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Abstract

This study examined land-use changes along the south-eastern coast of Sri Lanka before and after the 2004 tsunami to spot areas vulnerable to flooding and severe weather events like tsunamis. On December 26th, 2004, over 30,000 people lost their lives after an offshore earthquake caused a tsunami in Sri Lanka, which resulted in waves as high as 30 meters. A time-series vegetation change: (i) immediately after the tsunami between 2004 and 2005, (ii) pre-tsunami & long-term between 2004 and 2016, and (iii) post-tsunami & long-term between 2005 and 2016, were mapped using Landsat TM images. The resulting series of change detection models were then utilized to create a series of maps displaying considerable disturbance of vegetation patterns and agricultural activity along coastal and inland regions.

Introduction

This study examined the land-use changes along the south-eastern coast of Sri Lanka before and after the 2004 tsunami to spot areas vulnerable to flooding and severe weather events like tsunamis. On December 26th, 2004, 230,000 people, spanning 14 countries, lost their lives due to an offshore earthquake that led to a tsunami with waves reported as high as 30 meters (United Nations, 2007). The events of 2004 were powered by an unforeseen seismic event measuring 9.1–9.3 magnitude along the Indian-Burma boundary off the coast of Sumatra, Indonesia (UNESCO, 2009). When analyzing the effects of this incident, areas vulnerable to flooding and tsunamis can be identified due to their lower elevations relative to sea level, and topography. These coastal communities can become even more vulnerable due to vegetation loss and the introduction of invasive species, which can destabilize the coastal soil composition.

In the coming decades, these communities will be the primary indicator of ecological, agricultural, and sociological devastation. As global warming continues to fuel increased climate changes, the effects will manifest as more frequent and more extreme localized disasters. The resulting loss of more than 30,000 people in Sri Lanka (Miura *et al.*, 2006) was a key factor that motivated the Sri Lankan government to realize their limitations in addressing major climatic events and the severe impact this had on Sri Lanka. In 2005, efforts were made to mitigate future events from further devastating at-risk coastal communities along the southern coastal areas, ranging from Colombo to Trincomalee. Since then, the government of Sri Lanka has been working with the World Bank's

Disaster Risk Management Agency (DRM) to develop mitigation measures, such as government planning and regulation of coastal agriculture, removal of invasive species, and replanting of native species along Sri Lanka's southern coastline. The reduction techniques developed in Sri Lanka could easily be implemented to generate future models, mitigation measures, and recommendations for subsequent projects along the coastal communities of Humboldt County or anywhere along low-lying coastal regions around the globe.

Almost half of Sri Lanka's southern coastline was affected by sea water inundation and related debris contamination post-tsunami (Illangasekare, 2006). Much of the coastal and inland ecosystems were debilitated by salt water and a variety of other contaminants, which resulted in the 2005 Sri Lanka Disaster Management Act No. 13 and led to the establishment of the Disaster Management Centre (DMC) for risk management. The roads and infrastructure were already suffering from war damage and neglect before the tsunami and were left devastated. Because of this, it has taken over seven years and 530 million pounds (674 million U.S. dollars) to enact repairs to a fraction of the roads, railway tracks, and bridges that were damaged (New Civil Engineer, 2005).

A rapid assessment of coastal habitats' rehabilitation in the southern coastal Hambantota District was conducted 20 months following the disaster (Bambaradeniya *et al.*, 2006). Samples in different land uses and land cover classes such as mangrove, sea-shore, and coastal shrublands were taken, revealing good regeneration potential for lost coastal vegetation (**Fig. 1**). As coastal zone demarcation for vulnerabilities, an approximate two kilometer inland buffer (boundary from coastline to inland) was considered the threshold for what defines a coastal vegetation area in our model (Government of Sri Lanka, 1981; Kaplan *et al.*, 2009) and thus an appropriate geographic buffer for this study. The vegetation studies and the associated buffer zones were then used as reference for different vegetation classifications. This two kilometer buffer for coastal biomass estimation was used to assess the

Figure 1. Post-tsunami coastal vegetation regeneration sites in Hambantota District. Map prepared using the ground control points surveyed by the IUCN (Source: Bambaradeniya *et al.*, 2006).

vegetation's vulnerability to act as a protective shield against flooding and to stabilize coastal soils (i.e. mangrove vegetation, shelterbelts, windbreaks) and the potential impacts of a future tsunami. The vegetation within the two kilometer buffer zone is then defined as a biological shield (bioshield) and is characterized by vegetation composed of trees and shrubs grown along the coasts to protect coastal areas (Selvam *et al.*, 2005).

While coastal habitats are especially vulnerable to climatic change and tsunamis, 59% of the Sri Lankan population still lives in coastal districts with maritime boundaries (Nayanananda, 2007). Coastal vegetation belts, such as mangroves, have been shown to provide a natural buffer by absorbing the tsunami wave action and currents, thereby reducing human death from tsunamis (Kathiresan and Rajendran, 2005). Additionally, studies have measured the importance of sustainable management practices and the impact on tropical ecosystems such as mangrove forests, coral reefs, and seagrass beds (Dahdouh-Guebas, 2002).

The identification and assessment of stable coastal vegetation, or bioshield, along the coastline of Sri Lanka is useful for forecasting the specific areas at risk of large intermittent wave actions and the likelihood of risk to people and property, meaning it requires implementation of the best coastal management plans prior to coastal habitat rehabilitation. As a result, the vulnerability of these coastal areas to natural disasters is directly related to the risk management techniques of the Sri Lankan government (Jayawardane, 2006).

These coastal areas will continue to be vulnerable to sea level rise (SLR) along lands adjacent to wetlands and lowlands under the scenarios of 0.3 m and 1.0 m in coming decades (Weerakkody, 1996). According to UNDP (2007) SLR projections, the maximum SLR is estimated to be 0.59 m inundation. According to Madurapperuma *et al.* (2017), erosion at Oluvil beach has severely degraded coastal habitats and has led to a significant land mass inundation of 0.5 m and 2.0 m SLR. Predicted SLR in Sri Lanka will be 0.51 m in the next 25 years, 0.66 m in 50 years, and 0.96 m in 100 years (UNDP, 2007). The resulting sea water intrusion to wetlands and lowland paddy lands along these areas will likely destroy the ecosystem through inundation of saline water.

Since 2005 the government of Sri Lanka and the DRM have spent millions in the recovery effort by rebuilding coastal infrastructure and enforcing a 100 m buffer zone in the west and south and a 200 m buffer zone in the eastern and northern coastlines of Sri Lanka, restricting construction (Ratnasooriya, 2007). These efforts require an updated analysis of the coastal bioshield health to assess the effectiveness of the effort by the Sri Lankan government and the World Bank's DRM since 2005 (Jayawardane, 2006). A comprehensive change detection study needs to be implemented to assess mitigation efforts and measure the health and vegetation mass of the coastal bioshield.

The mangrove forests and coastal biomass need to be measured to better assess the effectiveness of the repair efforts as well as the return of biomass due to natural processes post-recovery efforts in 2005 along the south-western coastal regions from Colombo to the north-eastern coastal regions of Trincomalee. Additionally, a GIS-based assessment should be part of future studies as well, analyzing what coastal areas have not recovered and what coastal areas are still at risk of climate change-related wave action, saltwater contamination, and other occurring natural disasters.

This study focused on the current biomass of vegetation along the coastal region in and around Ampara Region, Sri Lanka using change detection within ENVI® image analysis software to develop a preliminary model. This model will later be expanded with *in-situ* data to update the DMC database on post-tsunami mitigation measures in Sri Lanka. Subsequent studies will develop a comparative analysis and model of tsunami mitigation techniques and coastal recommendations for the Northern California Humboldt coastline.

Methods

For this project a vegetation, or land-use, pre- and post-tsunami model for Ampara, Sri Lanka was developed (**Fig. 2**). The first step was to retrieve data

Figure 2. Locator map for Ampara (2017) and Hambantota (2006) IUCN study areas (Bambaradeniya *et al.*, 2006).

from Earth Explorer through the GLOVIS data visualizer for Landsat 5 TM and Landsat 8 with the dates: 12-2004, 04-2005, and 08-2016.

As depicted in the flow chart in **Fig. 3**, radiance to reflectance calculations were performed prior to analysis using the Band Math function in ENVI®. The brightness values, or radiance, of pixel values of the raw Landsat images were converted to reflectance using the calibrated reflectance values that can be found in the metadata of the Landsat images. The reflectance values were useful to delineate vegetation and moisture values of Landsat images and widely used to derive remotely-sensed indices. For example, vegetation health can be detected using the Normalized Differential Vegetation Indices (NDVI) (Madurapperuma *et al.*, 2017). When sunlight strikes vegetation, certain wavelengths of this spectrum are absorbed and other wavelengths are reflected. For instance, pigment in plant leaves, such as chlorophyll, strongly absorbs visible light (from 0.4 to 0.7 μm) for use in photosynthesis. The cell structure of the leaves, on the other hand, strongly reflects near-infrared (NIR) light (from 0.7 to 1.1 μm) (Weier and Herring, 2000). Near-infrared light refers to the main infrared component of the solar radiation (from 0.7 to 1.1 μm) reflected from the Earth's surface. The next step was to perform an NDVI analysis model within ENVI® to analyze biomass and health indicators for temporal elements (2004–2005, 2005–2016, and 2004–2016).

The bands used for the analysis were 3 (red band) and 4 (NIR band) for Landsat 5 and bands 4 and 5 (red and NIR band, respectively) for Landsat 8 imagery, with all results projected in WGS 1984 UTM zone 44N. The final comparisons performed were from pre-tsunami December 2004 to April 2005, from post-tsunami April 2005 to September 2016, and from December 2004 to September 2016.

Landsat 5 band description:

Band 3 - red 0.63 – 0.69 μm; Discriminates vegetation slopes

Band 4 - NIR 0.77 – 0.90 μm; Emphasizes biomass content and shorelines

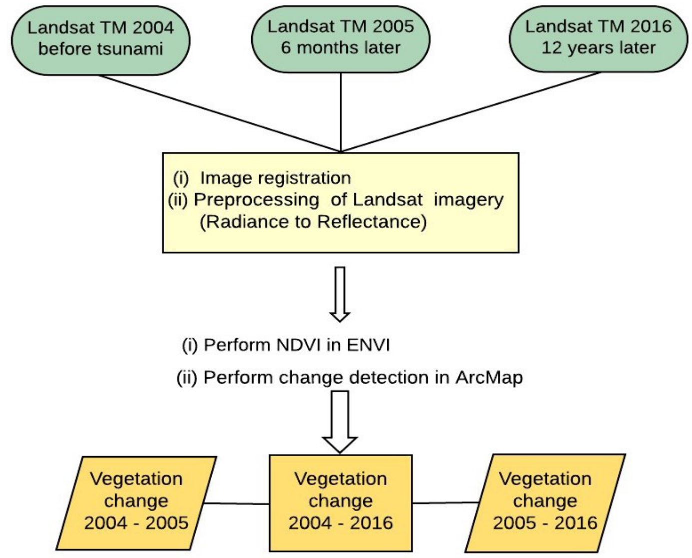

Figure 3. A change detection workflow for studying tsunami impact sites in Ampara, Sri Lanka.

Landsat 8 band description:

Band 4 - red 0.64 – 0.67 μm; Discriminates vegetation slopes

Band 5 - NIR 0.88 – 0.85 μm; Emphasizes biomass content and shorelines

The next step was exporting the images and data into ArcMap© for the development of all three maps. After importing into ArcMap©10.4 the NDVI raster images were then subset in ArcMap© using a two kilometer buffer to define functional coastline parameters (Government of Sri Lanka, 1981; Kaplan *et al.*, 2009). The resulting clipped NDVI images then underwent a pixel conversion from floating point to integer and were then reclassified by pixel values. The change detection process was then performed, resulting in three classifications:

a. All negative values or decreases below zero were classified as "-1"

b. All positive values or increases were classified as "1"

c. Any unchanged or zero values were classified as "0"

We then summarized the vegetation change and performed a spatial join of the features in terms of land-use classes in the Ampara study area to quantify the tsunami impact vulnerabilities for the best land-use practices in the future. The land uses within the two kilometer buffer were extracted and then vegetation change within each land use was estimated using the tabulate area function in ArcMap©.

Comparative graphs displaying increases or decreases in vegetation were then made to see how each land-use change was impacted by the tsunami. These values were then converted from raster to polygon layers to estimate area by cell size and pixel count. By comparing the difference in spectrally identified vegetation classes, a significant change in vegetation was identified post-tsunami in April 2005. The next comparison was for temporal elements of 2005–2016 which was done to develop a baseline model of what repair measures have been made since the 2004 tsunami. A change detection workflow chart between 2004–2005, 2005–2016, and 2004–2016 is given in **Fig. 3**.

Results & Discussion

After developing multiple change detection models spanning 12 years (**Figs. 4–6**), the resulting analysis shows a considerable amount of damage due to the 2004 tsunami, evidenced by vegetation loss due to saltwater contamination (Ratnasooriya, 2007). The NDVI is applied to detect areas of vegetation cover increase or decrease, which is given by positive and negative values and symbolized by green and red colors, respectively. The NDVI is useful to detect changes in vegetation over time. In this study, however, we used NDVI to detect vegetation health corresponding to high NDVI values in a particular time step and also

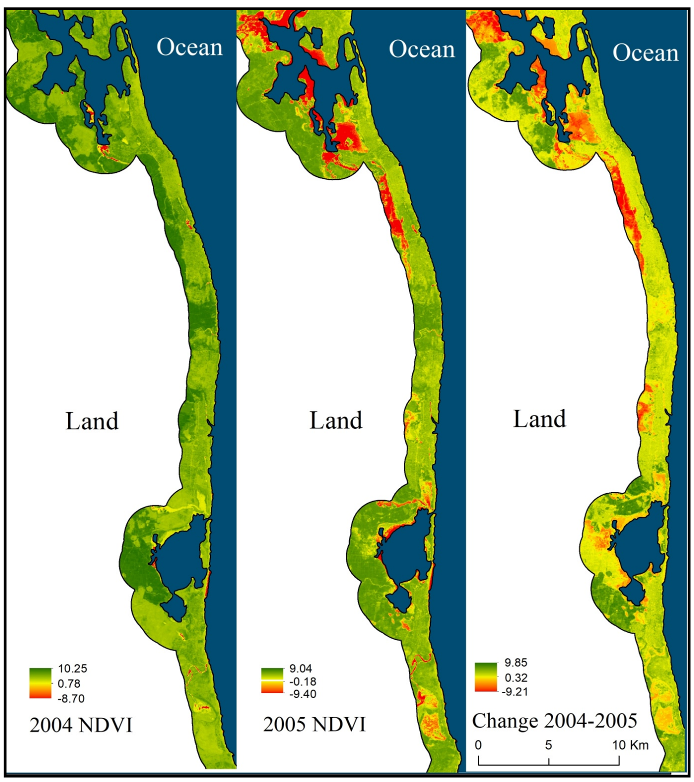

Figure 4. 2004 and 2005 NDVI images of Ampara pre- and post-tsunami with NDVI values (prior to change analysis) and 2004–2005 image with completed (short-term) change analysis. The 2004 and 2005 NDVI maps show vegetation health, where greens are healthy vegetation, reds are poor vegetation, and yellows are neutral vegetation health. In the change detection map, the greens are positive changes and the reds are negative changes, with yellow denoting few to no changes.

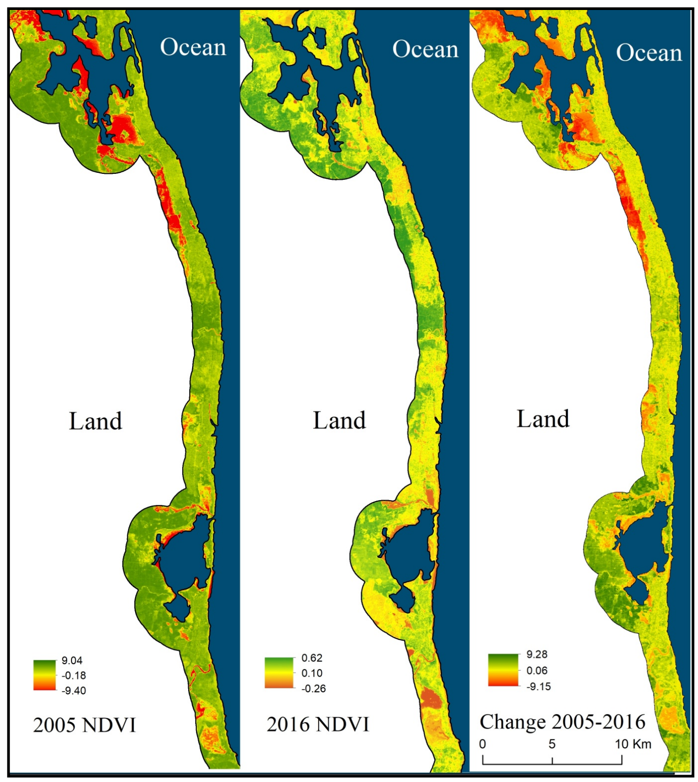

Figure 5. 2005 and 2016 NDVI images of Ampara over 11 years with NDVI values (prior to change analysis) and 2005–2016 image with completed (long-term) change analysis. The 2005 and 2016 NDVI maps show vegetation health, where greens are healthy vegetation, reds are poor vegetation, and yellows are neutral vegetation health. In the change detection map, the greens are positive changes and the reds are negative changes, with yellow denoting few to no changes.

detect vegetation changes between two time steps. As **Figs. 4–6** depict, some green areas in 2004 transformed to red in 2005 due to vegetation damage, or vegetation susceptible to tsunami wave impacts. A red area changing to green represents vegetation growth, or rehabilitation of coastal habitats. The change detection between 2004–2005 and 2004–2016 showed a significant decrease in vegetation mass post-tsunami (a more red color) compared to 2005–2016 (**Figs. 4–6**). This procedure was verified with a land-use database from the DATA.GOV (2015) and Google Earth for ground-truthing. The change detection analysis appeared to show cultivated areas were relocated further inland.

The coastal changes, both natural and cultivated, since December 26th, 2004 have resulted in a redistribution of natural vegetation and agricultural lands.

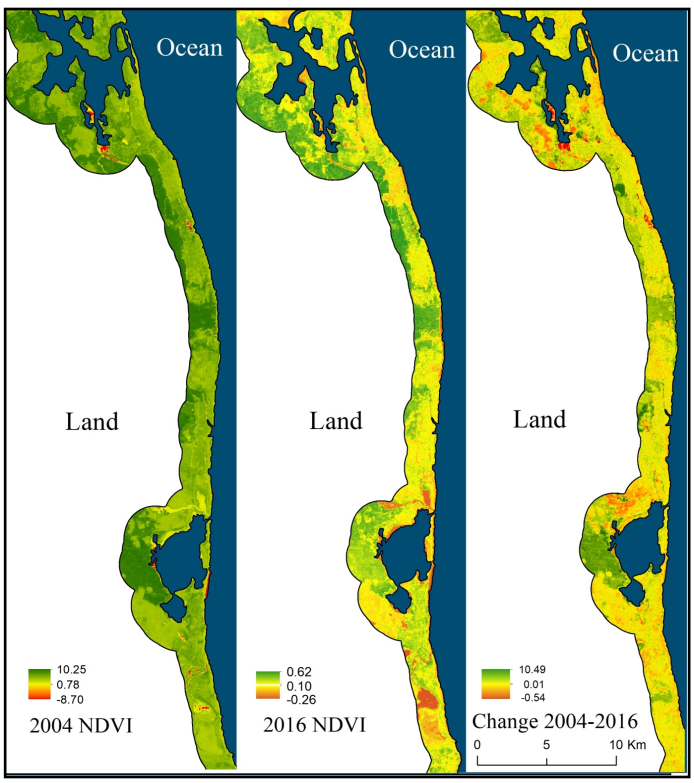

Figure 6. 2004 and 2016 NDVI images of Ampara over 12 years with NDVI values (prior to change analysis) and 2004–2016 image with completed (long-term) change analysis. The 2004 and 2016 NDVI maps show vegetation health, where greens are healthy vegetation, reds are poor vegetation, and yellows are neutral vegetation health. In the change detection map, the greens are positive changes and the reds are negative changes, with yellow denoting few to no changes.

The changes include the categories of tree cover (broad-leaved and deciduous) and closed vegetation. Much of these vegetation and cultivated areas appear to have relocated inland, likely due to the resulting soil contamination from seawater inundation (Mattsson *et al.*, 2009). This has left a lasting effect along the vegetation bioshields for tsunami mitigation from the coastal region of Ampara and immediately north to Batticaloa (Tanaka, 2009).

We summarized NDVI vegetation change in relation to land-use classes over time to see how each land-use class was impacted by the tsunami and how it recovered long-term with sustainable coastal management practices (**Fig. 7** and **Table S1**). The land-use change in relation to percent vegetation increased (i.e. natural and tree plantation for coastal habitat restoration) and/or vegetation decreased (i.e. tsunami and anthropogenic degradation, and sea water inundation) was then graphically presented by two bars for four land-use categories in **Fig. 7**. The raw figures on extents of per square acre land uses are given in **Table S1**. The land-use and land-cover changes derived from remotely sensed images were summarized into seven classes: dense forest, open forest, garden, other land, paddy, coconut, and undefined. There were no noticeable changes in open forest, coconut, and undefined (**Table S1**).

Of the land-use classes, natural vegetation, dense forests, and open forests have high resistance to tsunami wave actions, and thus, measured a lesser decrease in vegetation than anthropogenic land uses (i.e. garden, paddy, and other lands except coconut plantation) (**Table S1**). Therefore, implementing forests and trees as protective shielding of the coastline from tsunamis is effective (Fritz *et al.*, 2006). Mattsson *et al.* (2008) reported that natural forests and coconut plantations have contributed to high carbon sequestration in coastal ecosystems. In addition, extensive root mats of coconut trees offer protection from scouring and erosion (Forbes and Broadhead, 2007). Therefore, clear cutting coconut trees for harbor construction resulted in coastal erosion at Oluvil beach (Madurapperuma *et al.*, 2017).

According to the previous studies, buildings within one kilometer of the coastline in the eastern region have been severely damaged due to tsunami wave actions (Miura *et al.*, 2006). The maximum tsunami heights of the east coast were reported to be 3–7 m (Wijetunge, 2006). Therefore, transforming human-influenced land uses, such as paddy and home gardens, to natural coastal vegetation is beneficial to mitigating tsunami and cyclone effects. Based on these findings, we suggest that the government give incentives to landowners to convert their lands to more tsunami-resilient land uses.

Conclusion & Recommendations

After developing multiple change detection models spanning 12 years, the resulting analysis shows a considerable amount of devastation due to the wave action that inundated coastal communities from the 2004 tsunami. The changes and repairs since December 26th, 2004 resulted in the apparent relocation of agricultural lands, and the natural redistribution of vegetation further inland, which is likely due to the resulting soil contamination from seawater inundation (Mattsson *et al.*, 2009). This has left a lasting effect along the vegetation bioshields for tsunami mitigation (Tanaka, 2009), from the coastal region of Ampara and immediately north to Batticaloa. Additional research should be done using higher resolution imagery than the 30 m resolution provided by Landsat data. High resolution spatio-temporal data sets recorded from sequential aerial photography (i.e. unmanned aerial vehicle) would be essential for accurately mapping vegetation dynamics in Sri Lanka (Dahdouh-Guebas, 2002; Dahdouh-Guebas *et al.*, 2000). These additional data sets could then be utilized to identify which specific plant species were most and least affected by salt water inundation. To continue this process, high resolution images (i.e. drone images) could also be used to develop a more accurate digital elevation model to further identify lower elevation areas at risk of flooding. This could then be used to create SLR prediction models to identify specific waterways and corridors most vulnerable to SLR and inland salt water inundation. These improvements to the model would provide a highly accurate measurement of vegetation bioshields for the mitigation of tsunami wave action. The result would be a predictive model of inland coastal inundation patterns. These data could be developed further with existing SLR data with a statistical model measuring inland flooding patterns. The final result would be a study to repair and promote growth within at-risk coastal communities of Sri Lanka.

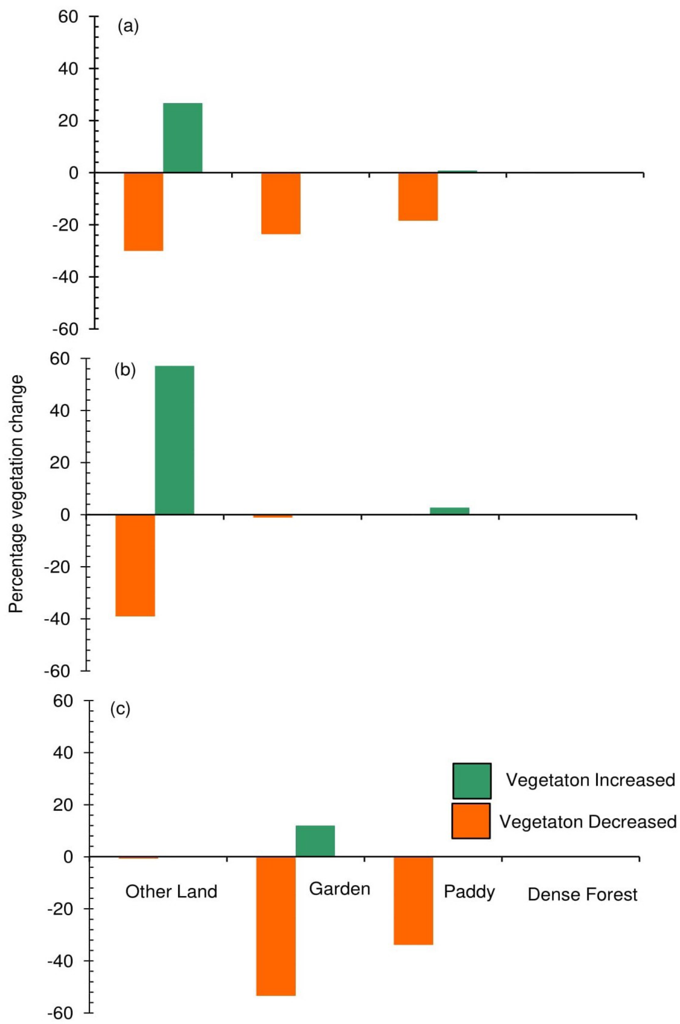

Figure 7. Vegetation biomass change in relation to land-use category in Ampara (a) 2004 –2005, (b) 2005–2016, and (c) 2004–2016.

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About the Authors

J.E. Dellysse graduated from HSU with a B.S. in Environmental Science in December 2017. He conducted this research for the intermediate remote sensing class project and further developed through his Directed Study advised by Dr. Madurapperuma. J.E. Dellysse visited Sri Lanka to collect the *in-situ* data to validate his change detection results over the summer of 2017.

Dr. Buddhika Madurapperuma is a Lecturer/Research Associate in the Departments of Forestry and Wildland Resources and Environmental Science and Management. He is a major advisor for J.E. Dellysse's Directed Study. He teaches GIS, remote sensing, forest ecology, and dendrology classes at HSU. Dr. Madurapperuma conducts multidisciplinary research on remote sensing (i.e. kite aerial photography and unmanned aerial vehicle), ecological studies on invasive species, and forest silviculture management.

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Supplementary Information

Table S1. Land-use/cover change in acres between 2004–2005, 2005–2016, and 2004–2016.

2004 – 2005	Decreased	Unchanged	Increased
Dense forest	9.79	5126.42	0
Open forest	0	20 188.53	0
Garden	711.22	19 637.88	0
Other land	906.26	97 036.28	805.07
Paddy	557.32	47 442.97	24.91
Undefined	0	49.37	0

2005 – 2016	Decreased	Unchanged	Increased
Dense forest	0	49.37	0
Open forest	0	5136.20	0
Garden	0.44	20 348.65	0
Other land	15.79	99 320.05	23.13
Paddy	0	48 024.09	1.11
Undefined	0	20 188.53	0

2004 – 2016	Decreased	Unchanged	Increased
Dense forest	0	5136.20	0
Open forest	0	49.37	0
Garden	168.80	100 074.19	37.81
Other land	2.22	48 022.76	0.22
Paddy	106.97	20 242.12	0
Undefined	0	20 188.53	0