

Soil Carbon Loss from Conversion of Sundarbans Mangroves to Aquaculture Ponds and Rice Fields, West Bengal, India

Anushka Sah

Department of Geography | Faculty of Science | McGill University | Montréal, Québec, Canada

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree
of Master of Science

© Copyright, All rights reserved | Anushka Sah, 2021

Abstract

There has been substantial deforestation of mangroves around the world. This loss is widely attributed to the transformation of mangroves for shrimp aquaculture. As one of the world's most efficient carbon sinks, substantial losses of its soil blue carbon occur with this transformation. I investigated these losses in West Bengal, India, which has the country's 2nd highest shrimp production and contains part of the world's largest contiguous mangrove forest area, the Sundarbans. I examined soil organic carbon (SOC) stocks in the Lot No. 126, of Jharkhali Island that previously was covered by mangroves. In this region of West Bengal, mangroves were first drained for rice cultivation 60 years ago, a type of mangrove transformation largely unrecognized. Later, some rice fields were transformed to aquaculture ponds while mangroves are still being cleared for shrimp aquaculture. My study targeted ponds that were constructed 6-7 years ago by clearing mangroves. Although in some locations I collected soils down to 1 m, I normalized my results to 50 cm depth, which was approximately the minimum depth retrieved. I found that the average SOC in the top 50 cm of aquaculture pond soil is $59 \pm 38 \text{ Mg C ha}^{-1}$ whereas the same depth in the rice field soil is $24 \pm 2 \text{ Mg C ha}^{-1}$. The loss of SOC from conversion of Sundarbans mangroves to aquaculture ponds is 14 Mg C ha^{-1} (20%) and through conversion to rice fields is 49 Mg C ha^{-1} (68%). IPCC Guidelines for National Greenhouse Gas Inventories provide estimates for SOC loss from shrimp ponds created directly from mangroves, but there are no estimates for losses when mangroves are transformed to rice fields. My measurements of SOC stocks in rice fields and active shrimp aquaculture ponds are the first for these mangrove transformations of the Sundarbans.

I also assessed the land use change pattern in a part of Lot no. 126 over the period of two decades using Google Earth imagery. The land use change pattern over the decades is useful to

understand the deforestation and transformation of Sundarbans mangroves. I mapped the pattern of human settlement, aquaculture, and agriculture in the deforested and the drained land. The size of the mapped area is 53 ha. The mapped area showed 12.08 ha (23%) is lost for construction of aquaculture ponds and 13.56 ha (26%) is lost to rice fields. The SOC loss is 322 Mg C through conversion of mangroves to rice fields and 710 Mg C through construction of aquaculture ponds. Overall, the data collected in my research will support national inventories of greenhouse gas emissions as required by the United Nations Framework on Climate Change and inform national land use policies.

Résumé

Il y a eu une importante déforestation de mangroves dans le monde entier. Cette disparition peut largement être attribuée à la transformation de mangroves vers l'aquaculture de crevettes. Des pertes considérables de son carbone bleu du sol se produisent avec cette transformation étant donné qu'il s'agit d'un des puits de carbone les plus efficaces au monde. J'ai étudié ces pertes au Bengal occidental en Inde, ayant la deuxième plus grande production de crevettes du pays et contenant des parties du territoire du plus grand forêt de mangrove contigu au monde, les Sundarbans. J'ai examiné les stocks de carbone organique du sol (SOC) dans le lot nr. 126 de l'île de Jharkhali ayant auparavant été couverte par des mangroves. Dans la région du Bengal occidental il y a 60 ans, les mangroves ont été drainés pour la culture de riz, s'agissant d'un type de transformation de mangroves largement non reconnu. Ultérieurement, quelques champs de riz ont été transformés en bassins d'aquaculture tandis que les mangroves continuent d'être défrichés pour l'aquaculture de crevettes. Mon étude cible des bassins qui ont été construits il y a 6 à 7 ans par le défrichage de mangroves. J'ai normalisé les résultats à 50 cm de profondeur ce qui représente approximativement la profondeur de prélèvement minimum alors que j'ai recueilli de la terre dans une profondeur de 1 m dans certains endroits. J'ai trouvé que le SOC moyen dans les premiers 50 cm de bassins d'aquaculture est à 59 ± 38 Mg C ha⁻¹ tandis que la même profondeur dans le sol des champs de riz est à 24 ± 2 Mg C ha⁻¹. La perte de SOC de la transformation des mangroves de Sundarbans en bassins d'aquaculture est de 14 Mg C ha⁻¹ (20%) et en champs de riz est de 49 Mg C ha⁻¹ (68%). Les directives du GIEC pour les inventaires nationaux de gaz à effet de serre fournissent des estimations pour la perte de SOC à cause de bassins de crevettes créés directement à partir de mangroves. Cependant, il n'y a pas d'estimations pour les pertes quand des mangroves sont transformées en champ de riz. Mes

mesures des stocks de SOC dans les champs de riz et dans des bassins d'aquaculture de crevettes actives sont les premières pour ces transformations de mangroves dans les Sundarbans.

En faisant recours à l'imagerie de Google Earth, j'ai aussi évalué le schéma de changement d'utilisation des terres dans une partie du lot nr. 126 sur une période de 2 décennies. Le schéma de changement d'utilisation des terres à travers les décennies est utile afin de comprendre la déforestation et la transformation des mangroves des Sundarbans. J'ai cartographié le schéma d'implantation humaine, d'aquaculture et d'agriculture sur les terres déboisées et drainées. La taille du terrain cartographié est de 53 ha. Le terrain cartographié a avéré que 12.08 ha (23%) sont perdus en raison de la construction de bassins d'aquaculture ainsi qu'en raison de champs de riz est de 13.56 ha (26%). La perte de SOC est de 322 Mg C par la transformation de mangroves en champs de riz et de 710 Mg C par la construction de bassins d'aquaculture. Dans l'ensemble, les données collectées dans mes recherches appuieront les inventaires nationaux des émissions de gaz à effet de serre comme l'exige le Cadre des Nations Unies sur les changements climatiques et éclaireront les politiques nationales d'utilisation des terres.

Table of Contents

Abstract.....	2
Résumé.....	4
Table of Contents.....	6
List of Tables.....	8
List of Figures.....	9
Appendix.....	11
Acknowledgments.....	12
Chapter 1. Introduction and Literature Review.....	14
1.1 Introduction.....	14
1.2 Literature Review.....	16
Chapter 2. Study Area Description and Methods.....	22
2.1 Study Area.....	22
2.2 Field Work.....	24
2.3 Soil Analyses.....	25
2.4 Analysis of Google Earth Imagery.....	26
Chapter 3. Results and Discussion	27
3.2 Soil Analyses.....	27
3.2 Landscape Change Analysis from 2002 to 2020.....	30
3.2.1 Road and dyke construction.....	31
3.2.2 Aquaculture ponds.....	32
3.2.3 Rice fields.....	32
3.2.4 Human settlement.....	33

Chapter 4. Conclusions.....	34
References.....	36
Tables.....	45
Figures.....	49
Appendix.....	63

List of Tables

Table 1 Studies on clearance of mangroves for aquaculture and agriculture.

Table 2 Soil C stock (Mg C ha^{-1}) in aquaculture ponds and rice fields with ± 1 standard deviation.

Table 3 Definition of features identified from Google Earth images

List of Figures

Figure 1 Location of Lot No. 126, Jharkhali Island, India. Lot No. 126 is surrounded by the Matla and the Vidyadhari Rivers and Herobhanga Creek.

Figure 2 Location of rice fields and aquaculture ponds in Lot No. 126, Jharkhali Island, India.

Figure 3 Soil carbon stocks (Mg C ha^{-1}) of aquaculture ponds and rice fields, adjusted to the depth of 50 cm in Lot No. 126, Jharkhali Island, India. Means labelled with the same letter are not significantly different.

Figure 4 Amount of soil C loss (Mg C ha^{-1}) from conversion of Sundarbans mangroves (green bar) to aquaculture ponds and rice fields (grey bar).

Figure 5 Comparison of soil C stocks (Mg C ha^{-1}) in different studies.

Figure 6 Google Earth image on 28 October 2002 showing the mangrove forest and mudflats.

Figure 7 Google Earth image on 13 November 2010 showing drainage channel (Point G).

Figure 8 Google Earth image on 2 March 2013 showing small embankment across Point C and E.

Figure 9 Google Earth image on 23 November 2014 showing polygonal structures around Point A, B and H. Rice fields are also apparent (Point I).

Figure 10 Google Earth image on 7 December 2018 showing major deforestation around Point A, B and C. Embankment across Point C and E is also visible.

Figure 11 Google Earth image on 17 April 2019 showing tidal gate (Point E), and inlets and outlets in ponds (Point A).

Figure 12 Google Earth image on 12 February 2020 showing subdivision of large ponds (Point A, B and around Point H) and long channel (Point F).

Figure 13 Google Earth image on 12 February 2020 showing area of mapped ponds as white borders.

Figure 14 Google Earth image on 12 February 2020 showing area of mapped rice fields as white borders.

Appendix

Appendix 1 Data from soil cores collected during fieldwork in Lot No. 126, Jharkhali Island, India. Ponds are designated by the letter P and rice fields by the letter R.

Acknowledgements

I would like to thank my supervisor Dr Gail L. Chmura for her guidance, motivation, and support throughout my degree. I am grateful for her assistance in my field work, and her invaluable time and efforts. Thanks to Dr Tim Moore and Dr Nagissa Mahmoudi for their critical review and feedback.

This work would not have been possible without the financial support of Lawrence Light fellowship, Rathlyn fieldwork award, and Theo Hills award. Thanks to the financial aid by 5th Mangrove, Macrobenthos and Management Conference (MMM5) at Singapore because of which I was able to join the conference, showcase my research work and get feedback. I am delighted to be a recipient of these awards.

Thanks to my senior and alumnus D.S. Bhaduria for helping me to visit different places in Sundarbans to finalise my research site. Thanks to my colleague and friend Mr. Arunabha Dey for his assistance in the field work and helping me to interview the Bengali speaking pond and rice field owners. Special thanks to people of Lot No. 126, who helped me in my field work and allowed me to work on their ponds and rice fields. I am grateful for the hospitality of Royal Sundarban Wild Resort. Thanks to the manager, chef, driver and the whole Royal Sunderban Wild resort team.

Thanks to Dr Supriyo Kumar Das for his gracious welcome and his generosity in providing a lab and equipment to dry my soil samples in India. Thanks to Presidency University, Kolkata for allowing me to work in its labs. Thanks to Subham Chatterjee, Sourav Adhya and Pravat Kumar for assisting me in my lab work at Presidency University.

Thanks to Mike Dalva and Paula Kestelman for arranging equipment and their assistance during my lab work. I am grateful that even during COVID-19 they were available for me to help me to process my soil samples – and to Dr. Raja Sengupta for transporting my samples from India to Canada. Thanks to Anna Jung for guiding me through use of the programmable muffle furnace and arranging everything in the McGill's Earth and Planetary Sciences lab.

Thanks to my friends and colleagues Wendy Ampuero Reyes, Oi Yin Lai, Lee Van Ardenne, Sophie Comer-Warner, and Recho Dong for their advice and help throughout my journey at McGill University.

Last but not the least, to my mom and dad who believed in me and always supported me. To my amazing friends and family in India and Canada, thank you for your love and prayers.

Chapter 1. Introduction and Literature Review

1.1 Introduction

Mangroves are salt tolerant trees in the intertidal zones of tropical and sub-tropical coasts. They are found in 118 countries and cover an area of about 137,600 km² with the greatest portion in Asia, i.e. 38.7% (Bunting et al., 2018). Mangroves provide a range of ecological services such as water filtration, coastal storm protection, food, timber, and carbon storage (Rönnbäck, 1999). They store more belowground carbon (C) than terrestrial forests (Mcleod et al., 2011) and are called ‘blue carbon’ sinks. Although the global area of mangroves is smaller than that of terrestrial forests, their contribution to long-term C sequestration is much greater (Alongi, 2012). The high net ecosystem productivity and slow decomposition rates explain the high soil C sequestration. Donato et al. (2011) reported that the belowground C stock dominates the C storage in mangrove ecosystems. The organic rich soil of mangroves ranges from 0.5 to 3 m depth and together the aboveground and belowground components of the mangroves contain an average of 1,023 Mg C ha⁻¹ (Donato et al., 2011). However, transformations of mangroves are causing mineralization of the soil organic matter adding CO₂ to the atmosphere. Mangroves are disappearing at the rate of 0.13% per year as they are converted for use in agriculture, aquaculture, salt production ponds, and human settlements (Cornforth et al., 2013; Duke et al., 2007; Goldberg et al., 2020; Rahman et al., 2010).

Aquaculture, primarily for shrimp, presently is the major threat to mangroves (Murdiyarso et al., 2015; Kauffman et al., 2017; Polidoro et al., 2010; Rahman & Asaduzzaman, 2013). Valiela et al. (2001) reported that we have lost around 1.89 million ha of mangroves due to aquaculture alone whereas the FAO (2006) estimated that we have lost 3.6 million ha of mangrove forests to

aquaculture since 1980. In the Indo West Pacific region alone, 1.2 million ha of mangroves were displaced by aquaculture (Primavera, 1995).

Aquaculture is the farming of aquatic organisms including fish, crustaceans, mollusks, and aquatic plants (FAO, 1988). Among these, shrimp is the most economically important (Rahman et al., 2010; Rönnbäck, 1999). Aquaculture ponds are constructed in mangroves as the nearby waters are major nursery areas providing abundant supply of shrimp fry for stocking ponds (Ashton, 2008; Rönnbäck, 1999). Three types of aquaculture ponds are constructed in mangrove sites: extensive, semi-intensive and intensive ponds. Extensive farming adopts traditional techniques of aquaculture and is conducted in areas >5 ha. It relies on little or no input of feed and fertiliser, hence the quantity of fish produced per unit area is low (Fast & Lester, 1992). With stocking densities of 25,000 ha⁻¹, these ponds produce 1 tonnes shrimp ha⁻¹ yr⁻¹ (Tacon, 2002). In contrast, intensive aquaculture systems adopt a full complement of aquaculture techniques and utilize areas of 0.25- 2 ha (Fast & Lester, 1992). Due to high stocking density in intensive systems, the production per unit area is >20-tonnes shrimp ha⁻¹yr⁻¹ (Kongkeo, 1997). The management of semi-intensive systems falls between extensive and the intensive systems with a medium rate of production and area of 1-20 ha (Fast & Lester, 1992). Management of semi-intensive systems is partially dependent on natural productivity, but also includes fertilization, supplementary feeding, and mid-level technology. The stocking density of these ponds is 100,000 to 300,000 ha⁻¹ producing 3 to 4 tonnes shrimp ha⁻¹ yr⁻¹ (Tacon, 2002).

The other major cause for mangrove conversion is agriculture. Mangroves are converted for rice/paddy cultivation. Dykes (embankments) are constructed to prevent the saline tidal water from entering the rice fields. During the growing season, rice fields remain flooded with freshwater up to 30 cm deep (Tripathi et al., 2016). Sasmito et al. (2019) report that the soil C

loss from mangrove conversion to rice fields is larger than other land use changes i.e. 65% $\pm$ 28%. However, there is little data on C stocks in rice systems converted from mangroves (Andreetta et al., 2016; Sasmito et al., 2019).

The research reported in this thesis examines loss of soil organic carbon through conversion of mangroves to aquaculture ponds and rice fields. The thesis is composed of four chapters. Chapter 1 is divided into two parts- introduction and literature review. The introduction is about mangrove and reasons for their conversion to aquaculture and agriculture. Chapter 2 provides a description of my study area in Sundarbans, West Bengal, India, and methods used to examine the soil C stocks and analysis of land-use change. In Chapter 3, I report results of measurements of soil C stocks in aquaculture ponds and rice fields, and the landscape changes in Lot no. 126 over two decades (2002-2020). In Chapter 4, I address the strengths and limitations of my study as well as future research needs.

1.2 Literature Review

Globally, there has been limited study of how much organic C (OC) has been lost to aquaculture and agriculture transformations out of which only a few studies have actually *measured* the OC. Only seven studies in seven countries *measured* the loss of soil OC from conversion of mangroves to shrimp aquaculture ponds and only one study *measured* losses with conversion to rice fields (Table 1). The depth of soil cores for aquaculture ponds in those studies varies from 59-300 cm and for rice fields are 80 cm.

Andreetta et al. (2016) measured the soil OC (SOC) in active and abandoned rice fields in Northern Guinea-Bissau. This is the only study to measure SOC in rice fields constructed by conversion of mangroves. Their cores were between 60-100 cm deep. The rice fields had been

abandoned for 15-20 years due to soil salinization and acidification. In the active rice fields, the carbon input is mainly from plant residues. The rice fields were abandoned, due to which there is no vegetation which results in consequent loss of organic carbon. Hence, they found more SOC in mangroves than in abandoned and active rice fields. In their review, Sasmito et al. (2019) examined the influence of land-use and land-cover change on mangrove carbon stocks, but the only data available was from Andreetta et al. (2016). From that study Sasmito et al. (2019) estimated the SOC loss was $65 \pm 28\%$ when mangroves were converted to rice fields.

There has been considerably more study of SOC loss with transformation of mangroves to aquaculture. Kaufmann et al. (2014) quantified the ecosystem OC stock (aboveground and belowground) of mangroves and abandoned shrimp ponds in the Dominican Republic. The shrimp ponds in their study were constructed by clearing the mangroves in 1983 and were actively used for 10 years. The shrimp ponds had been abandoned for 19 years before sampling. The average soil depth Kaufmann et al. (2014) cored to was 71.3 cm. The SOC stocks of abandoned shrimp ponds were 95.5 Mg ha^{-1} . They cored mangrove soil and compared it with soil cores from shrimp ponds. They found that mangroves covered 76% of the study area but store 96% of the SOC whereas shrimp ponds converted from mangroves covered 24% of the area but store only 4% of the SOC. They estimated the emissions from conversion of 1 ha of mangrove forest to shrimp ponds is equivalent to emissions from 11.5 ha of tropical dry forest or 5 ha of tropical evergreen forest.

Kauffman et al. (2017) estimated the potential greenhouse gas emissions from conversion of mangroves to two shrimp ponds in Costa Rica, three in the Dominican Republic, three in Honduras, and 10 in Indonesia as well as three cattle pastures of Mexico. The shrimp ponds in Honduras were still active, while others had been used for 5-10 years prior to abandonment. The

mean soil C measured in pond bottoms was $351.5 \pm 50.1 \text{ Mg ha}^{-1}$. They calculated that the land use C footprint of 1 kg shrimp is 1603 kg CO₂e, which is higher than 1 kg of beef i.e. 1440 kgCO₂e.

In the Philippines, Castillo et al. (2017) measured the SOC stocks in mangrove forests and three abandoned aquaculture ponds. They cored aquaculture ponds to average depth of 84 cm. The SOC stored in ponds is $454 \pm 32 \text{ Mg C ha}^{-1}$. The mean SOC stock in mangrove forests was $851.93 \text{ Mg C ha}^{-1}$. The SOC stock in aquaculture ponds was 53% of that in mangrove forests.

In Northeastern Brazil, Kauffman et al. (2018) measured the SOC in shrimp aquaculture ponds constructed by clearing mangrove forests. They cored three ponds to depths of 103 cm, 144 cm and 60 cm. The soil C in shrimp ponds range from $37\text{-}282 \text{ Mg C ha}^{-1}$. The cored mangrove soil and found that soil C stock in mangroves ranged from $53\text{-}600 \text{ Mg C ha}^{-1}$.

There have been two additional studies of SOC in Indonesian shrimp ponds. Cameron et al. (2019) measured the SOC in aquaculture ponds in Sulawesi. They sampled two ponds. The average depth of soil cored from ponds was 62.5 cm. They reported the SOC stock to be between 114.9 ± 17.9 and $665.8 \pm 59.4 \text{ Mg C ha}^{-1}$. Arifanti et al. (2019) measured SOC in 10 abandoned shrimp ponds on the Mahakam Delta. They cored to a depth of 3 m and reported a mean SOC stock of $486 \pm 55 \text{ Mg C ha}^{-1}$. The ponds had a traditional/extensive management system with low input and production operations. Arifanti et al. (2019) calculated the C footprint of 1 kg of shrimp was 2250-4874 kg CO₂e.

To date, only one study of SOC loss by transforming mangroves to shrimp ponds has been conducted in India. Bhomia et al. (2016) sampled two abandoned aquaculture ponds in Orissa, a state on the eastern coast of India. The average depth cored in the ponds was 70 cm. For

comparison, they also cored soils of dense mangroves, scrub mangroves, and 5-year-old restored mangroves to depths from 60-189 cm. The average SOC stocks for the mangrove sites were 134 ± 2 , 177 ± 1 , 92 ± 2 Mg C ha⁻¹, respectively. The SOC stock of the abandoned aquaculture ponds averaged 61 ± 8 Mg C ha⁻¹. This would mean that conversion of the different mangrove types would result in SOC losses of 54%, 35% and 34%, respectively.

Sasmito et al. (2019) reviewed the results of studies on SOC loss by conversion of mangroves to both aquaculture ponds and rice fields. The data was based on studies in Mahakam Delta, Indonesia, Tanakeke Island and Tiwoho, Indonesia, Philippines, Costa Rica, Honduras, and Brazil by Arifanti et al. (2019), Cameron et al. (2019), Castillo et al. (2017), Kauffman et al. (2017), and Kauffman et al. (2018), respectively. Based on their review Sasmito et al. (2019) calculated that an average of $52 \pm 20\%$ SOC is lost when mangroves are converted to aquaculture ponds.

Previous studies suffer from a lack of consistency with respect to the variable depth of soil cores and types of aquaculture practices represented by the ponds sampled. The different aquaculture practices (extensive, semi intensive and intensive) could vary in SOC storage. Also, in some studies, the number of ponds sampled are not enough to determine the impact of shrimp aquaculture on the mangroves.

The IPCC guidelines for National Greenhouse Gas Inventories with mangrove transformation (Kennedy et al., 2014) provide guidance for calculation of SOC loss for excavation and construction of aquaculture ponds assuming that only 1 m is soil is disturbed. The guidelines provide no estimates for SOC stocks in active or abandoned ponds. Although conversion to rice fields is among one of the major factors for soil C loss, the IPCC guidelines (Ogle et al., 2019)

include only one study of SOC loss from conversion of mangroves to rice fields that of Andreetta et al. (2016).

In India, ~ 580 km² of mangroves were lost from 2000 to 2012 due to development for agriculture, aquaculture and other uses (Giri et al., 2015). India's largest mangrove forest area is part of the Sundarbans, which lies in the state of West Bengal. West Bengal is also the state with the 2nd highest shrimp production. The Sundarbans lies in the Ganga-Brahmaputra Delta on the Bay of Bengal. Although data and research are available on Sundarbans mangroves and its SOC stocks, I have located no studies reporting soil C loss from conversion of Sundarbans mangroves to aquaculture ponds or rice fields.

Samanta and Hazra (2012) conducted research on land use and land cover change (LULCC) on Jharkhali Island, India and revealed disappearance of mangroves between 1986-2009. However, their study does not include the land use change pattern. The land use change pattern over the decades is useful to understand the deforestation and transformation of Sundarbans mangroves. The loss of SOC stocks from conversion of mangroves coupled with mapping the land use change pattern is helpful in estimating the loss of SOC at a local/village level. In turn this could aid in assessing how economic incentives such as REDD+ or carbon markets could be utilized to advance mangrove preservation (Pendleton et al., 2012).

Recognizing these limitations in documenting the SOC loss with land use change in West Bengal, the overall objective of my research is to provide data on SOC loss from land use change and to map the deforestation and draining of Sundarbans mangroves at a local level. My research is focussed on rice fields and aquaculture ponds of Jharkhali, West Bengal, India that were once part of the Sundarbans mangrove system. My research asks:

1. What is the SOC stock of shrimp aquaculture ponds and rice fields?
2. How much SOC is lost from conversion of mangroves of these mangroves to shrimp aquaculture ponds and rice fields?
3. What is the pattern of mangrove forest deforestation and drainage for human settlement, aquaculture, and agriculture on Jharkhali Island?
4. How much SOC loss likely occurred due to this local landscape transformation?

Chapter 2. Study Area Description and Methods

2.1 Study Area

In India, West Bengal is the state with 2nd highest shrimp production. It also contains part of the world's largest contiguous mangrove forest area, the Sundarbans (Figure 1). The Sundarbans lies in the Ganga-Brahmaputra Delta on the Bay of Bengal. The Delta is formed by the confluence of three major rivers- the Ganga, Brahmaputra and Meghna.

There are 27 mangrove species found in the Sundarbans (Ghosh et al., 2016). Sundri (*Heritiera fomes*) and Gewa (*Excoecaria agallocha*) are the principal tree species which cover 73% and 16%, respectively of the total forest area (Rahman and Asaduzzaman, 2013). The tidal amplitude is 3-4 m (Ellison et al., 2000) with semi-diurnal tides (Pramanik, 2015; Rahman and Asaduzzaman, 2013). The salinity of the western Sundarbans is 28.

The region's mean annual rainfall is 1600 mm. Precipitation falls mainly from June to September (Southwest monsoon) and October to February (Northeast monsoon). The temperature is lowest from December to February (12-25°C) and highest from March to June (30-35°C) (Rahman and Asaduzzaman, 2013).

I chose Lot No. 126 (22.0306° N, 88.7013° E) of Jharkhali Island as my research site because of the presence of both rice fields and shrimp ponds that had replaced mangrove forests. Jharkhali is a part of Sundarban group of islands and is about 130 km south of Kolkata, West Bengal.

Jharkhali is surrounded by the Matla and the Vidyadhari Rivers and Herobhanga Creek (Figure 1).

During British colonial rule, a part of the Sundarban mangroves was cleared, drained and reclaimed for cultivation (Ghosh et al., 2015). The partition of India and Bangladesh led to mass

migration from Bangladesh to India. People also migrated from adjoining districts of West Bengal especially for construction of embankments. The increasing population led to the conversion of mangrove forests to agricultural land and settlements (Ghosh et al., 2015). Under the refugee rehabilitation program, from 1952 to 1960, mangrove forests on Jharkhali Island were converted into agriculture lands with ~5.655 km² of mangrove area converted for settlements and agriculture (Samanta and Hazara, 2012). In 1986, the mangroves prevalent in the southeastern part of Jharkhali Island (Ghosh et al., 2015) were converted for use in aquaculture or rice production. Manna et al. (2010 & 2013) report that about 16 km² of mangrove area were deforested and converted to agriculture and aquaculture. Agriculture and aquaculture are now the prime activities in Lot No. 126. The rice fields are on the west side whereas the shrimp ponds are located on the east side of the island (Figure 2).

The rice fields sampled were directly transformed from mangroves during the first phase of clearance, about 60 years ago. There are two rice crops a year. The Aman strain is sown in the rainy season, July-August and boro in the winter, December-January (Mistri, 2013). Aman rice cultivation requires no irrigation as the fields are inundated with the monsoon rains. Boro rice cultivation is dependent on irrigation. To sow seedlings, the farmers plough 3 cm of topsoil by hand, or use bulls or cows, and keep the stubble from the previously harvested rice plants in the field. The harvest is usually by hand. For a short period after harvests, goats and cows graze in the rice fields, but rice seedlings may be sown soon after the harvest. Due to changing rainfall patterns especially decline in rainfall, the rice production in Sundarbans is decreasing (Mistri, 2013).

The ponds are constructed for the mixed culture of fish-shrimp-crab. The ponds sampled are managed as traditional or extensive aquaculture ponds known as bhery and were built 5-7 years

before my field visit in December 2019. The ponds are 1 m deep. Four ponds were directly transformed from the mangroves whereas one pond was converted from a rice field (which had been created from drained mangroves). *Penaeus monodon* is predominantly cultured in these traditional behries. One to two crops of shrimp are produced each year. In winter the shrimp crop is substituted with crabs. The shrimp fry is obtained from hatcheries located elsewhere in West Bengal or adjacent states. The stocking density is 4-8 post-larvae/m² with no water exchange and used locally. The food consists of eggs, milk powder, multivitamin drop, shrimp meat, crab fat, etc. (Mr. D S Bhaduria, personal communication, June 2019). Due to lack of storage facilities, most of the shrimp and fish are sold locally.

2.2 Field Work

I went to India in June 2019 to conduct interviews with locals regarding land cover and land use changes, the history and pattern of human settlement, aquaculture practices, rice farming and mangroves on the Sundarbans Islands (Interviews with farmers were conducted under the permit from McGill Research Ethics Board). Then I finalised my research site and in December 2019, I collected my samples for SOC analysis.

My goal was to core the top 1 m sediment as it is more susceptible to land use change (Pendleton et al., 2012). Soil density and consistency required the use of two different coring devices. Soil cores were obtained using either a Dutch gouge auger with a 25 mm diameter or a Russian peat corer with a 55 mm diameter – both allow collection of soils with negligible compaction.

I cored five active aquaculture ponds and five active rice fields. In each aquaculture pond and rice field I took 3-5 soil cores. The cores are obtained from the corners and middle of the aquaculture pond and rice fields. The soil cores are obtained within 3-5 days of pond drainage. A

few days before the coring, the remaining shrimps and fishes in the drained ponds were hand-picked by gleaners. The gleaning activity disturbed the pond bottom which limited my research to three samples per pond.

2.3 Soil Analyses

Soils were dried at 60°C to constant weight to calculate the dry bulk density. Samples were ground with a mortar and pestle or an electric spice grinder. After grinding, sub samples were placed in crucibles and oven-dried for a minimum of 12 hours at 60°C then cooled in a desiccator before weighing, prior to performing LOI (loss-on-ignition). Samples were heated in a programmable muffle furnace at 350°C for 1 h, followed by 4 h at 550°C and then held in the furnace at 60°C until they could be transferred to a desiccator to bring to room temperature before weighing.

For pond sediments the %SOC was calculated from the LOI% using the conversion equation for mangroves by Ouyang and Lee (2020):

$$\% \text{ Soil Organic Carbon} = (0.21 \pm 0.01)LOI^{1.12 \pm 0.02}.$$

For rice field soils, SOC was calculated using the conversion factor reported by Ping and Dobermann (2006):

$$\%SOM = \%LOI \times 0.805$$

$$\text{Soil Organic Carbon} \left(\frac{g}{kg} \right) = \frac{SOM}{1.724}$$

Soil C density is calculated as:

$$\text{Soil C density} \left(\frac{g}{cm^3} \right) = \frac{\text{Soil Organic Carbon} \left(\frac{g}{kg} \right)}{1000} \times \text{Soil dry bulk density} \left(\frac{g}{cm^3} \right).$$

The C content per sample both for ponds and rice fields is calculated using,

$$C \text{ content per sample } (\frac{g}{cm^2}) = \text{Soil C density } (\frac{g}{cm^3}) \times \text{thickness (cm)}$$

Then C stock per core was normalized to the minimum depth cored which was ~50 cm as:

$$\text{Adjusted depth to 50cm} = \left(\frac{50}{\text{original depth of the core}} \right) * \text{total SOC of original core}$$

I performed statistical analysis using IBM SPSS 26. Analysis of variance (ANOVA) was used to determine if there were significant differences among soil C stocks in aquaculture ponds and rice fields. I applied a Bonferroni test for significant differences among ponds and fields.

2.4 Analysis of Google Earth Imagery

To assess the mangrove cover change in Lot No. 126, imagery was accessed through Google Earth Pro software. Using the historical imagery function from the years 2002 to 2020, seven (of 19) images were selected based on image quality and clarity. The images were acquired on 28 October 2002, 13 November 2010, 2 March 2013, 23 November 2014, 7 December 2018, 17 April 2019, and 12 February 2020. The total mapped area is 52.92 ha. All the images were taken at 662 m eye altitude. Interpretation of land cover and land use features were guided by field observations.

Chapter 3. Results and Discussion

3.1 Soil Analyses

The average SOC stock in the top 50 cm of soil within each of the five rice fields ranges from 21-27 Mg C ha⁻¹ with an overall average of 23.73 ±2.17 Mg C ha⁻¹ (Table 2). There are no significant differences among the rice field C stocks (Figure 3). This is expected, because ponds are of same age i.e. 60 years and have the same management practices, with only rice grown in these fields for 60 years.

The pond SOC in the top 50 cm of soil ranges from 21-104 Mg C ha⁻¹ with an overall average of 58.80 ±38.28 Mg C ha⁻¹ (Table 2). The average SOC stock of the ponds is higher than the rice fields. There is no significant difference between ponds 2, 4 and 5. Ponds 1 and 3 have significantly higher SOC than the other ponds and the rice fields. In fact, the average SOC stock in Ponds 1 and 3 is almost double that of the other ponds and rice fields (Figure 3).

A possible explanation for the difference between Pond 1 and other ponds and rice fields is its conversion from a rice field. Mangroves were initially cleared for the construction of a rice field that was then converted to Pond 1. Another reason could be the management of Pond 1, which differs from the other ponds. Pond 2, 4, and 5 are managed under extensive aquaculture, that is, they receive little or no input of feed or fertiliser while Pond 1 is managed under semi-intensive aquaculture that includes fertilization, supplementary feeding, and mid-level technology. Pond 3 also is managed under extensive aquaculture, yet also has significantly higher SOC stock than the other ponds. It is possible that since the ponds were recently converted from the mangroves, the cores in Pond 3 may have included some of the original mangrove soil. The high amount of SOC in Pond 1 also suggests that maybe the different aquaculture practices (extensive, semi

intensive and intensive) could result in differing SOC stocks. If so, semi-intensive aquaculture may be better than extensive in terms of SOC storage.

Donato et al. (2011) reported an average SOC stock in the Sundarbans mangroves of 438.90 Mg C ha⁻¹ over 300 cm depth. Normalizing this value to be comparable to the 50 cm depth used in my study, gives an average SOC of 73.15 Mg C ha⁻¹. If I assume that this value is representative of the soils of Jharkhali Island prior to mangrove clearance, then 14.35 Mg C ha⁻¹ was lost through pond conversion and 49.42 Mg C ha⁻¹ through conversion to rice fields (Figure 4). Hence, loss of SOC from conversion of mangroves to aquaculture ponds and rice fields is 19.6% and 67.5%, respectively.

Previous studies have reported the loss of SOC stocks from conversion of mangroves to aquaculture ponds and rice fields ranging from 40 to 312 Mg C ha⁻¹ and 21 Mg C ha⁻¹, respectively (adjusted to 50 cm depth) (Figure 5). The measurements in mangroves transformed to aquaculture ponds are based on Kauffman and Donato (2012). Although the methodology for calculating the OC is same in all of these studies, the SOC content varied substantially.

All the previous studies use an elemental analyzer for measuring the SOC in samples from mangroves and mangrove transformed aquaculture ponds. My study measures the SOC content using LOI. Richards et al. (2020) suggest that the OC in soil samples may have been significantly over-estimated due to unsuitable conversion factors. Ouyang and Lee (2020) compared the conversion factors for LOI to OC to results from an elemental analyzer and suggest the following conversion:

$$OC = 0.21 * LOI^{1.12}$$

Application of conversion factor by Ouyang and Lee (2020) resulted in estimates of loss of mangrove SOC stocks in the South East Asia to be 35% lower (Richards et al., 2020). The revision in conversion factor not only changes the numbers of SOC loss but also the way we look at conversion and land use change of mangrove ecosystem.

The aquaculture ponds in all the previous studies were abandoned except in Honduras (Kauffman et al., 2017), Brazil (Kauffman et al., 2018) and Indonesia (Cameron et al., 2019), where they were active at the time of sampling. The SOC measured in Honduras was 50.12 Mg C ha⁻¹ and Brazil was 67.47 Mg C ha⁻¹, similar to the average of 58.80 Mg C ha⁻¹ that I measured in West Bengal. The 332.90 Mg C ha⁻¹ measured in Indonesia, however, was five or more times greater than what I measured in West Bengal or what was measured in Brazil or Honduras. The status of ponds could be an explanation for substantial difference in the SOC stocks, but the nature of pond management was not consistently reported.

The IPCC guidelines for loss of mangroves through conversion to aquaculture ponds (Kennedy et al., 2014) provide a default value of 471 Mg C ha⁻¹ for mangrove SOC stocks to a depth of 1 m. The guidelines provide no estimates for SOC stocks of active or abandoned ponds. Applying the IPCC default value for SOC in mangroves adjusted to a depth of 50 cm, (i.e. 235.50 Mg C ha⁻¹) would result in an SOC loss of 176.7 Mg C ha⁻¹. This SOC loss is much more than that calculated using the SOC stock value of Sundarbans mangrove by Donato et al. (2011) i.e. 14.35 Mg C ha⁻¹.

Conversion to rice fields was one of the major causes of mangrove loss, but the IPCC guidelines (Ogle et al., 2019) include only one study that of Andreetta et al. (2016) for SOC loss from conversion of mangroves to rice fields. Andreetta et al. (2016) measured SOC stocks from two active and two abandoned rice fields in Northern Guinea-Bissau. They reported an average SOC

of 21 Mg C ha⁻¹ which is slightly lower than the 24 Mg C ha⁻¹ measured on Jharkhali Island (Figure 5). Like aquaculture ponds, additional studies in rice fields are merited to assess the loss of SOC stocks from conversion of mangroves.

The SOC stocks of mangroves varies regionally (Kauffman & Bhomia 2017). Thus, regional SOC stocks of mangroves should be used to calculate the loss of soil C from aquaculture ponds and rice fields. As these measurements varied substantially, we clearly need more research and data on SOC loss from conversion of mangroves to aquaculture ponds and rice fields.

3.2 Landscape Change Analysis from 2002 to 2020

The fieldwork elicits personal observations and oral histories which combined with Google Earth Pro's imagery shows two decades of mangrove deforestation and land cover change in Lot No.126 (Table 3). The earliest image available, taken in 2002, shows a dyke (Point E) paralleling the eastern shore of the channel (Point F). Irregular networks of dykes are visible on both sides of the channel, presumably in preparation for drainage of the land they surround. Mangroves are visible on the channel sides of the dykes and mangroves or mudflat still remain within the dyked areas (Figure 6).

By 2010, 8 years later, a new, 6 m wide dyke (Point H) is visible on west side of the channel. The dyke at Point E has been fortified and a tidal gate has been installed at Point G. The area around Point I is drained and under cultivation. Initial pond construction is apparent between Points B and H. Human settlements have been constructed around point J (Figure 7).

Three years later, in 2013, a 2 m wide causeway from Point C to Point E is evident. The area around Points H and A is more drained compared to previous years. Small waterbodies inland of

the dyke (around Points H, I, and J) can be seen within the now extensively drained area (Figure 8).

In 2014, more polygonal structures are visible between and around Points A, B and H. The small causeway between Points C and E is flooded by the high tide. Much of the area north of Point I is visible as rice fields. Denser human settlement is also visible around point J (Figure 9).

Four years later, by 2018, major changes can be seen around Points A, B and C as most of the area north of the causeway is deforested, drained and converted to polygonal units. The causeway from Point C to E and is now 7 m wide. The dyke identified by Point H is broadened and continues till the end of the newly created pond at Point A. Further subdivisions are visible in big pond at Point A. Regulation of tidal water flow in the channel is now obvious, as the causeway holds back tidal water to the south. Human settlement is now visible around Point B (Figure 10).

By 2019, Point A is a large pond having inlet and outlet for tidal water (Figure 11). By the next year, in 2020, the pond Point A is sub-divided into small ponds. North of the causeway between Points C an additional causeway has been placed across the channel (Figure 12). Evidently, the areas represented by Points A, B and F are converted to aquaculture ponds. Dykes or embankments represented by Point C and H are transformed to roads. Point E is tidal gate. Area around Point I is converted to rice fields, and the structures associated with human settlement in the areas near Points D and J have grown.

3.2.1 Road and dyke construction

Parallel to the conversion of mangrove forest to aquaculture ponds and rice fields, the road network also expanded. Initially, dykes were constructed to prevent tidal flooding of the fields

and ponds. But over the years, a few dykes were broadened and ultimately transformed to roads (represented by Point C, E, and H). Locally they are known as ‘Kuccha’/ ‘Kacha’ roads or dirt roads as they are unpaved. These roads facilitate the movement of construction material and machinery, enhancing the rapid landscape change of this area. Today the road between Point C and H are one of the major Kuccha roads, connecting ponds and human settlements.

3.2.2 Aquaculture ponds

The whole mangrove belt in the western area is converted to aquaculture ponds (around Point A and B). The aquaculture ponds are traditional or extensive farming types with a mixed culture of fish-shrimp-crab. These traditional or extensive ponds require less input in terms of labor and capital hence preferred by farmers compared to other intensive aquaculture farming (Fast & Lester, 1992). As shrimp can tolerate salinities from 5 to 40 ppt (Kungvankij et al., 1986), the newly converted areas are immediately suitable for shrimp farming. The development of aquaculture ponds is visible in recent years (2018-2020 around Point A, B, C and H) (Figure 10 and 12) owing to the reason that aquaculture farming is among high income generating sectors.

About 22.82% of the area is converted from mangroves to aquaculture ponds which is 12.08 ha. In this area total 72 aquaculture ponds were constructed (Figure 13). Applying the SOC stock for aquaculture ponds I calculated in this area, indicates that a minimum of 710.48 Mg C was lost through aquaculture development alone.

3.2.3 Rice fields

The rice fields are visible around 2010, earlier than the aquaculture ponds. They are predominant on the western side of the channel. Around 2010, when the area was still draining, rice fields can be seen as dark brown colored polygonal patches. During the harvest season, the rice fields turn

brown and characterized by the bundles of rice stalk tied together (Figure 7 and 9). As rice crops are grown in freshwater, a drainage channel (Point G) was needed to drain the saline water from the area.

About 25.62% of mangrove area is converted to rice fields. I mapped 47 rice fields in the google earth imagery which covers an area of 13.56 ha (Figure 14). Applying the SOC stock for rice fields I calculated in this area, indicates that a minimum of 321.97 Mg C was lost through conversion of mangroves to rice fields.

3.2.4 Human settlement

The first sign of human settlement in this particular area is apparent in 2010. Although the majority of the human settlement is visible around Point D and J, with development of aquaculture ponds in the area, human settlement is established around Point B and C also. The houses and sheds near the field and ponds are visible. The use of structures for storage is not apparent from the Goggle Earth imagery but were noticed during my field visit (near to Point C). It has been suggested that human settlement leads to agriculture and aquaculture expansion (Ghosh et al., 2015; Samanta & Hazara, 2012) but, considering the recently transformed area of Lot No. 126 I analyzed, the expansion of aquaculture and agriculture has preceded human settlement. This is because people started leasing and occupying this lowland area once it was drained and suitable for agriculture and aquaculture purposes.

Chapter 4. Conclusions

The measurements of SOC stocks in active shrimp aquaculture ponds and rice fields in this study are the first for these mangrove transformations of the Sundarbans. My research found that the average SOC in the top 50 cm of soil in aquaculture ponds is $59 \pm 38 \text{ Mg C ha}^{-1}$ whereas in the rice fields it is $24 \pm 2 \text{ Mg C ha}^{-1}$. The SOC lost from conversion of Sundarbans mangroves to aquaculture ponds is 14 Mg C ha^{-1} and through conversion to rice fields is 49 Mg C ha^{-1} . Hence, loss of soil C from conversion of mangroves to aquaculture ponds and rice fields is 20% and 68%, respectively.

The landscape of Lot No. 126 region is mosaic of aquaculture ponds, rice fields, mangroves and human settlements. The eastern side of the channel is dominated by rice fields whereas the western side by aquaculture ponds. The drainage of mangrove forest had already begun by 2002. The rapid landcover change was apparent from 2002-2010 and then from 2014-2018, when remaining mangroves were deforested and drained. Construction of dykes or embankments further led to construction of roads which helped in advancing the landscape change by movement of construction material and machinery. The size of the area in Lot No. 126, mapped through google earth imagery is 53 ha. In the mapped area 12.08 ha (23%) is lost for construction of aquaculture ponds and 14 ha (26%) is lost to rice fields. The SOC loss is of 322 Mg C through conversion of mangroves to rice fields and 710 Mg C through construction of aquaculture ponds.

The main limitation of my research is the age dissimilarity between aquaculture ponds and rice fields. The aquaculture ponds are relatively young (5-7 years old) compared to the rice fields (60 years). Further study that includes younger rice fields is needed to determine if one land use change is less detrimental in terms of SOC loss.

To understand the soil C loss from land use change in mangrove forests, there should be more comparisons of SOC stocks in active and abandoned ponds with control for the longevity of ponds and the management system used. Such additional research is needed to determine if the higher SOC storage found in the semi-intensive aquaculture pond I sampled is indeed due to management regime. As importantly, more data needs to be collected from mangrove to rice field conversions over varied periods of drainage to better compare the changes in SOC stock in the two types of land use change. I believe that my study is the first to measure SOC in ponds converted from rice fields. As pressures from reduced rice yields and greater income from aquaculture are likely to continue to drive this type of conversion, it is just as important to study changes in its impact on SOC.

These landscape transformations may impact fluxes of other, more potent greenhouse gases, i.e., methane and nitrous oxide. To properly compare the impact of conversion of mangroves to rice or aquaculture, or rice to aquaculture examination of fluxes of these greenhouse gases also should be undertaken.

The data collected in my research helps to refine the IPCC estimates (Kennedy et al. 2013; Ogle et al., 2019) for assessment of SOC loss from mangrove transformation to active aquaculture ponds and rice fields. It will also support the national inventories of greenhouse gases (GHG) emissions and inform national land use policies relevant to climate change mitigation. The results from research on Jharkhali Island can be used for calculation of GHG emissions, carbon dynamics in changed landscapes, and design C offset strategies in coastal wetlands.

References

- Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Management*, 3(3), 313–322. <https://doi.org/10.4155/cmt.12.20>
- Andreetta, A., Huertas, A. D., Lotti, M., & Cerise, S. (2016). Land use changes affecting soil organic carbon storage along a mangrove swamp rice chronosequence in the Cacheu and Oio regions (northern Guinea-Bissau). *Agriculture, Ecosystems & Environment*, 216, 314–321. <https://doi.org/10.1016/j.agee.2015.10.017>
- Arifanti, V. B., Kauffman, J. B., Hadriyanto, D., Murdiyarso, D., & Diana, R. (2019). Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: The case of the Mahakam Delta, Indonesia. *Forest Ecology and Management*, 432, 17–29. <https://doi.org/10.1016/j.foreco.2018.08.047>
- Ashton, E. (2008). The impact of shrimp farming on mangrove ecosystems. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 3(003), 12. <https://doi.org/10.1079/pavsnr20083003v>
- Aziz, A., & Paul, A. (2015). Bangladesh Sundarbans: Present status of the environment and biota. *Diversity*, 7(3), 242–269. <https://doi.org/10.3390/d7030242>
- Bhomia, R. K., MacKenzie, R. A., Murdiyarso, D., Sasmito, S. D., & Purbopuspito, J. (2016). Impacts of land use on Indian mangrove forest carbon stocks: Implications for conservation and management. *Ecological Applications*, 26(5), 1396–1408. <https://doi.org/10.1890/15-2143>
- Bunting, P., Rosenqvist, A., Lucas, R., Rebelo, L.-M., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., & Finlayson, C. (2018). The Global Mangrove Watch—A New 2010

Global Baseline of Mangrove Extent. *Remote Sensing*, 10(10), 1669.

<https://doi.org/10.3390/rs10101669>

Cameron, C., Hutley, L. B., Friess, D. A., & Brown, B. (2018). Community structure dynamics and carbon stock change of rehabilitated mangrove forests in Sulawesi, Indonesia. *Ecological Applications*, 29(1), 1810. <https://doi.org/10.1002/eap.1810>

Castillo, J. A. A., Apan, A. A., Maraseni, T. N., & Salmo, S. G. (2017). Soil C quantities of mangrove forests, their competing land uses, and their spatial distribution in the coast of Honda Bay, Philippines. *Geoderma*, 293, 82–90. <https://doi.org/10.1016/j.geoderma.2017.01.025>

Cornforth, W., Fatoyinbo, T., Freemantle, T., & Pettorelli, N. (2013). Advanced land observing satellite phased array type L-Band SAR (ALOS PALSAR) to inform the conservation of mangroves: Sundarbans as a case study. *Remote Sensing*, 5(1), 224–237.

<https://doi.org/10.3390/rs5010224>

Directorate of Census Operations West Bengal. (2011). *District Census Handbook South Twenty-four Parganas*. Manager, Government of India Press (Series-20).

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297. <https://doi.org/10.1038/ngeo1123>

Duke, N. C., Meynecke, J.-O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K. C., Field, C. D., Koedam, N., Lee, S. Y., Marchand, C., Nordhaus, I., & Dahdouh-Guebas, F. (2007). A world without mangroves? *Science*, 317(5834), 41b–42b. <https://doi.org/10.1126/science.317.5834.41b>

- Ellison, A. M., Mukherjee, B. B., & Karim, A. (2000). Testing patterns of zonation in mangroves: scale dependence and environmental correlates in the Sundarbans of Bangladesh. *Journal of Ecology*, 88(5), 813–824. <https://doi.org/10.1046/j.1365-2745.2000.00500.x>
- FAO (1988). Definition of aquaculture, Seventh Session of the IPFC Working Party of Experts on Aquaculture, IPFC/WPA/WPZ, p.1-3, RAPA/FAO, Bangkok.
- Fast, A. W., Lester, L. J. (1992). Marine Shrimp Culture: Principles and Practices Development in Aquaculture and Fisheries Sciences. Fast AW & Lester LJ (eds.), Volume 23. *Developments in Aquaculture and Fisheries Science*, Elsevier. Amsterdam, 349-361.
- Food, Fisheries Agriculture Organization of the United Nations, and Aquaculture Department (2016). The State of World Fisheries and Aquaculture: Contributing to Food Security and Nutrition for All. State of World Fisheries and Aquaculture, 1020-5489; 2016. Rome: Food and Agriculture Organization of the United Nations.
- Ghosh, A., Schmidt, S., Fickert, T., & Nüsser, M. (2015). The Indian Sundarban mangrove forests: History, utilization, conservation strategies and local perception. *Diversity*, 7(2), 149–169. <https://doi.org/10.3390/d7020149>
- Ghosh, M., Kumar, L., & Roy, C. (2016). Mapping long-term changes in mangrove species composition and distribution in the Sundarbans. *Forests*, 7(12), 305. <https://doi.org/10.3390/f7120305>
- Giri, C., Long, J., Abbas, S., Murali, R. M., Qamer, F. M., Pengra, B., & Thau, D. (2015). Distribution and dynamics of mangrove forests of South Asia. *Journal of Environmental Management*, 148, 101–111. <https://doi.org/10.1016/j.jenvman.2014.01.020>

Goldberg, L., Lagomasino, D., Thomas, N., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. *Global Change Biology*, 26(10), 5844–5855.

<https://doi.org/10.1111/gcb.15275>

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., Pidgeon, E. (2014). Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.

Kauffman, J. B., & Donato, D. C. (2012). *Protocols for the measurement, monitoring and reporting of structure, biomass, and carbon stocks in mangrove forests* (50). Bogor, Indonesia: CIFOR.

Kauffman, J. B., Heider, C., Norfolk, J., & Payton, F. (2014). Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecological Applications*, 24(3), 518–527. <https://doi.org/10.1890/13-0640.1>

Kauffman, J.B., Arifanti, V. B., Hernández Trejo, H., del Carmen Jesús García, M., Norfolk, J., Cifuentes, M., Hadriyanto, D., & Murdiyarso, D. (2017). The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. *Frontiers in Ecology and the Environment*, 15(4), 183–188. <https://doi.org/10.1002/fee.1482>

Kauffman, J. B., & Bhomia, R. K. (2017). Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: global and regional comparisons. *PloS one*, 12(11), e0187749.

Kauffman, J. B., Bernardino, A. F., Ferreira, T. O., Bolton, N. W., Gomes, L. E. O., & Nobrega, G. N. (2018). Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in

northeastern Brazilian mangroves. *Ecology and Evolution*, 8(11), 5530–5540.

<https://doi.org/10.1002/ece3.4079>

Kennedy, H., D.M. Alongi, A. Karim, G. Chen, G.L. Chmura, S. Crooks, J.G. Kairo, B. Liao, G. Lin, and T.G. Troxler. (2014). Chapter 4: Coastal Wetlands. IN: *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Published: IPCC, Switzerland.

Kongkeo, H. (1997). Comparison of intensive shrimp farming systems in Indonesia, Philippines, Taiwan and Thailand. *Aquaculture Research*, 28(10), 789–796. <https://doi.org/10.1111/j.1365-2109.1997.tb01003.x>

Kungvankij, P., Chua, T. E., Pudadera Jr, B. J., Corre, K. G., Borlongan, E., Tiro Jr, L. B., ... & Talean, G. A. (1986). Shrimp culture: pond design, operation and management. Selected publication no. 2 for commemorating World Food Day 1986.

Manna, S., Chaudhuri, K., Bhattacharyya, S., & Bhattacharyya, M. (2010). Dynamics of Sundarban estuarine ecosystem: eutrophication induced threat to mangroves. *Saline Systems*, 6(1), 8. <https://doi.org/10.1186/1746-1448-6-8>

Manna, S., Mondal, P.P., Mukhopadhyay, A., Akhand, A., Hazra, S. and Mitra, D., (2013). Vegetation cover change analysis from multi-temporal satellite data in Jharkhali Island, Sundarbans, India. *Indian Journal of Geo-Marine Sciences* 42(3), 331-342.

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: toward an improved

understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, 9(10), 552–560. <https://doi.org/10.1890/110004>

Mistri, A. (2013). Migration and sustainable livelihoods: a study from Sundarban biosphere reserve. *Asia Pacific Journal of Social Sciences*, 5(2), 76-102.

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S., & Kurnianto, S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, 5(12), 1089–1092. <https://doi.org/10.1038/nclimate2734>

Ogle, S. M., McConkey, J., Baldock, J., Kishimoto, A. Mo., Chirinda, N., Bernoux, M., Hergoualc’h, K., Ishizuka, S., Pan, X., Regina, K., Vazquez-Amabile, G., Wang, C., Alsaker, C., Corre, M. D., Gurung, R., Lehmann, J., Mori, A., van Straaten, O., Veldkamp, E., & Woolf, D. (2019). Chapter 5: Cropland. IN: *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, Switzerland.

Ojima, D. S., Galvin, K. A., & Turner, B. L. (1994). The global impact of land-use change. *BioScience*, 44(5), 300-304.

Ouyang, X., & Lee, S. Y. (2020). Improved estimates on global carbon stock and carbon pools in tidal wetlands. *Nature Communications*, 11(1), 1–7. <https://doi.org/10.1038/s41467-019-14120-2>

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., Craft, C., Fourqurean, J. W., Kauffman, J. B., Marbà, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., & Baldera, A. (2012). Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE*, 7(9), e43542.

<https://doi.org/10.1371/journal.pone.0043542>

Ping, J. L., & Dobermann, A. (2006). Variation in the precision of soil organic carbon maps due to different laboratory and spatial prediction methods. *Soil Science*, 171(5), 374-387.

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., Farnsworth, E. J., Fernando, E. S., Kathiresan, K., Koedam, N. E., Livingstone, S. R., Miyagi, T., Moore, G. E., Ngoc Nam, V., Ong, J. E., Primavera, J. H., Salmo, S. G., Sanciangco, J. C., Sukardjo, S., Yong, J. W. H. (2010). The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS ONE*, 5(4), e10095.

<https://doi.org/10.1371/journal.pone.0010095>

Pramanik, M. K. (2015). Changes and status of mangrove habitat in Ganges Delta: case study in Indian part of Sundarbans. *Forest Research: Open Access*, 4(3).

Primavera, J. H. (1995). Mangroves and brackishwater pond culture in the Philippines. *Hydrobiologia*, 295(1–3), 303–309. <https://doi.org/10.1007/bf00029137>

Rahman, M. M., Rahman, M. M., & Islam, K. S. (2010). The causes of deterioration of Sundarban mangrove forest ecosystem of Bangladesh: conservation and sustainable management issues. *Aquaculture, Aquarium, Conservation & Legislation*, 3(2), 77-90.

Rahman, M. R., & Asaduzzaman, M. (2013). Ecology of Sundarban, Bangladesh. *Journal of Science Foundation*, 8(1–2), 35–47. <https://doi.org/10.3329/jsf.v8i1-2.14618>

Richards, D. R., Thompson, B. S., & Wijedasa, L. (2020). Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. *Nature Communications*, 11(1), 1–7. <https://doi.org/10.1038/s41467-020-18118-z>

Rönnbäck, P. (1999). The ecological basis for economic value of seafood production supported by mangrove ecosystems. *Ecological Economics*, 29(2), 235–252. [https://doi.org/10.1016/S0921-8009\(99\)00016-6](https://doi.org/10.1016/S0921-8009(99)00016-6)

Samanta, K., & Hazra, S. (2012). Landuse/landcover change study of Jharkhali Island Sundarbans, West Bengal using remote sensing and GIS. *International Journal of Geomatics and Geosciences*, 3(2), 299-306.

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M. F., Benson, L., Bukoski, J. J., Carnell, P., Cifuentes-Jara, M., Donato, D., Duncan, C., Eid, E. M., Ermgassen, P., Lewis, C. J. E., Macreadie, P. I., Glass, L., Gress, S., Jardine, S. L., Jones, T. G., Nsombo, E. N., Rahman, M. M., Sanders, C. S., Spalding, M., Landis, E. (2018). A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environmental Research Letters*, 13(5), 055002. <https://doi.org/10.1088/1748-9326/aabe1c>

Sasmito, S. D., Taillardat, P., Clendenning, J. N., Cameron, C., Friess, D. A., Murdiyarso, D., & Hutley, L. B. (2019). Effect of land-use and land-cover change on mangrove blue carbon: A systematic review. *Global Change Biology*, 25(12), 4291–4302. <https://doi.org/10.1111/gcb.14774>

Tacon, A. G. (2002). Thematic review of feeds and feed management practices in shrimp aquaculture. *Report prepared under the World Bank, NACA, WWF and FAO consortium program on shrimp farming and the environment. Work in Progress for Public Discussion. Published by the Consortium*, 69.

Tripathi, R., Shukla, A. K., Shahid, M., Nayak, D., Puree, C., Mohanty, S., Raja, R., Lal, B., Gautam, P., Bhattacharyya, P., Panda, B. B., Kumar, A., Jambhulkar, N. N., & Nayak, A. K.

(2016). Soil quality in mangrove ecosystem deteriorates due to rice cultivation. *Ecological Engineering*, 90, 163–169. <https://doi.org/10.1016/j.ecoleng.2016.01.062>

Valiela, I., Bowen, J. L., & York, J. K. (2001). Mangrove Forests: One of the World's Threatened Major Tropical Environments: At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. *Bioscience*, 51(10), 807-815.
[https://doi.org/10.1641/0006-3568\(2001\)051\[0807:MFOOTW\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2)

Tables

Table 1

Studies on clearance of mangroves for aquaculture and agriculture.

Research site	Land use	Average Soil Core Depth (cm)	No. of ponds	Soil C stock (Mg C ha ⁻¹)	Study
Northern Guinea- Bissau	Rice	85	4	32 ±3 to 37 ±2	Andreetta et al., 2016
Dominican Republic	Aquaculture	71	5	96	Kauffman et al., 2014
India	Aquaculture	70	2	61 ±8	Bhomia et al., 2016
Costa Rica, Honduras, Indonesia	Aquaculture	300	-	352 ±50	Kauffman et al., 2017
Philippines	Aquaculture	84	3	454 ±32	Castillo et al., 2017
Brazil	Aquaculture	102	3	37 ±282	Kauffman et al., 2018
Mahakam Delta, Indonesia	Aquaculture	190	10	486 ±55	Arifanti et al., 2019
Tanakeke Island and Tiwoho, Indonesia	Aquaculture	62	2	115 ±18 to 666 ±59	Cameron et al., 2019

Table 2

Soil C stock (Mg C ha⁻¹) in aquaculture ponds and rice fields with ± 1 standard deviation.

Site	Type	Soil C stock (Mg C/ha)
JHP1	Aquaculture pond	104 $\pm$ 38
JHP2	Aquaculture pond	34 $\pm$ 4
JHP3	Aquaculture pond	96 $\pm$ 15
JHP4	Aquaculture pond	21 $\pm$ 2
JHP5	Aquaculture pond	39 $\pm$ 4
JHR1	Rice field	24 $\pm$ 7
JHR2	Rice field	24 $\pm$ 3
JHR3	Rice field	27 $\pm$ 3
JHR4	Rice field	23 $\pm$ 5
JHR5	Rice field	21 $\pm$ 5

Table 3*Definition of features identified from Google Earth images*

Feature	Definition	Structure
Mangrove cover	Salt tolerant trees along the water/tidal channel	Green colored patches of continuous or discontinuous canopy
Mudflats	Intertidal areas without macrophyte vegetation	Light brown muddy feature within and around mangroves
Drainage channel	Constructed passage through which water flows	Eroded brown colored structure with lines formed towards the direction of the water drain
Aquaculture ponds	Shrimp and fishponds	Polygonal structures filled with water
Agriculture fields	Rice or paddy fields	Polygonal green colored structures. During the harvesting season these structures turns brown and characterized by the bundles of rice stalk tied together
Human settlements	House, shops, storage spaces, shed for animals, small processing units etc.	Orange, white and grey colored structures
Dykes and roads	A long wall or embankment to avoid intertidal water	Long continuous brown colored lines

Figures

Figure 1

Location of Lot No. 126, Jharkhali Island, India. Lot No. 126 is surrounded by the Matla and the Vidyadhari Rivers and Herobhanga Creek.

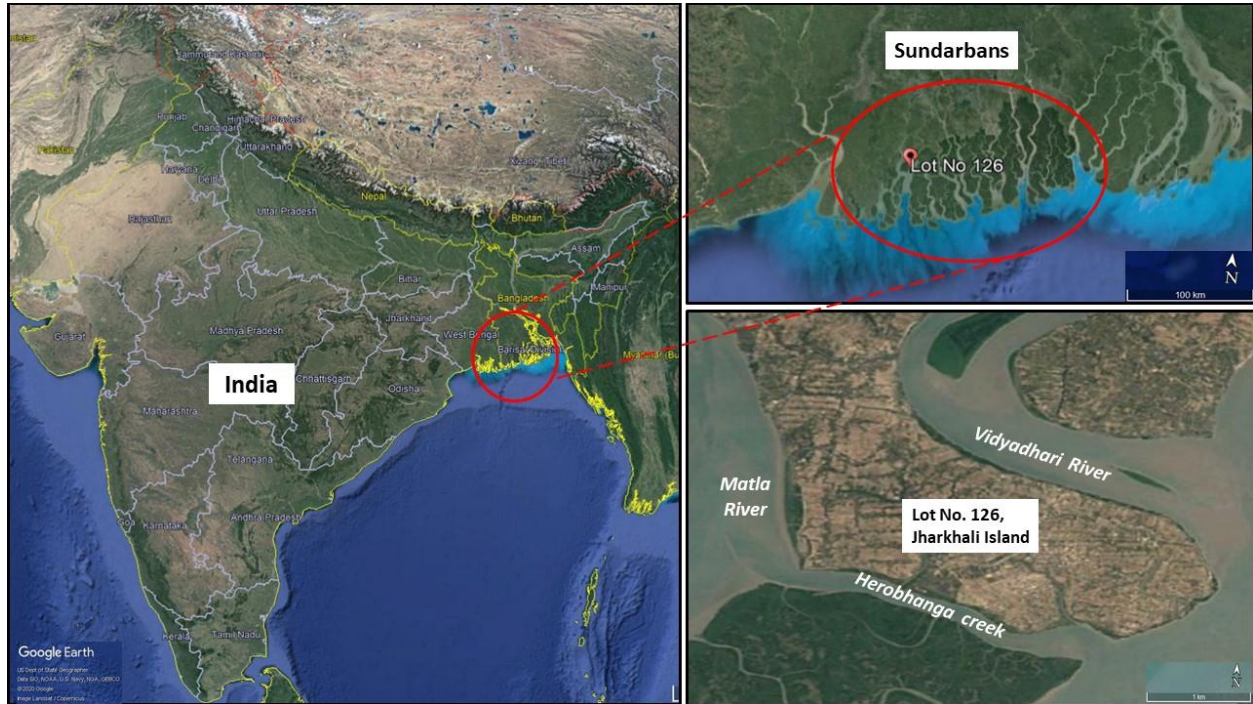


Figure 2

Location of rice fields and aquaculture ponds in Lot No. 126, Jharkhali Island, India.



Figure 3

Soil carbon stocks (Mg C ha^{-1}) of aquaculture ponds and rice fields, adjusted to the depth of 50 cm in Lot No. 126, Jharkhali Island, India. Means labelled with the same letter are not significantly different.

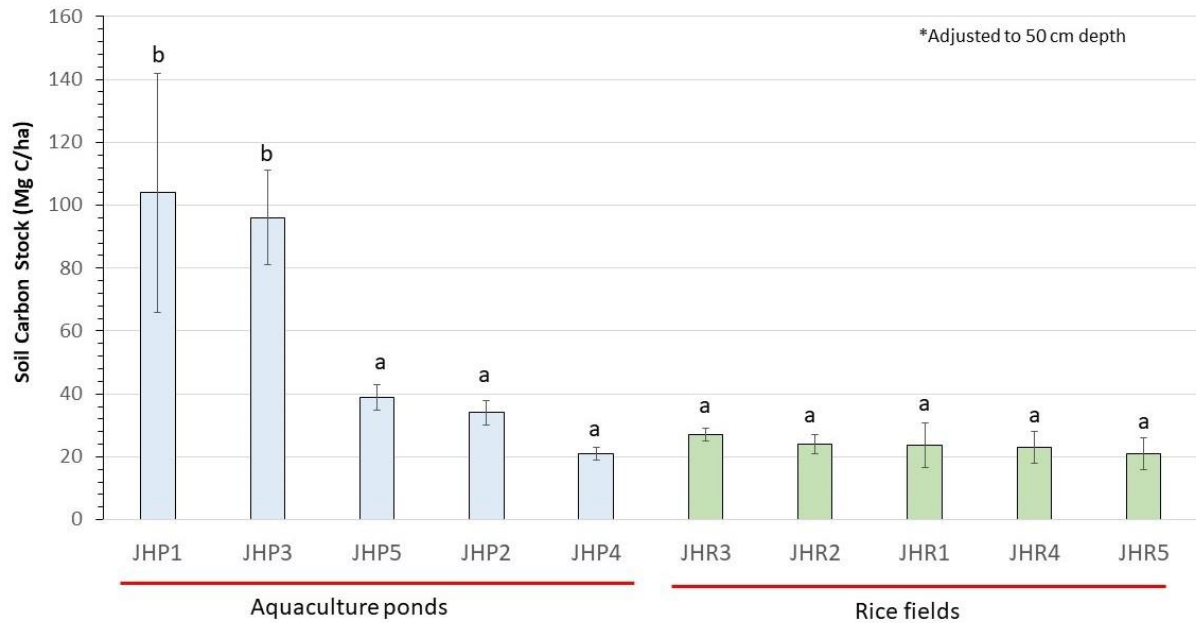


Figure 4

Amount of SOC loss (Mg C ha^{-1}) from conversion of Sundarbans mangroves (green bar) to aquaculture ponds and rice fields (grey bar).

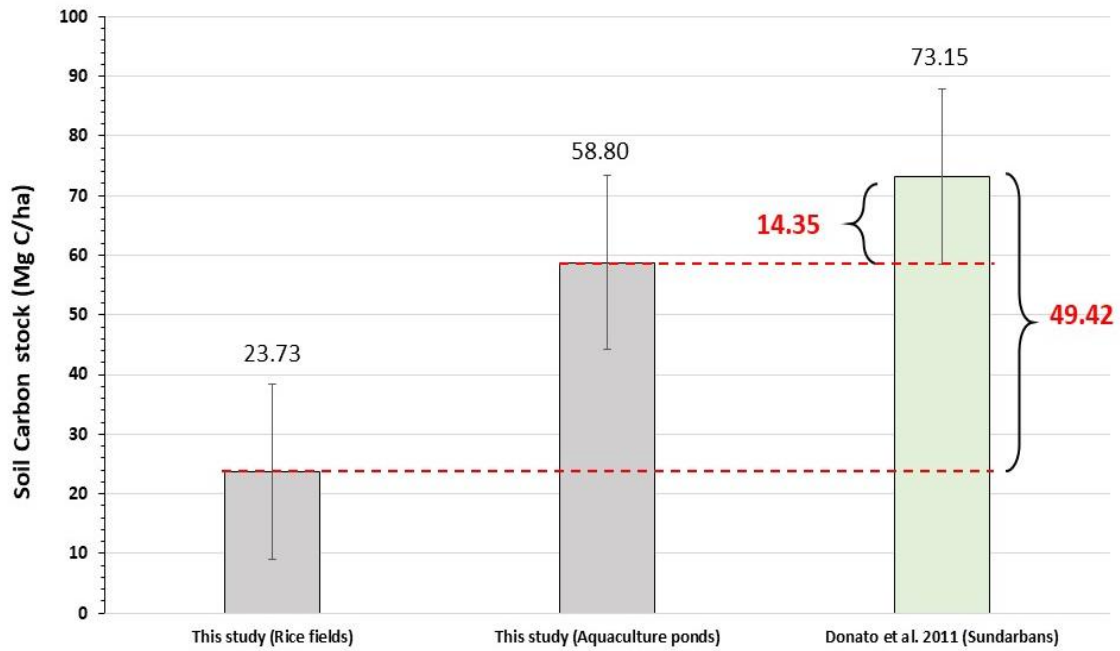


Figure 5

Comparison of SOC stocks (Mg C ha^{-1}) in different studies.

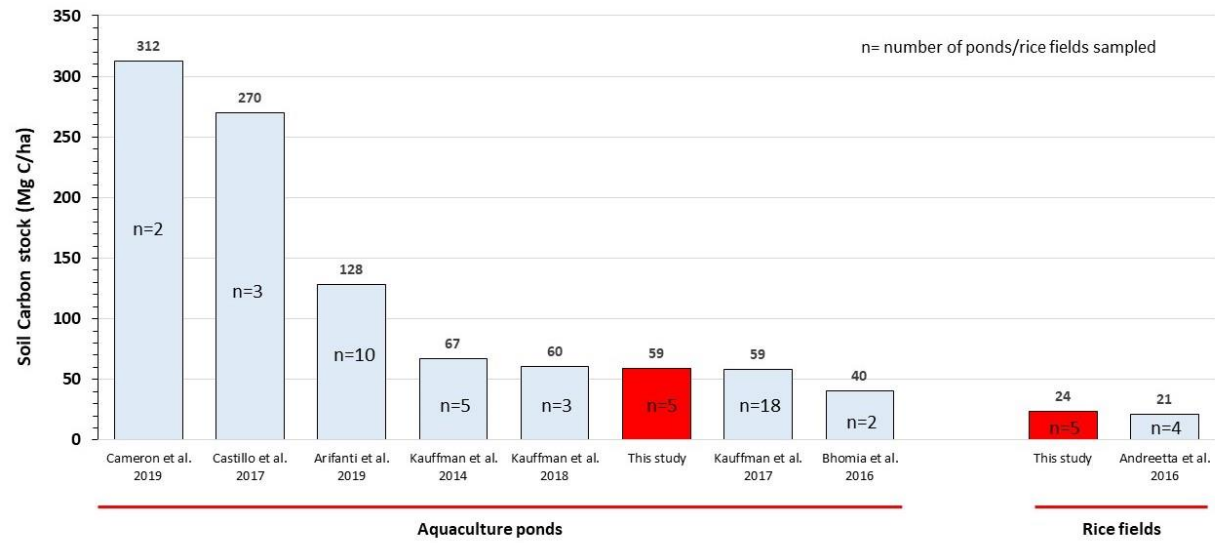


Figure 6

Google Earth image on 28 October 2002 showing the mangrove forest and mudflats.



Figure 7

Google Earth image on 13 November 2010 showing drainage channel (Point G).



Figure 8

Google Earth image on 2 March 2013 showing small embankment across Point C and E.



Figure 9

Google Earth image on 23 November 2014 showing polygonal structures around Point A, B and H. Rice fields are also apparent (Point I).



Figure 10

Google Earth image on 7 December 2018 showing major deforestation around Point A, B and C. Embankment across Point C and E is also visible.



Figure 11

Google Earth image on 17 April 2019 showing tidal gate (Point E), and inlets and outlets in ponds (Point A).



Figure 12

Google Earth image on 12 February 2020 showing subdivision of large ponds (Point A, B and around Point H) and long channel (Point F).



Figure 13

Google Earth image on 12 February 2020 showing area of mapped ponds as white borders.



Figure 14

Google Earth image on 12 February 2020 showing area of mapped rice fields as white borders.



Appendix

Appendix 1

Table 1. Data from soil cores collected during fieldwork in Lot No. 126, Jharkhali island, India.

Ponds are designated by the letter P and rice fields by the letter R.

Core Segment					
Core	Core length (cm)	Upper depth (cm)	Lower depth (cm)	Bulk Density (g cm ⁻³)	% LOI
JHP1A	74.0	0.0	74.0	1.353	4.136
JHP1B	78.0	0.0	5.0	0.478	3.914
JHP1B	78.0	5.0	15.0	1.053	3.658
JHP1B	78.0	15.0	30.0	1.233	4.056
JHP1B	78.0	30.0	50.0	1.382	3.853
JHP1B	78.0	50.0	78.0	1.446	4.413
JHP1C	77.5	0.0	5.0	0.688	4.375
JHP1C	77.5	5.0	15.0	2.000	4.194
JHP1C	77.5	15.0	30.0	2.863	4.270
JHP1C	77.5	30.0	50.0	3.097	4.545
JHP1C	77.5	50.0	77.5	2.535	6.377
JHP1D	64.5	0.0	17.0	1.646	5.757
JHP1D	64.5	17.0	64.5	2.079	4.383
JHP1E	75.0	0.0	20.5	1.648	3.728
JHP1E	75.0	20.5	51.0	2.364	5.660
JHP1E	75.0	51.0	55.0	2.194	5.128
JHP1E	75.0	55.0	75.0	2.191	5.021
JHP2A	100.0	0.0	6.5	0.413	6.036
JHP2A	100.0	6.5	32.0	0.538	5.284
JHP2A	100.0	32.0	50.0	0.596	4.714
JHP2A	100.0	50.0	100.0	0.632	4.409
JHP2B	100.0	0.0	8.5	0.391	4.804
JHP2B	100.0	8.5	21.5	0.508	6.048
JHP2B	100.0	21.5	50.0	0.503	6.120
JHP2B	100.0	50.0	100.0	0.561	4.715
JHP2C	100.0	0.0	5.0	0.331	4.118
JHP2C	100.0	5.0	50.0	0.515	4.638
JHP2C	100.0	50.0	100.0	0.579	4.665
JHP3A	74.5	0.0	23.5	1.941	4.205
JHP3A	74.5	23.5	41.5	1.280	3.842

Appendix 1, Table 1, continued...

Core	Core length (cm)	Upper depth (cm)	Lower depth (cm)	Bulk Density (g/cm³)	% LOI
JHP3A	74.5	41.5	74.5	2.402	3.923
JHP3B	70.0	0.0	16.0	1.167	3.923
JHP3B	70.0	16.0	32.0	1.717	3.987
JHP3B	70.0	32.0	70.0	2.544	3.619
JHP3C	90.0	0.0	90.0	1.824	4.876
JHP4A	50.0	0.0	8.5	0.228	4.487
JHP4A	50.0	8.5	16.5	0.369	4.155
JHP4A	50.0	16.5	50.0	0.635	2.746
JHP4B	50.0	0.0	8.5	0.320	3.982
JHP4B	50.0	8.5	31.5	0.440	3.650
JHP4B	50.0	31.5	50.0	0.622	3.903
JHP4C	50.0	0.0	10.0	0.327	3.965
JHP4C	50.0	10.0	29.0	0.423	4.193
JHP4C	50.0	29.0	50.0	0.624	3.349
JHP5A	50.0	0.0	12.0	0.335	4.046
JHP5A	50.0	12.0	47.0	0.469	8.085
JHP5A	50.0	47.0	50.0	0.765	3.103
JHP5B	50.0	0.0	8.0	0.409	4.405
JHP5B	50.0	8.0	43.5	0.528	6.585
JHP5B	50.0	43.5	50.0	0.650	4.476
JHP5C	50.0	0.0	11.0	0.393	3.725
JHP5C	50.0	11.0	46.0	0.572	5.426
JHP5C	50.0	46.0	50.0	0.865	3.555
JHR1A	55.5	0.0	13.0	2.094	4.453
JHR1A	55.5	13.0	30.0	2.271	3.859
JHR1A	55.5	30.0	55.5	2.527	3.778
JHR1B	47.5	0.0	17.0	1.937	4.066
JHR1B	47.5	17.0	47.5	2.566	3.746
JHR1C	49.5	0.0	13.5	1.360	4.650
JHR1C	49.5	13.5	49.5	2.687	3.383
JHR1D	46.0	0.0	14.5	2.004	4.437
JHR1D	46.0	14.5	46.0	2.685	3.709
JHR2A	61.0	0.0	25.0	1.300	5.328
JHR2A	61.0	25.0	31.0	0.954	4.537
JHR2A	61.0	31.0	61.0	2.471	4.651
JHR2B	61.0	0.0	13.0	1.838	5.723
JHR2B	61.0	13.0	61.0	2.405	4.478
JHR2C	50.0	0.0	13.0	1.890	5.312
JHR2C	50.0	13.0	50.0	2.554	4.219

Appendix 1, Table 1, continued...

Core	Core length (cm)	Upper depth (cm)	Lower depth (cm)	Bulk Density (g cm⁻³)	% LOI
JHR2D	51.0	0.0	14.0	1.750	5.876
JHR2D	51.0	14.0	51.0	2.383	4.603
JHR3A	48.0	0.0	8.0	1.103	6.073
JHR3A	48.0	8.0	48.0	2.548	4.813
JHR3B	49.0	0.0	9.0	1.512	6.008
JHR3B	49.0	9.0	49.0	2.343	6.107
JHR3C	45.5	0.0	10.0	1.333	5.846
JHR3C	45.5	10.0	45.5	2.407	4.907
JHR4A	55.5	0.0	11.0	1.478	6.622
JHR4A	55.5	11.0	55.5	2.370	5.567
JHR4B	58.5	0.0	9.5	1.189	5.396
JHR4B	58.5	9.5	22.0	2.156	4.802
JHR4B	58.5	22.0	34.0	1.086	4.367
JHR4B	58.5	43.0	58.5	3.766	4.764
JHR4C	56.0	0.0	7.0	1.354	5.584
JHR4C	56.0	7.0	56.0	2.382	4.556
JHR4D	59.0	0.0	8.5	1.309	5.638
JHR4D	59.0	8.5	59.0	2.192	4.605
JHR5A	76.8	0.0	4.3	1.180	6.213
JHR5A	76.8	4.3	54.0	2.738	4.353
JHR5B	63.0	0.0	6.0	1.796	5.477
JHR5B	63.0	6.0	63.0	1.956	4.408
JHR5C	68.0	0.0	8.0	1.944	5.754
JHR5C	68.0	8.0	16.0	2.083	5.332
JHR5C	68.0	16.0	46.5	1.040	4.242
JHR5C	68.0	46.5	68.0	2.405	4.493