RESEARCH ARTICLE

Remote Sensing

Multiscale analysis of land use and land cover changes in Sri Lanka by remote sensing: the impacts of post-war infrastructure development in the last 20 Years (2002-2022)

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Abstract: On a worldwide scale, land use and land cover changes (LULCC) is a major driver of global change and biodiversity erosion. This study aims to monitor at the scale of Sri Lanka, LULCC and vegetation dynamics, to identify the main changes and their drivers. It places emphasis on multiscale geospatial monitoring with satellite data but also mobilises the interdisciplinary knowledge of a research programme. First, national scale data allows the identification of major changes with the MODIS NDVI dataset using Mann-Kendall tests and time profile analysis. A second local scale was mobilised with a systematic diachronic visual interpretation of high-resolution images on Google Earth. The third step, a macro-regional scale focus on the South and East coasts, used LANDSAT imagery (Stacked K-means) verified by field studies (botanical and vegetation analysis, and interviews). About 92.5% of the island of Sri Lanka is stable or presents no significant trends in the vegetation cover. 5% show a significant positive (greening) trend between 2000 and 2020 around the Puttalam lagoon, west of the Samanalawewa Reservoir, in the Udawalawe National Park, east and north of Ella, and the Nuwaragala Forest Reserve. Only about 2.5% (165,000 ha) of the Island shows a negative significant trend mainly in the periphery of Colombo and Trincomalee. The first driver is a set of national planning decisions in terms of infrastructure development (including urban growth, housing programmes and agricultural fields, and the management of protected areas). The second driver comes under rural dynamics with increasing tree density in rural landscapes over the Uva Province. Infrastructure development initiated by the state, creates both underlying conditions for other activities and negative impacts on coastal ecosystems, such as degradation of wetlands (including protected areas).

Keywords: Infrastructure development, LULCC, NDVI, South and East Coast.

INTRODUCTION

Changes in land cover and land use largely contribute to a global environmental crisis, combining the threats of climate change (IPCC, 2021) with biodiversity loss (IPBES, 2019). Land use and land cover changes (LULCC) mainly include deforestation and urbanization (Hu *et al.*, 2021). These dynamics, are however often poorly explained (Lambin *et al.*, 2001). Rapidly

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developing countries are environmental hotspots because of the inherent relationship between economic growth and resource exploitation (Andrée *et al.*, 2019); additionally, many are located in the tropical zone, characterised by high genetic, specific, and ecological biodiversity (Myers *et al.*, 2000).

Despite decelerated growth due to civil war (Ganegodage & Rambaldi, 2011), Sri Lanka initially experienced a boost to growth in the immediate post-war period (2009-2012) but with a sharp decline thereafter (Weerakoon, 2018), followed by the worldwide economic downturn caused by the COVID-19 pandemic (Rishandani, 2021). This growth was mainly sustained by infrastructure development, based on multilateral, bilateral, and private-sector loans (Weerakoon, 2018). The external debt incurred by the country became largely unsustainable, as the share of non-concessional loans grew from a mere 7% in 2006 to 53% in 2016 (Weerakoon, 2018).

Sri Lanka has also undergone considerable population growth from 18.7 to 21.8 million between 2001 and 2019 (CBSL, 2020). Population growth has been accompanied by urban growth and urban sprawling in both the capital (Antalyn & Weerasinghe, 2020) and small sized cities (Manesha *et al.*, 2021). During the last 20 years, in particular since the armistice of 2009, Sri Lanka embarked on large-scale, planned development programmes. Major infrastructure development has been implemented on the South and East coasts (Perera, 2014). A good example is the region of Hambantota, on the South coast where a lagoon has been converted to a port associated with a chemical industry complex, an international airport and some urban development projects, including housing, administrative complexes, conference hall, stadium, and hospital. Resettlement programmes for those displaced by war were implemented in territories in the North and East, of which the government regained full control after 2009.

Sri Lanka is placed in the main list of Biodiversity Hotpots (Myers *et al.*, 2000) because of species richness and endemism rates (*e.g.*, birds and plants), particularly in the southwestern part of the country (*e.g.*, Gabadage *et al.* 2015; Wikramanayake *et al.*, 2022). Trade-offs between the environment and development are unavoidable (Dasanayaka *et al.*, 2022). However, the state of the environment in Sri Lanka is far from being exhaustively studied and very little systematic assessment on LULCC is available. Based on a multiscalar approach, this paper therefore aims to first map the main LULCC on national scale, and then focus on the South and East coasts of Sri Lanka, to identify the main drivers of these changes on a macro-regional scale. Such knowledge might later be used to better plan infrastructure development with regard to past environmental impacts of planning. Remote sensing is an efficient and well recognized method to monitor LULCC and vegetation dynamics (Alqurashi & Kumar, 2013). However, it is still rarely used in Sri Lanka. It has been applied to monitor urban growth (Subasinghe *et al.*, 2016; Antalyn & Weerasinghe, 2020; Manesha *et al.*, 2021) and its links with urban heat and vegetation (Senanayake *et al.*, 2013, Dissanayake *et al.*, 2019), to carry out studies focusing on one type of LULCC, such as deforestation for planting of rubber (Cho *et al.*, 2022) or locally specific interventions, such as a protected area (Perera & Tsuchyia, 2009; Lindstöm *et al.*, 2012; Wickramaarachchi *et al.*, 2013; Perera *et al.*, 2021). Changes at the national level, using LANDSAT data processed with the LandTrendr algorithm (Kennedy *et al.*, 2015), have been monitored (Rathnayake *et al.*, 2020), detecting changes for 13.5% of the Island surface between 1993 and 2018.

Moderate Resolution Imaging Spectroradiometer (MODIS) has been mobilized either in a local land cover study (Perera & Tsuchyia, 2009) or with a focus on agricultural phenology (Jayawardhana & Chathurange, 2016). Sri Lanka has also been included in studies on the macro-regional scale (Mondal *et al.*, 2020; Fu *et al.*, 2022) delivering, however, little precision on the country *per se*.

The present study basically aims to monitor, on a national scale, a large spectrum of changes, including LULCC and vegetation dynamics, in order to identify the main changes and when possible, identify the drivers and the processes of change. More precisely, three questions are targeted: a) What are the main land cover and vegetation trends in Sri Lanka? b) What drivers underlying these changes and processes, can be identified by a multiscalar remote sensing approach? c) What do changes along the South and East coasts reveal of the environment/development nexus in Sri Lanka?

MATERIALS AND METHODS

Study areas within a multiscale framework

To assess social-ecological changes on the South and East coasts of Sri Lanka, a multiscale approach was chosen (Figure 1). First, small (national) scale (Figure 2) data allows the identification of major changes with the MODIS Normalized Difference Vegetation Index (NDVI) dataset. However, this dataset, because of its coarse

spatial resolution, does not easily reveal the drivers of the detected changes and requires further analyses. A second large (local) scale was mobilised with a systematic diachronic visual interpretation of high-resolution images on Google Earth. The third step, a medium scale (macro-regional) one, focuses on the South and East coasts, with the same MODIS Time series, allowing environmental and social processes to be put in synergy. The fourth step was a local focus on a few sites studied with LANDSAT imagery with diachronic land cover mapping (micro-
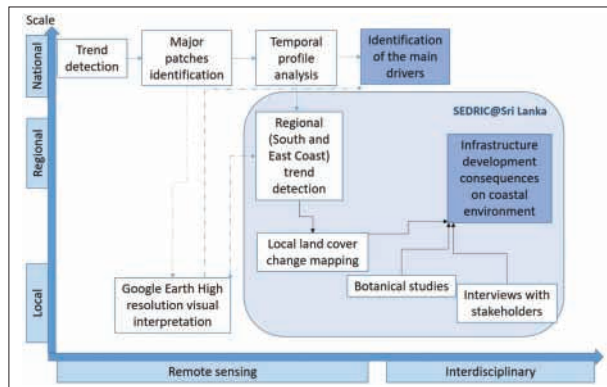

Figure 1: Multiscale and interdisciplinary flow chart

Figure 2: Elevation map of Sri Lanka showing the study areas and locations of case studies on the South and East coasts

regional), verified by field study (botanical and vegetation analysis, and interviews).

Mapping LULCC is a synthetic and transversal way of approaching the issue of social-ecological changes (Rogan & Chen, 2004). Indeed, without being able to reveal certain fine, discrete or complex ecological (fauna, flora) or social (economic, demographic dynamics) changes, they nonetheless reveal the main changes through the transformation of landscapes (deforestation, reforestation, urban growth, changes in the coastline, etc.). In addition, these transformations can then be associated with more complex dynamics that can be the causes of these changes (demographic growth or rural exodus explaining urban growth) or their consequences (deforestation causing soil erosion and destabilising the watercourse regime) (Mondal *et al.*, 2020).

Remote sensing

Remote sensing allows the combining of various scales and resolutions (Mondal *et al.*, 2020). The multiscale approach has a lot of advantages. First, the consistent observation of phenomena at two scales enables its validation. Next, it might bring different knowledge
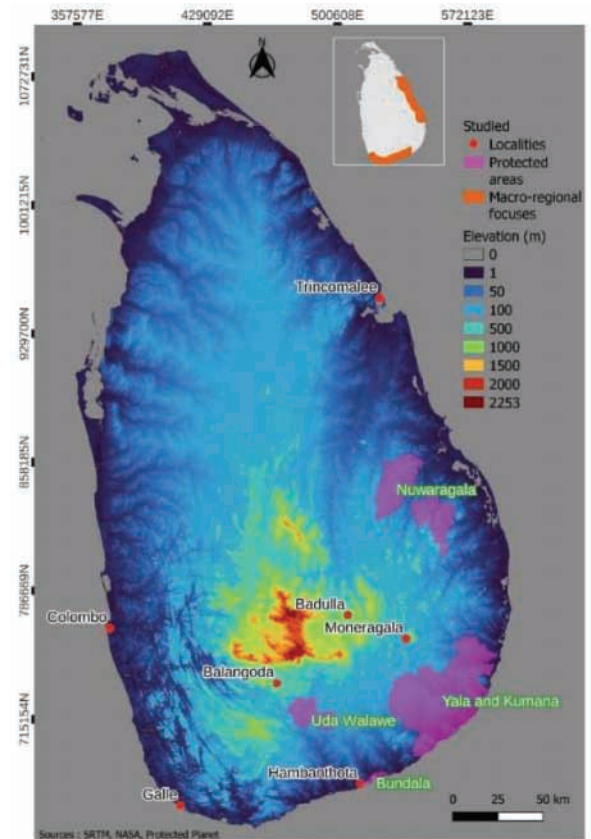
about the change itself. If the local scale brings more precision and possible identification of drivers, the broad scale enables it to be placed in relation to general trends, and indicates if a studied change corresponds to a general trend or is a unique process. The present work is the first one mobilizing 3 different types of remotely sensed imagery at 4 different scales even if there have been many earlier studies with remote sensing in Sri Lanka (Perera & Tsuchyia, 2009; Lindstöm *et al.*, 2012; Wickramaarachchi *et al.*, 2013; Alqurashi & Kumar, 2013; Senanayake *et al.*, 2013; Subasinghe *et al.*, 2016; Dissanayake *et al.*, 2019; Antalyn & Weerasinghe, 2020; Rathnayake *et al.*, 2020; Manesha *et al.*, 2021; Perera *et al.*, 2021; Cho *et al.*, 2022).

MODIS time series analysis

MODIS satellites are a set of two satellite-based sensors used for earth and climate measurements in Earth orbit, mostly used for data accessible as pre-processed time

series. Of the 6th version of the NDVI from MOD13Q1 downloaded, two tiles (V8H25; V8H26) were necessary to cover Sri Lanka. Images are a synthesis covering a 16-day period (23 images per year) with a spatial resolution of 230 meters. The time series starts in February 2000 and runs until December 2021. Further details on this well-known dataset can be found in Didan *et al*. (2015).

The dataset has been filtered with a Fourier inverse filter (Cochran *et al*., 1967). The Kendall correlation, or Kendall's Tau (Kendall, 1938), is regularly used to identify data, especially with the NDVI time series (De Jong *et al*., 2011). The Kendall correlation is associated with a P value test set up, here, at 0.0001. Even tested by the P value, the Kendall test is known to be very sensitive to the first and last years of the time series (Dardel *et al*., 2014). The same analysis was computed after removing the first year, the two first years, the last year and the two last years. Only the trends that are robust (P-value under 0.0001 and not sensitive to changes in the first and last years) were considered in this analysis. Then the South and East coasts studied as part of the interdisciplinary research programme were isolated. Similar trends in NDVI can result from various processes. Therefore, at the first level of analysis these trends are only named as 'greening' and 'browning' until further analysis enable more precise understanding and description.

In order to get a finer understanding of the detected changes, the main patches of changes (a group of adjacent pixels with the same trend in NDVI values) were isolated: five main patches of negative significant trends in NDVI 'browning' (larger than 1600 ha) and five main patches of positive significant trends in NDVI 'greening' (larger than 9300 ha). For each, two temporal profiles of the NDVI were produced and studied. The first is a profile at raw temporal resolution (16 days) over the whole time series. It enables calculation of a trend for a group of pixels but also tests like binary segmentation (Killick & Eckley, 2014). The second kind of profile is based on the division of the time series into two periods (2000–2010; 2011–2021), and for each period, the mean of the NDVI for every 16 days of the MODIS year division. This enables a comparison of the mean annual profiles of two decades in order to interpret the changes (Andrieu, 2017).

Unlike the LandTrendr algorithm, the trend detection is not based on a 'year-to-year comparison'. Therefore, it is less accurate for identifying in space and time a precise landcover but it will be more reliable for detecting a regular change in vegetation, which the LandTrendr might not detect as it is based on break-out. The trends in NDVI are, in this paper, used as a wide change detection tool bringing one stratum of information in a multiscalar approach, but are not built to provide either classified land cover maps or a statistical view of LULCC. Hence, it is associated with both the Google Earth visual interpretation and some local field-verified LULLC maps based on classification.

Visual control and interpretation of the changes in MODIS time series based on Google Earth high spatial resolution image excerpts

Trends in NDVI values can be explained by a large spectrum of changes as LULCC (deforestation, reforestation) but also changes within the same land use or land cover category, either agricultural (change in irrigation system resulting in a change in agricultural rhythms and biomass) or natural (phenological or biomass reaction to climate change). Therefore, for the main patches of change at the national scale and on the South and East coasts, visual interpretation of high-resolution (varying from a few meters to submeter level) image excerpts on Google Earth was carried out (Cha & Park, 2007). These image excerpts are RGB colour composites of very high spatial resolution satellite images, *i.e.*, images with sub-metric or metric pixel sizes. The whole process was accomplished in a double-blind interpretation between different remote sensing specialists, and only consistent results were validated. Visual interpretation was based on a set of criteria, mobilizing colour(s), structure, and texture (Figure 3, C&D). When possible, the interpretation was validated using different images of the same year but different seasons. The differences observed and interpreted between the beginning of the 2000's decade and the most recent images were double-checked by images with intermediate dates. The combined results of temporal profiles and visual interpretation are synthetized in Tables 2 and 3 with full details provided in Supplementary Material 1 (Figures SM1.1 to SM1.30).

LANDSAT applied to LULCC mapping

At the micro-regional scale, the National Aeronautics and Space Administration (NASA) LANDSAT program was chosen for two technical characteristics that make it superior to other satellite imagery programs: the availability of images since the mid-1980s and the spectral resolution (at least 7 bands from blue to thermal infrared images come from Landsat 5 and Landsat 8). Four images are required to cover the areas studied at this scale (Table 1).

Table 1: Information on the LANDSAT Images used for the study

	Path	Row	Date 1	Intermediate date	Date 2
Batticaloa & Arugam bay	140	55	1994	2005	2019
Hambanthota	140	56	1991	-	2019
Galle	141	56	1988	-	2020
Trincomalee	141	54	1994	2000	2020

Our method consisted of a series of interlocked unsupervised classifications (K-means algorithm) followed, for each classification, by an interpretation of the mean radiometric curves of each class (Andrieu, 2018). A first classification was made with an ample number of classes to increase the probability of perceiving nuances in the wavelength variations of some similar land cover types. The interpretation then consisted of grouping them into a small number of classes, corresponding to a basic nomenclature of land cover (water, woodland, croplands, and, when present, mangroves, bare soils, sand and rocks, and built-up areas). The interlocked classifications then enabled the subdivision of each class into a small number of sub-classes (same algorithm, same interpretation of the curves) to search for possible classification errors and, if necessary, correct them (Andrieu *et al.*, 2019). In the sites where field visits were possible, field verification led to assess accuracy between 81 and 83% (see supplementary material 3, Tables SM3.1 and SM3.2).

Pluridisciplinary approach

This paper mobilised data gathered during a two-year interdisciplinary monitoring of the environmental changes of coastal ecosystems and infrastructure development to better discuss the results from remote sensing. Some field studies in botany and interviews with stakeholders on various sites of the study areas were used for analysis at the local scale.

Vegetation dynamics in two wetlands on the South Coast of Sri Lanka

A field survey was conducted from 2018 to 2020 in Garanduwa and Kalametiya. In the first site, five plots of 30 m × 30 m were randomly studied, and six plots were covered in the second site. All trees and mature shrubs were counted and identified to the species level. In addition, the girth at a height of 130 cm of tree species was measured and the seedling bank was studied.

In February 2022, in addition to assessing the accuracy of the recent maps, a set of regions of interest were selected on the temporary maps of land cover changes in order to try to check the dynamics when possible, with simple landscape observation (*e.g.*, old trees, testifying to the presence of woodland in the 1980's or 1990's; new buildings testifying that urban sprawl had recently expanded), as well as some elementary interviews on the memory of land cover few decades before.

Interviews with stakeholders on the East Coast

To provide an analysis of the evolution of key social, economic, and environmental issues related to both infrastructure development and nature conservation, a literature review on the historical context and semi-structured qualitative interviews with stakeholders were conducted in case study sites. The stakeholders included national and district level key informants, as well as residents of coastal communities, using remote/virtual or face-to-face methods, depending on the changing COVID context during the fieldwork period. Altogether 27 semi-structured key informant interviews with government officers and representatives of civil society organizations (CSOs) in sectors relevant to the study, such as planning, tourism, industry, fisheries, wildlife conservation, forestry, local administration, community development, and women's empowerment were conducted at the national level and in the two study districts of Trincomalee and Batticaloa. Based on these interviews, five coastal Grama Niladhari (GN) divisions (three in Trincomalee, two in Batticaloa) which had experienced infrastructure development were identified and 50 semi-structured, open-ended household interviews with purposive samples of women and men, affected and unaffected by infrastructure development and indicative of different types of livelihoods within coastal communities, were conducted.

The social study was based on the conceptual approaches of political ecology and social wellbeing. The political ecology lens used here was influenced by Bennett (2019), who emphasizes the role of power in the ocean and coastal environment, and the marginalisation of small-scale fishing/indigenous/coastal communities, and Fabinyi *et al.* (2015), who addresses local inequalities and perceived marginalities in fisheries governance in the Pacific. The analysis of the society-environment interface was also informed by Frerks *et al.* (2014) and

Bavinck & Gupta (2014), who have challenged earlier mono-causal theories of conflict over natural resources centred on scarcity, greed, or grievance, arguing that such conflicts are multi-causal, multi-level, and involving multiple actors. Within this broader and more nuanced approach, environmental factors are combined with socio-political factors to explain conflict or contestation. In this study, overt conflict over resources has not been encountered, but, in several instances, contestation of access to resources did take place. The political-ecological perspective supported the analysis of contestation among different groups for natural resources, coastal land, and the sea, where they occurred, the differential benefits and costs of development to groups, the space for participation by local communities in decision-making in relation to coastal governance and transformations, as well as factors for the presence or absence of collective action and social movements. The social wellbeing approach (McGregor, 2008) was used to assess the impacts of infrastructure development on the lives of women and men in coastal communities, especially to understand the extent to which wellbeing outcomes were material (economic), relational (social) or subjective (emotional).

RESULTS AND DISCUSSION

Loss in vegetation cover on the coasts and the greening process in the Uva Province

About 92.5% (*i.e.*, 6,046,000 ha) of the Sri Lanka Island is stable or presents no significant trends in the vegetation cover. Further, 5% (*i.e.*, 327,000 ha) of the territory shows a significant positive (greening) trend between 2000 and 2020. Only half of it (2.9%) keeps a significant positive trend if one or two (first or last) years are not taken into account. The greening appears in areas located in the following places: around the Puttalam lagoon, west of the Samanalawewa Reservoir, in the Udawalawe National Park, east and north of Ella, or the Nuwaragala Forest Reserve (Figure 3).

A significant negative trend is shown in 2.5% (165,000 ha) of the Island. Only two-thirds of it (1.8%) retain a significant positive trend if one or two (first or last) years are not taken into account. The main patch of decreasing values (browning) is situated in the periphery of Colombo, the capital of Sri Lanka, experiencing significant urban sprawl in the last 20 years. Three important patches can be observed south of Trincomalee (further identified as E, C, and W for East, Centre and West). Then small patches are scattered over the east of
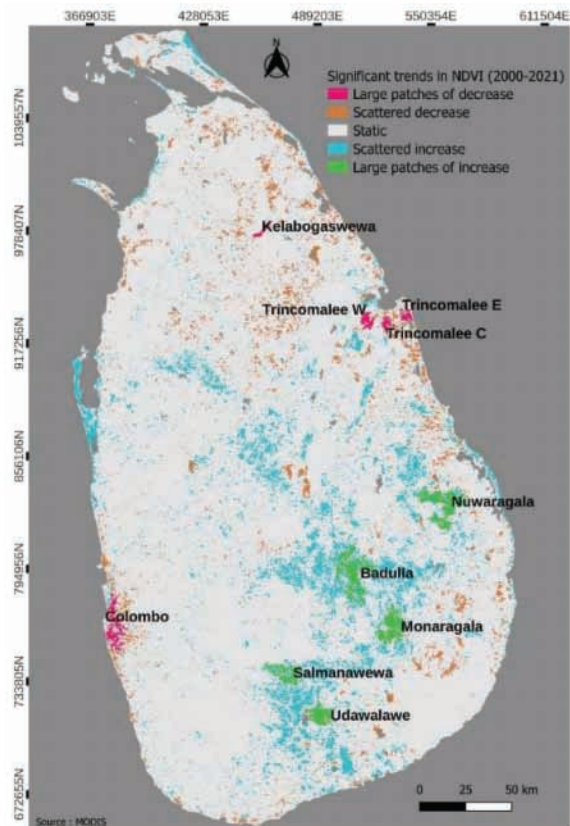

Figure 3: Trends in NDVI from 2000 to 2021

the island. Detailed graphs of NDVI temporal profiles are presented in the Supplementary material 1, while only two synthesis tables are given here.

The five main patches of significant negative Kendall correlation (Table 2) present different comportments revealed by the profile analysis. The patch in the suburb of Colombo shows a gradual decrease in NDVI values in the 21-year profile, while a comparison of the NDVI mean annual profiles of the two decades shows parallel profiles with a moderate difference between them. This is consistent with the visual interpretation of Google Earth's high-resolution imagery: progressive densification of buildings replacing trees.

The four other curves show a long stable period and a neat breakout in the time series followed in some cases by another stable period or an unstable one. This is consistent with the visual interpretation of Google Earth's high-resolution imagery: sudden deforestation and conversion to cropland.

Table 2: Interpretation of the five main patches of decreasing NDVI values.

Locality	Change in NDVI regime 2000–2010 / 2011–2021	Trend and breakout	Land cover 2000's	Land cover 2020's
Kelabogaswewa	Same seasonal profile with lower values	Clear breakout in 2013	Forest	Scattered buildings in fields
Trincomalee E	Same seasonal profile with lower values	Breakout in 2009	Open woodland	Rice fields
Trincomalee W	Sempervirent becomes unimodal (max November)	Breakout in 2009	Forest	Rice fields
Trincomalee C	Sempervirent becomes unimodal (max May)	Breakout in 2009	Mangrove	Rice fields
Colombo	Same seasonal profile with lower values	Regular negative slope	Scattered buildings	Dense urban

The five biggest patches with significant positive trends in NDVI (Table 3) reveal in common a series of minor breakouts in the time series, with the first breakout quite early on. The three patches in the northeast show fewer changes than the two located more toward the south. Some of the sites have changed seasonal regimes, revealing a dry season with low NDVI values in the first decade, followed by an evergreen regime in the second decade. We hypothesize that irrigation and perennial cultivation could be responsible but a change in rainfall regime is also possible as a trigger of the greening of vegetation during the driest season.

Table 3: Interpretation of the five main patches of decreasing NDVI values.

Locality	Change in NDVI regime 2000-2010 / 2011-2021	Trend and breakout	Land cover 2000's	Land cover 2020's
Nuwaragala	Bimodal (max Mars) becomes Unimodal (max October).	Regular increase	Open woodland	Dense woodland
Badulla	Same seasonal profile with higher values	Regular increase	Cropland mosaic	Cropland mosaic
Monaragala	Same seasonal profile with higer values	Regular increase	Cropland mosaic	Cropland mosaic
Salmanawewa	Unimodal (max Mars) becomes Sempervirent	Regular increase	Cropland mosaic	Cropland mosaic
Udawalawe	Unimodal (max Mars) becomes Sempervirent	Regular increase	Open woodland	Dense woodland

Therefore, on this scale, the main LULCC in Sri Lanka revealed by the trends analysis of MODIS and Google Earth visual interpretations can be explained by different factors imposing their own dynamics. The first one is urban growth. On a national scale, the growth of Colombo appears first but various patches reveal subaltern urbanization as well. The second driver of change detected is a set of national planning decisions in terms of infrastructure development. This driver covers the planned settlement of houses and agricultural fields, and the management of protected areas (creation, replantation). The third driver comes under rural dynamics (apart from settlement programmes). Interestingly, the only rural dynamic revealed by this method is an increase in tree density in rural landscapes over the Uva Province, constituting a general increase in tree cover replacing seasonal cropland.

Detection of trends along the South and East coasts

By isolating the South and East coasts, a similar series of LULCC directly or closely linked with rapid development, and in particular, infrastructure development driven by political interests, especially in tourism development, is observed. Various examples of the first two dynamics can be found and studied at a finer scale on the South Coast (Figure 4). Several patches of urban growth have been mapped (Galle, Matara) (see Supplementary Material 2, Figure SM2.1). Infrastructure development can be perceived as patches of deforestation at the sites of the Mattala International Airport and the industrial complex adjacent to the port of Hambantota (Figure SM2.2). Settlement programmes are detected in the northeast of Hambantota (Wediwewa), along with urban growth in the form of wooded 'home gardens' in newly

built-up areas (Figure SM4.4). Two patches of increase of vegetation cover and biomass appear in protected areas of the South Coast, Kalametiya Lagoon and Bundala National Park (Figure SM4.2). These dynamics were further studied based on high resolution remote sensing, field observation and interviews.
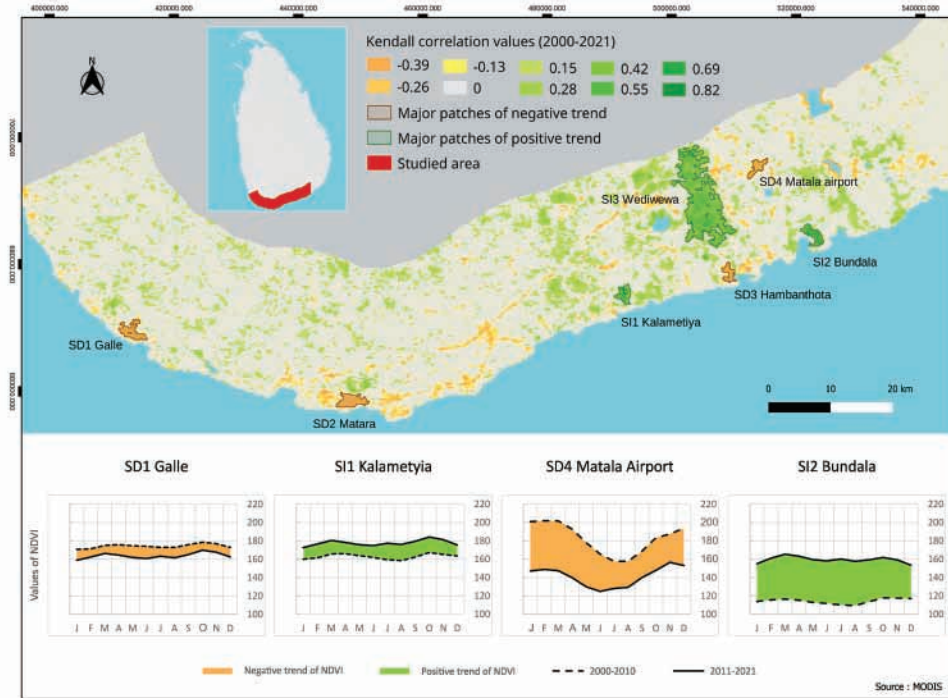

Figure 4: Changes in NDVI values from 2000 to 2021 on the South Coast

The coastal stretch presents a series of lagoons where mangroves develop. Since the Tsunami of 2004 and the 'Reducing emissions from deforestation and forest degradation in developing countries' (REDD+) programme, the restoration of mangroves is an important concern in Sri Lanka. Mangroves in Galle have shown a moderate (17.3 ha) increase from 1988 to 2020; in particular, 30.7 ha which constituted water downstream of the lagoon in 1988 became mangrove in 2020, in the main patch, east of the city. In the same period, 13.4 ha of mangroves disappeared into many small scattered patches (Figure SM 2.1).

Further east on the south coast, the Kalametiya lagoon appears as one of the significant patches of increase in vegetation cover and biomass. Sedimentation, botanical changes, and water pollution were studied during the research programme. The rate of area increase in the Kalametiya mangrove cover was 5.82 ha in year 1. With a total percentage increase of 1451% (Figure SM4.3).

from 1956 to 2021, the vegetation was also made of mixed stands of four true mangrove species. After 2000, due to cryptic ecological degradation, only *Sonneratia caseolaris* has increased in cover. This took place with a drastic decrease in salinity and bulk sedimentation. Excess freshwater generated from the Udawalawa irrigation project which came into operation in 1967 happened to bring a large amount of sediment/silt (Madarasinghe *et al*., 2020; Kodikara *et al*., 2022). Due to this ill-planned project, lagoon salinity has drastically dropped (nearly freshwater condition) and a low saline mangrove species (*e.g*., *S. caseolaris)* has dramatically increased. However, the measured heavy metal pollution (brought by inland freshwater and sediments) remains under the thresholds of concern for public health (Kodikara *et al*., 2022). A similar trend could be observed at the Bundala lagoon.

On the East Coast (Figure 5), some patches of the significant decrease in NDVI values occur in the Muttur

area (c.f. supra), south of Trincomalee, corresponding to post-war settlement programmes, corroborated by stakeholder interviews in three communities in the case study area, outlined below (Figure SM2.3). On the other hand, a significant increase in NDVI values occurs on the East Coast. Many forest reserves have been declared, especially in Eastern Province around 2013 by the Forest Department. On the Batticaloa coastline, the greening results from the combination of three dynamics all converging toward more tree cover. First, this coastline has been the object of replanting, especially of *Casuarina equisetifolia* especially after the 2004 Asian tsunami (Mathiventhan & Jayasingam 2014). Second, cashew orchards (*Anacardium occidentale*) have increased in this region along with the agricultural crops in certain coastal areas. Third, touristic and wooded urbanization also occurred. Stakeholder interviews in study sites in coastal Batticaloa did not indicate the destruction of forests or mangroves during the last decade. Destructive environmental activities reported were mostly limited to instances of sand mining (Mathiventhan, 2013) and some very local degradation of mangroves (Dahdouh-Guebas

Figure 5: Trends in NDVI on the East Coast (2000–2021)

et al., 2021). Mangrove destruction had also been noticed before 2009, for security reasons, along both sides of the main driveway during the armed conflict (Mathiventhan, 2007).

Discussion

This paper is aimed at linking national scale trends detected in NDVI values with interdisciplinary research generated by local case studies, based on MODIS and Landsat satellite data.

Accuracy, robustness of change detection and analysis

Results from MODIS on a national scale have been tested for significance, and appear consistent with the other data. It is an example of very robust but simple results.

At larger scales (coastal regions and local case studies) the same trends have been observed and confirmed by all the other data sets (visual interpretation from Google Earth images, land cover changes from LANDSAT with precision around 80–85%) and field observation, when this has been possible. These integrated results can therefore be considered trustworthy in relation to the main interpretations:

- Sri Lanka is mostly stable in its vegetation cover and in the case of changes analysed, greening is more important than browning. This encompasses a variety of processes (tree densification in agricultural landscape, biomass increase in protected areas), not all corresponding to a 'healthier' environment (biomass increase explained by invasive species).
- The main driver of change is national scale infrastructure development (direct and indirect changes), based on political interests. Urban growth (including the sprawl of home gardens, which appears as greening), rural settlement, and port and airport construction are the main changes observed.

However, limitations need to be considered. The first is that each scale of observation (and for imagery each resolution) reveals its scale of changes. The visual interpretation of metric resolution Google Earth enables us to see individual trees grow or being cut. The Landsat 30 meters resolution enables a fine scale mapping by classification methods where a change between 2 land cover types (*i.e.*, forest cleared for crops) can be detected if larger than a few hectares. MODIS, at 230 meters of resolution might smooth changes of very fine grain. Some minor changes might, therefore, not have been detected. That might give a first explanation of the
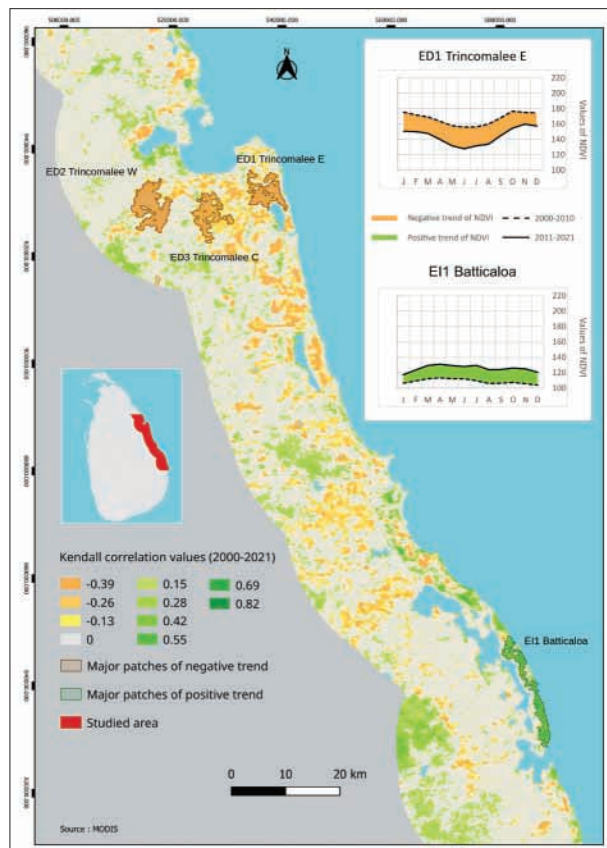
smaller proportion of changes detected, in comparison to Rathnayake *et al.* (2020). Changes of surfaces of the size of a LANDSAT Pixel (900 m²) surrounded by a stable land cover of the size of a MODIS pixel (53 000 m²) would have been detected by their method but not by ours. Another explanation might be given by two steps of our method dedicated to filtering significant changes from insignificant ones: with the P-value test set at 0.0001 the removal of changes sensitive to the 2 first and or the 2 last years of the time series. It is normal that a method filtering only significant changes shows fewer changes than a method listing all detected changes. With similar data (LANDSAT) focussed on the LULCC Hotspot on the South and East coast, we found high LULCC rates ranging from 23% for Hambantota-Bundala to 31% for Trincomalee and 48% for Galle.

Therefore, in addition to the previous state of the art describing 13.5% of LULCC in the Island, the present multiscale approach brings a more contrasted estimation. First, by revealing only changes appearing on a large scale (250 m), only 7.5 % of the Island appears with significant (p value 0.0001) changes. Then, by focusing on hotpots of coastal changes at a higher resolution, changes locally appear as much more important.

Coastal environment and infrastructure development on South and East coasts

Infrastructure development emerged as the main driver of LULCC in the case study areas on the south and east coasts when the results of remote sensing were compared with social analysis, based on a literature review and stakeholder interviews, as previously stated by Rathnayake *et al.* (2020). For nearly half a century, Sri Lanka has undergone a major move towards development of infrastructure of different sizes and types (Perera, 2014). From major industrial port projects, the expansion of irrigated areas (*e.g.*, Mahaweli Development Programme) and tourism resorts, the spectrum of this infrastructure is wide, as is its consequences on physical spaces and social dynamics already impacted by a post-conflict (civil war) and post-disaster (tsunami of 2004) context. The main thrust of the state's economic strategy in both the Southern and Eastern Provinces of Sri Lanka in the post-war period (since 2009) has been on such infrastructure development (Perera, 2014). In the Eastern Province, this strategy has been particularly focused on increasing connectivity and trade with the rest of the island by developing roads, railways, transport, electricity and water supply, hotels and tourism, as well as improving the economic and living conditions of the population (Perera, 2014). National poverty reduction programmes were implemented alongside infrastructure for livelihood development through micro-small enterprise promotion and micro-credit services, targeted at the large numbers of returning internally displaced persons (IDPs), who needed to be resettled. The government also supported private sector investment in establishing manufacturing industries, as well as tourism facilities. However, the dominant approach to infrastructure development has been accompanied by a heavy military presence (Buthpitiya, 2013; Perera, 2014), exclusion of local communities in decision-making and/or access to employment in these development programmes (Buthpitiya, 2013), inadequate power-sharing between central and provincial government (Perera, 2014), and lack of attention to political and socio-economic grievances, peace building and reconciliation (Perera, 2014). In the Southern Province, infrastructure development (in the form of roads, port, airport, industrial zone, hospital, conference centre, stadium), has also been accompanied by livelihood development in agriculture, micro-small enterprises and industries, as well as expansion of human settlements. However, as this province was not directly affected by war, negative political, economic, and social impacts might not have been as severe as in the Eastern Province.

While population growth, expansion of human settlements, and agricultural activities have contributed to LULCC in Sri Lanka, these processes also appear to be largely driven by infrastructure development initiated by the state, creating underlying conditions for the expansion of other activities. In the desired trade-off between development and environment conservation, Sri Lanka thus appears to emerge in a median position where recent strategies have neglected neither the economy nor biodiversity. However, stakeholder interviews revealed that projects implemented by the state in the last decades have targeted material wellbeing of coastal communities, without adequately addressing relational and subjective wellbeing, which were perceived as important by coastal communities. Moreover, negative impacts of infrastructure development on coastal ecosystems, such as sand mining, degradation and filling of wetlands and lagoons were reported by research participants in these communities on the east coast. Similar impacts also emerged on the south coast, where Hundlani (2019) referring to the port of Hambantota, wrote that 'Tourism and industries as well as the construction of new infrastructures (dams, power plants, roads, ports), aiming to foster and sustain development, are causing displacement, pollution, land degradation and water shortage, particularly affecting the communities of farmers and fishermen whose livelihoods are based on such natural resources. To do so, 40,000 m³ of material

was dredged from the nearby Karagan Levava Lagoon, which essentially destroyed the entire ecosystem of the lagoon and surrounding habitats.' Weerasekara *et al.* (2015) studied the impacts of pollution (solid waste and untreated industrial effluents) while Senevirathna *et al.* (2018) mentioned coastal erosion in this area.

Thus, infrastructure development has had negative impacts on both the coastal environment and well-being of communities on the South and East coasts of Sri Lanka.

CONCLUSION

Overall, the remote sensing results of this study reveal stability in Sri Lanka's vegetation indexes, therefore in its vegetation cover and activity. It also reveals that greening, rather than browning in vegetation cover, is the more prominent trend in Sri Lanka. Regionally, this increase in tree density in agricultural landscapes is most visible in the Uva Province, as well as several locations in the Sabaragamuwa and Northwestern provinces. The Local Hotspot of LULCC studies with LANDSAT revealed 30% (Hambantota-Bundala) to 50% (Galle) of land cover change. However, infrastructure development in coastal areas, more specifically in the Southern and Eastern provinces, chosen as case study sites in this research, has resulted in a decrease in vegetation cover, especially in the Hambantota and Trincomalee districts. The changes in LULC are confirmed by stakeholder interviews on the ground. In coastal areas of both districts, the decrease in vegetation cover is a consequence of the implantation of major infrastructure such as ports, industrial zones, roads, and irrigation devices, as well as the expansion of social infrastructure, such as displacements followed by new settlements.

Stakeholder interviews revealed that the state's attention to the impacts of infrastructure development on coastal ecosystems was inadequate as revealed by sand mining or degradation of wetlands. A better focus on preventing environmental destruction, pollution, and waste, and increased awareness among all stakeholders on conservation of the coastal environment is necessary. Moreover, the main development thrust of the state in implementing infrastructure development has been the material well-being of coastal communities without adequate consultation of these communities. A broader and inclusive policy approach to wellbeing would improve benefit-sharing with communities affected by infrastructure development, and sustain better the coastal environment, upon which they depend.

With remote sensing results as a proxy for environmental assessment, no major environmental degradation is observed on the South and East coasts. Some landscapes have been transformed during the last decades, but without a major negative trend (*e.g.*, deforestation). Protected areas seem to play an important role in preserving stable landscapes on the coast. However, some major infrastructure seems to have seriously impacted the environment on a local scale, such as the area surrounding the port of Hambantota, constructed around a coastal lagoon. Protected areas seem to be more affected by external threats (*e.g.*, construction of major infrastructure, upstream pollution, encroachment) than by activities of the local population (*e.g.*, pasture) but the regulation of protected areas focuses overwhelmingly on social and economic activities, rather than the impacts of infrastructure. The development and conservation of coastal areas in Sri Lanka come under the Coast Conservation Act No 57 of 1981 and Amendment No 49 of 2011. However, a multitude of other acts and regulations pertaining to wildlife, forestry, fisheries, and marine environment also apply. There is often a lack of coordination, sometimes duplication, by the institutions mandated to regulate development activities that impinge on coastal protected areas. Thus, there is a need for integrated area-based management to prevail over sectorial policies so that conflicts between the conservation of protected areas and the implementation of industrial hubs are avoided.

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