of recovery of ponds.

The Sri Lankan government still considers aquaculture as an important industry for further development (Department of National Planning, 2013). There is also now strong demand from the EU for sustainable shrimp products (Lei, 2012). Therefore, there is policy and economic potential for the rehabilitation of some of the abandoned ponds, which must involve careful planning to ensure a correct balance between mangroves and aquaculture. Achieving this would involve active policy support and intervention and must learn from the mistakes of the past two decades, linking development to sustainability, climate change adaptation and mitigation (Harkes *et al.*, in prep.).

4.2 Impacts of shrimp farming on carbon storage and sequestration

The exceptional ability of mangrove forests to sequester carbon and to store it belowground makes carbon storage one of their most important regulating ecosystem services. By assessing land-use changes in Puttalam during the two last decades, the present study underlines the consequences of these dynamics for carbon stores. The land use patterns studied in this research have caused a net loss of stored carbon of 191 584 tC between 1992/1994 and 2012. The conversion of vegetated areas into aquaculture ponds represents a total loss of 188 861 tC in the 19-year period (S1). Mangroves were converted into coconut plantations, especially between 1992/1994 and 2007, leading to a loss of some 2 081 tC during the last two decades (S1). Reconversion of aquaculture ponds into vegetation is a minor change, which has produced a total sequestration of 103 tC, contributing only an estimated 0.2% of the total C accumulation in Puttalam over the study period.

5. Conclusion

This study shows that Puttalam lagoon has experienced significant land use changes in the past two decades. There are implications for a range of ecosystem services; here we document the effects on one, carbon sequestration, with a net loss of 191 584 tC in the 19-year period. It is obvious that the development of shrimp farming has had a negative impact on the coastal environment in Puttalam, and the loss of ecosystem services has not been balanced by permanent economic benefits since 90% of ponds are now abandoned.

The results presented in this paper emphasise the requirement for integrated planning in the Puttalam area. Most of the aquaculture in the study area is currently unproductive, has lost natural ecosystem services such as carbon sequestration and has increased vulnerability to natural hazards and climate change. Therefore there is a pressing need for reconversion or rehabilitation of abandoned ponds in Puttalam lagoon. The findings of this study highlight the need for more control over pond site selection and shrimp farming licences. The economic and ecological advantages in implementing sustainable aquaculture practices in Puttalam are potentially considerable.

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Supplementary table S1: *Carbon loss or gain induced by land cover/use conversion around Puttalam lagoon in 1992/1994-2012 in tC. M=mangrove; SF=shrimp farms; SP=salt pan; C=coconut plantations; other= other land-use; No change represents unchanged mangrove areas, included here to show amounts of carbon sequestered by untouched mangroves.*

	Carbon stocks lost			**Carbon stocks gained**		
	1992/1994-2007	2007-12	1992/1994-2012	1992/1994-2007	2007-12	1992/1994-2012
C → M	161.9	239.5	401.4			
C→ SF	852.6	1 104.1	1 956.7			
C → SP	48.3	496.7	545			
M → C	2 017.8	62.7	2 080.5			
M → SF	161 153.1	23 600.3	184 753.4			
M → SP	979.4	626.3	1 605.7			
M → other	12 462.9	40 772.8	53 235.7			
SF → C				0.43	58	58.43
SF → M				6	21,5	27.5
SP → M				11	0.02	11.02
SP → C				0	5.6	5.6
M – no change				44 048.6	8 843.7	52 892.3
Total	177 676	66 902.4	244 578.4	44 066	8 928.8	52 994.9
Carbon balance: 191 584						