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Chapter

Utilization of Remote Sensing Technology for Carbon Offset Identification in Malaysian Forests

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Abstract

Rapid growth of Malaysia's economy recently is often associated with various environmental disturbances, which have been contributing to depletion of forest resources and thus climate change. The need for more spaces for numerous land developments has made the existing forests suffer from deforestation. This chapter presents an overview and demonstrates how remote sensing data is used to map and quantify changes of tropical forests in Malaysia. The analysis dealt with image processing that produce seamless mosaics of optical satellite data over Malaysia, within 15 years period, with 5-year intervals. The challenges were about the production of cloud-free images over a tropical country that always covered by clouds. These datasets were used to identify eligible areas for carbon offset in land use, land use change and forestry (LULUCF) sector in Malaysia. Altogether 580 scenes of Landsat imagery were processed to complete the observation period and came out with a seamless, wall to wall images over Malaysia from year 2005 to 2020. Forests have been identified from the image classification and then classified into three major types, which are dry-inland forest, peat swamp and mangroves. Post-classification change detection technique was used to determine areas that have been undergoing conversions from forests to other land uses. Forest areas were found to have declined from about 19.3 Mil. ha (in 2005) to 18.2 Mil. ha in year 2020. Causes of deforestation have been identified and the amount of carbon dioxide (CO₂) that has been emitted due to the deforestation activity has been determined in this study. The total deforested area between years 2005 and 2020 was at 1,087,030 ha with rate of deforestation of about 72,469 ha yr.⁻¹ (or 0.37% yr.⁻¹). This has contributed to the total CO₂ emission of 689.26 Mil. Mg CO₂, with an annual rate of 45.95 Mil. Mg CO₂ yr.⁻¹. The study found that the use of a series satellite images from optical sensors are the most appropriate sensors to be used for monitoring of deforestation over the Malaysia region, although cloud covers are the major issue for optical imagery datasets.

Keywords: Landsat images, tropical forests, deforestation, carbon offset, climate change

1. Introduction

Tropical forests are crucial for mitigating climate change, but many forests continue to be driven from carbon sinks to sources through human activities. To support more sustainable forest uses, therefore forests carbon needs to be measured and monitored at high spatial and temporal resolution. Tropical forest is one of the key ecosystems in addressing issues relating to climate change as it known to store large amount of carbon [1]. Retrieving tropical forest carbon over large areas has been challenging since decades due to the limited data resource, accessibility, and numerous technical issues. Remote sensing has been used actively for forest carbon estimation since the last three decades and it is proven to be effective [2, 3]. Although there are issues and arguments raised in the estimation accuracy, research is continuously being carried out. Optical or synthetic aperture radar (SAR) system has its own potential in retrieving biomass, but several issues remain unaddressed. While optical remote sensing is usually hindered by cloud, SAR systems are always limited by signal saturation at high biomass levels [4]. However, optical sensors offer better solutions for biomass assessment. Various spectral signatures and several vegetation indices can be derived from multispectral images can make the interpretation of biophysical properties of forests can be carried out conveniently. These are the most significant difference between optical and SAR systems that has made optical satellite data preferable in vegetation studies.

While the world has growing demand energy sector, it is crucial that nations put a collective effort to reduce anthropogenic greenhouse (GHG) emission and limit the global warming below 2°C above pre-industrial times, thus prevent catastrophic effects of global climate change. Mitigating the consequences of global climate change may be a critical societal objective now and within the forthcoming decades. Tropical countries contribute to carbon emissions mainly through deforestation and forest degradation, which accounts for approximately 10% of the world's annual total carbon emissions [5]. National and international initiatives such as reducing emission from deforestation and forest degradation, and forest conservation (REDD+) and carbon offset are dedicated to mitigating the impacts of global warming. To achieve this objective, each nation's carbon emissions resulting from deforestation and forest degradation need to be quantified and tracked over time. At such large geographic scales, a precise, cost-effective, and high-resolution means to monitor changes in aboveground carbon stocks is needed. This chapter is focusing on the roles of space borne remote sensing, especially free-access satellite data in assessing biomass of forest in various ecosystems in Malaysia, i.e., inland dipterocarp forests, mangrove forest, and peat swamp forest.

1.1 Forests in Malaysia

Major forest types in Malaysia are lowland dipterocarp forest, hill dipterocarp forest, upper hill dipterocarp forest, oak-laurel forest, montane ericaceous forest, peat swamp forest and mangrove forest. In addition, there also smaller areas of freshwater swamp forest, melaleuca forest, heath forest, forest on limestone and forest on quartz ridges. Considering the composition of these forests in Malaysia, the types can be generalized into three types, which are inland, peat swamp and mangroves.

The forests in Malaysia are mostly dominated by trees from the Dipterocarpaceae family, hence the term 'dipterocarp' forests. The dipterocarp forest occurs on dry land just above sea level to an altitude of about 900 meters. The term also refers to the fact that most of the largest trees in this forest belong to Dipterocarpaceae family. This type of forest can be classified according to altitude

into lowland dipterocarp forest, up to 300 m above sea level, and hill dipterocarp forest found in elevation of between 300 m and 750 m above sea level, and the upper dipterocarp forests, from 750 m to 1,200 m above sea level. However, in Sarawak and Sabah both the lowland and hill dipterocarp forests are known as mixed-dipterocarp forest.

Currently, lowland dipterocarp forest is very few left outside of protected areas such as parks and wildlife reserves. While most of the country was covered with lowland forest in the past, today the majority has been cleared for other land uses. The few remaining pockets are under the gazetted land as Forest Reserves. Moreover, forest in this regime is also being central attraction for timber extractions. There is a real need to put more effort in saving and protecting this precious habitat type. Fortunately, some State (i.e., Provincial) Governments have halted land clearing for agriculture. It is vital that all remaining forest areas are protected. In this way, this valuable natural habitat can be managed on a sustainable basis.

1.2 Reducing emission from deforestation and forest degradation, and forest conservation (REDD+) in Malaysia

The REDD+ mechanism was agreed at the 15th Session of the Conference of Parties (COP 15) United Nations Framework Convention on Climate Change (UNFCCC), 2009 in Copenhagen. The REDD+ mechanism includes reducing emissions from deforestation, forest degradation, conservation, sustainable management of forest and carbon stock enhancement. It was also agreed that parties implementing REDD+ would need an effective national strategy or action plan and a transparent national forest monitoring and governance system. Ultimately, this mechanism was created to provide an incentive for developing countries to protect, better manage, and wisely use their forest resources, thereby contributing to the global fight against climate change.

Following COP 15, the progress in the REDD+ negotiations have been relatively rapid, with the most significant developments occurring in the last couple of years. Seven important decisions were adopted in 2014 for REDD+ governing methodological issues on safeguards, measurement, reporting and verification (MRV), development of national forest monitoring systems, addressing drivers of deforestation, and technical assessment of reference levels. In addition, the modalities for institutional arrangements at the national level for REDD+ implementation and results-based payments were also agreed.

Consensus on REDD+ was reached at the UNFCCC's COP 15, which agreed on the need to provide positive incentives. This is followed by the Warsaw Framework for REDD+ providing guidance on all the requirements to obtain Results Based Payments (RBP). The agreed REDD+ to capture activities are (i) reduction of emissions from deforestation, (ii) reduction of emissions from forest degradation, (iii) conservation of forest carbon stocks, (iv) pursuance of sustainable management of forests, and (v) enhancement of forest carbon stock.

Malaysia's forests can be categorized according to the degree of protection and land use classification. Management of forest land falls under three broad categories, which are: (i) Protected Areas/Totally Protected Area which consist of, national and state parks, wildlife sanctuaries, and nature reserves, (ii) Permanent Reserved Forests (PRFs) /Permanent Forest Estate (PFEs)/Permanent Forest Reserves (PFR), which are primarily natural forests to be maintained and managed sustainably for production and protection, and (iii) Stateland forest which are forest land reserved for future development purposes.

REDD+ is more than just a means of assigning monetary value to forest carbon stocks. It is also about ensuring the livelihoods of those whose culture, survival and heritage depend on the forests themselves.

1.3 The Paris agreement

The Paris Agreement builds on the Convention by bringing all nations together for the first time to commit to ambitious efforts to prevent climate change and adapt to its effects, with increased support for developing countries. As a result, it sets a new direction for the global climate effort.

The main goal of Paris Agreement is to enhance the global response to the issue of climate change by keeping a global temperature rise this century not more than 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C [6]. In addition, the agreement intends to improve countries' ability to deal with the effects of climate change. Appropriate financial flows, a new technology framework, and expanded capacity building frameworks will be put in place to achieve these lofty goals, allowing developing countries and the most vulnerable countries to pursue their own national ambitions. Through a more rigorous transparency structure, the Agreement also provides for increased action and support transparency.

1.4 Nationally determined contribution (NCD)

Nationally determined contributions (NDCs) are at the core of the Paris Agreement and the achievement of these long-term goals. Malaysia intends to reduce the emission intensity of the greenhouse gas by 45% by 2030; in which corresponding to GDP [7]. In this circumstance, developed countries should involve 35% on an unconditional basis and a further 10% is condition upon receipt of climate finance for advanced technology transformation in construction capacity enhancement. In fact, this can assist in monitoring GHG.

Since the Paris Climate Agreement was signed in late 2016, governments all over the world have been submitting plans for reducing CO₂ emissions through their NDCs. The NDCs was previously known as "Intended Nationally Determined Contributions" (INDC) and it is submitted to the United Nations Framework Convention on Climate Change (UNFCCC) once the countries ratified to the Paris Agreement. Currently, 197 parties to the Convention had submitted their INDCs and 150 had ratified it including Malaysia.

There has been no baseline prediction or quantified analysis of baseline measures provided, but Malaysia's NDC indicated a 2005 as base-year emission level of 288 Mil Mg CO₂e, which includes emissions of 25 Mil Mg CO₂ from the LULUCF sector.

In 2014, Malaysia produced an Emissions Intensity Reduction Roadmap. According to the report, the country has chances across many sectors to fulfill the reduction target of a 40% decrease in GDP emissions intensity [8]. However, even if these opportunities exist, significant work would be necessary to achieve these emissions reductions, given the challenges of a 4.8 percent yearly rate for the per capita emissions between years 2000 and 2030. [9]. Energy for transportation is expected to rise at a pace of 5.3 percent per year over the next 25 years, making it the fastest-growing sector. Malaysia's ultimate energy needs are predicted to treble by 2030, compared to present levels of consumption.

While the "ambitious scenario" indicates that Malaysia would be able to meet its Paris agreement NDC reduction target, substantial assistance from international funders is required. When both LULUCF emissions and removals are included, the

GHG emission intensity per GDP in 2030 increases when compared to 2005 levels. This is since increase in removals by the LULUCF sector is much lower than the increase in emissions from the other sectors.

To achieve this target, a carbon offset project must be developed. Forest conservation is one of the options that can be explored since the forests are able to sequester CO₂ at considerable amount. Several options have been recognized by the Verified Carbon Standards (VCS) that there are 7 types of projects related to forest conservation that can be intervened as carbon offset project (**Table 1**) [10].

1.5 Carbon offset initiative

Carbon offsetting is the process of compensating for CO₂ pollution (carbon footprint) by avoiding similar pollution from occurring elsewhere. One carbon offset entail compensating for the emission of 1 Mg of CO₂ into the atmosphere by preventing the emission of 1 Mg of CO₂ somewhere on Earth. The underlying concept is that developed countries pay poor countries (or assist them in other ways) to reduce global emissions on their behalf. In theory, carbon offsetting can assist the world to combat global warming if offsets are used to fund good, long-term environmental projects that would not have occurred otherwise.

There are dozens of different techniques to reduce carbon dioxide emissions, ranging from energy efficiency and renewable energy to forest planting. The most popular projects are those involving renewable energy; the most contentious are those involving forestry [11].

Malaysia has a lengthy history of forest management. However, some forest areas have been damaged as a result of prior management practices. The cost of

No.	Project type	Definitions
1	Avoided planned deforestation	Avoided or stopping any logging/ plantation concession that involves deforestation. Carbon stock refers to the carbon stored in trees, whereas abatement refers to the net reduction in greenhouse gas emissions as a result of a project.
2	Wetland restoration and conservation	Increasing GHG removals by restoring wetland ecosystem by rewetting or avoiding the degradation of wetlands.
3	From low to high productivity forest	Convert low-productivity forests to high-productivity forests to increase carbon sequestration. Improved stocking density in low-productivity forests can help to boost carbon stores.
4	Conversion of logged forests to protected forests	Converting logged forests by eliminating harvesting of timber, biomass carbon stocks are protected, and can increase as the forest grows and/or continues to grow.
5	Reduced impact logging	Switching from conventional logging to RIL during timber harvesting. Carbon stocks can be increases by reducing damage to other trees, improve selection of trees, improve logging plan, etc.
6	Afforestation / Reforestation	Increase carbon sequestration via planting or human-assisted natural vegetation to develop, increase, or restore vegetative cover (forest or non-forest).
7	Extending the rotation age of evenly aged managed forests	Extending the forest rotation age or cutting cycle and increase carbon stocks. No fixed period of years to be extended, but generally the longer the period, the more average carbon stock increases.

Table 1.
Types of potential carbon offset project in Malaysia.

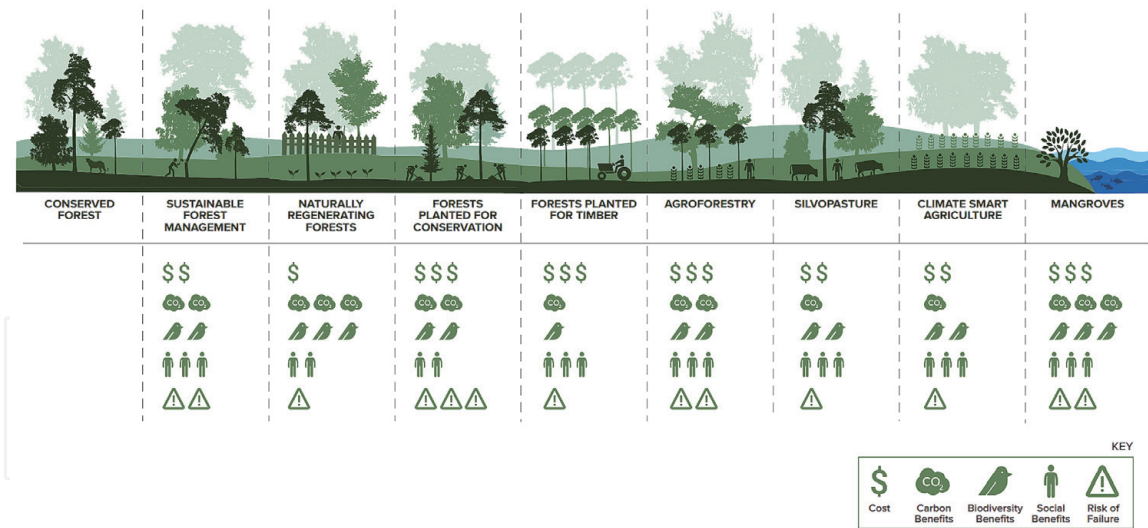


Figure 1. Different restoration strategies can be used for different purposes and have different trade-offs.

restoring and rehabilitating these forests is high, as is the cost of caring for them. Each project type will have different implications on the cost, carbon benefits, biodiversity benefits, social benefits, and risk of failures. **Figure 1** illustrates how these implications could occur when a project type is chosen as carbon offset project [12].

2. Methodological framework

This study includes estimation of the national greenhouse gas emission trends from 2005 through 2020. This is to ensure that the LULUCF sector is the right area to venture for the carbon offset project. This is because the LULUCF sector also does emit CO₂ in various manners. Therefore, instead of CO₂ sink, it can be a source of CO₂ emission as well at some extend. To ensure that the GHGs reported in this study is comparable to UNFCCC, the estimates presented here were calculated by using methodologies consistent with those recommended in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. This study will not be used as regard to the carbon offset under the Paris Agreement and other international obligations but can be considered as an index that shows the extent of Malaysia mitigation measures implemented to combat the global warming.

2.1 Activity data

Remotely sensed data was used in this study for the years between 2005 and 2020 to estimate greenhouse gas emissions/removals, with 5-year interval. The reason for using these data due to its availability as independent data, it has a consistent time series and compatible with alternative data sources. In addition, the activity data obtained from Landsat satellite images are not found in any publication. Since the optical images over Malaysia are always hindered by cloud covers, a considerable number of datasets were required to produce a seamless mosaic of the images (without clouds). The Landsat images, covering the entire Malaysia that were used in this study are summarized in **Tables 2 and 3** and **Figure 2**.

2.2 Production of seamless mosaic, time series Landsat images

According to **Table 2**, only 29 scenes of Landsat images are required to produce a mosaic that cover the entire Malaysia. However, being in the tropical regions, Malaysia is always covered by clouds that is almost impossible to be removed completely. Therefore, several images acquired at different dates over the same scenes are required to produce a cloudless image. The study has set a limit of five best images of the same scenes acquired circa three years of the targeted year to be used for further processes. These images must have <30% cloud cover and acquired within the specific periods (**Table 3**). Even though Landsat has 16-day repeat cycle, which are producing about 22 images over the same scene in a year, it is still difficult to find the best five images within 3 years. This is due to the heavy cloud covers in the atmosphere of Malaysia, especially at the mountainous areas and during the monsoon season (October – February). Cloud covers in most of the scenes are ranging from 10 to 90% and therefore, the chance to obtain <30% cloud cover is very small.

However, this issue has been solved by having several good quality scenes. The clouds on these images were detected and masked by using F_Mask algorithm [13]. **Figure 3** shows the example of cloud masking a process was carried out to produce a cloudless mosaic of the scene 126/058 (**Figure 4**) that were acquired from various dates. This process is repeated for the other scenes and throughout the intervals (2005, 2010, 2015 and 2020). Altogether 580 scenes were processed to produce a seamless mosaic image for each time series. The final product is shown in **Figure 5**. Although the image looks clean, there is about ~1% of hollow pixels still appear on

Satellite	Sensor	Date of acquisition	Time series (year)
Landsat-5	Thematic Mapper (TM)	January 2004–December 2006	2005
		January 2009–December 2011	2010
Landsat-8	Operational Land Imager (OLI)	January 2014–December 2016	2015
		January 2018 – March 2020	2020

Table 2.
 Satellite images that were used as activity data.

Region	Landsat Scene		
	West Malaysia	East Malaysia	
State	Peninsular Malaysia	Sarawak	Sabah
Scene ID (Path/Row)	128/055–057	121/058–059	118/055–057
	127/056–058	120/058–059	117/055–057
	126/056–059	119/057–059	116/056–057
	125/058–059	118/058–059	
Scenes required to cover Malaysia	12	9	8
Scenes acquired to produce cloud-free data	60	45	40
Scenes acquired to produce time series data (4 series)	240	180	160
Total scenes acquired	580		

Table 3.
 Summary of Landsat scenes datasets required to produce seamless mosaics over the entire Malaysia.

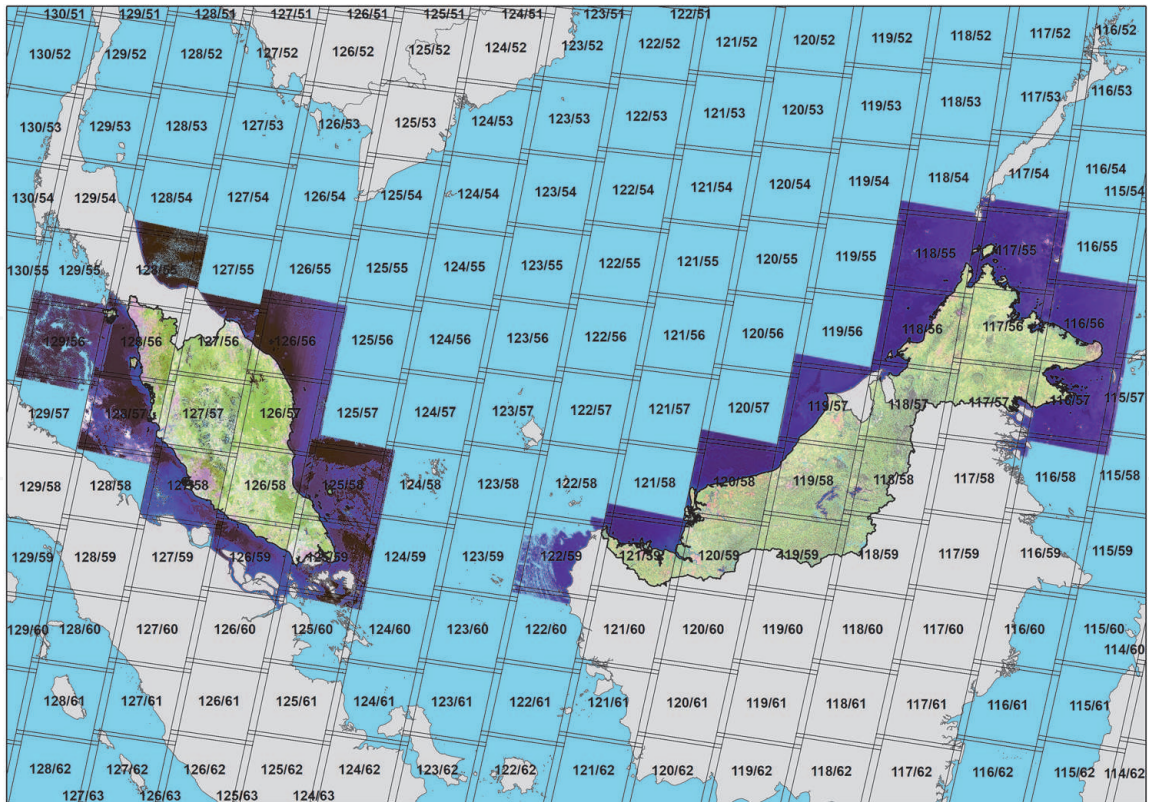


Figure 2.
Landsat scenes coverages over the entire Malaysia.

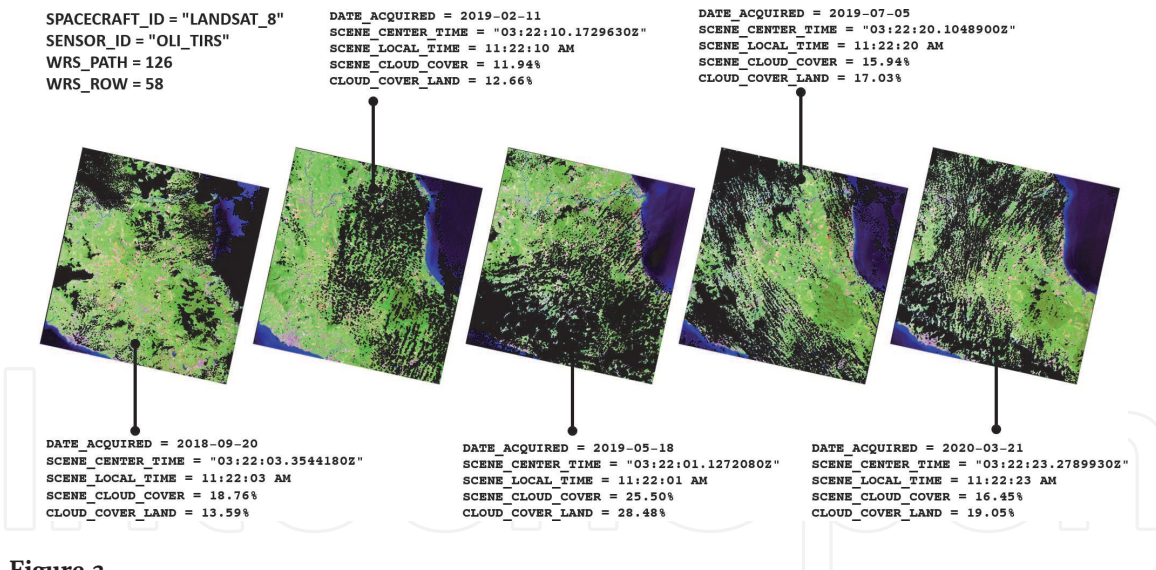


Figure 3.
Cloud masking process of Landsat scene 126/058.

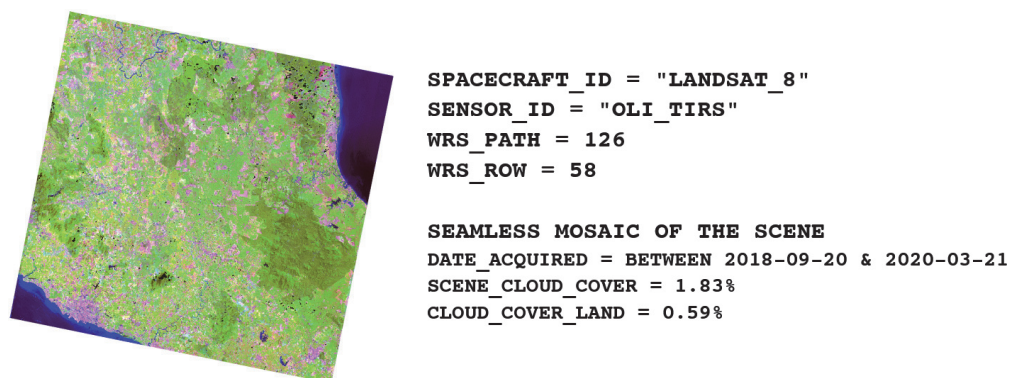


Figure 4.
Cloudless image of Landsat scene 126/058.

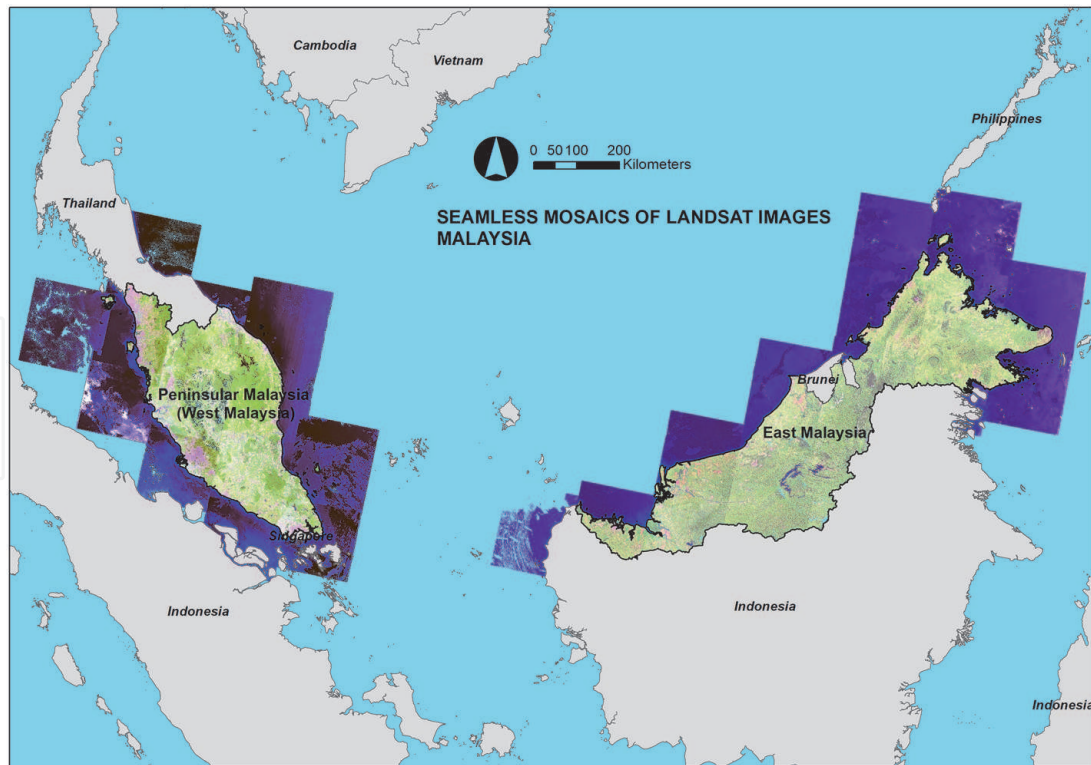


Figure 5.
Cloudless image of Landsat images over Malaysia.

the images, especially at the highlands and top of mountains areas. This is due to the clouds that always there all the time regardless weather conditions and seasons.

2.3 Image classification

Forest includes all land with woody vegetation consistent with threshold (minimum mapping unit (MMU) is 0.5 ha, minimum crown cover is 30% or minimum height at maturity is 5 m) used to define forest land in the national statistic. It also includes system with vegetation structure that currently falls below threshold, but in situ could potentially reach the threshold value is expected to exceed (the threshold of forest land category is sub-divided at the national level into managed and unmanaged and by ecosystem type as specified in the IPCC Guidelines) [14]. In this study, forests are divided into three major ecosystem types, which are inland forest, peat swamp forest and mangrove forest. These areas were further divided into Permanent Reserved Forests (PRFs)/Permanent Forest Estate (PFEs)/Permanent Forest Reserves (PFR) as managed category and the remaining areas outside the managed areas as stateland forest [15]. **Figure 6** illustrates how the forests is defined and various conditions (due to management practices and natural disturbances) that possibly occur in the forests in Malaysia.

Understanding these conditions and management practices in forestry sector in Malaysia are crucial before these forests are interpreted and classified on the satellite images. Having several secondary data before hands are desirable and can facilitated the classification processes. Spatial information such as boundary of the PRFs, the management regimes, types and locations of varying ecosystems are required to ensure that the classification is performed accurately. In this case, the classification was performed to delineate forests from other land features. This process was performed by using traditional supervised classification method. Several training sets were selected on the images. Unchanged forest areas, which were determined from secondary spatial data were used as forest training sets, and the

other land cover classes were determined from the image interpretation. The same training set was used for forest class for all time series.

The biggest challenge in the image classification was about to deal with huge data size and to produce classification results with minimal uncertainties. Manual editing of the classification results was typical and need to be done repeatedly, which is a tedious process and time consuming. However, the results are satisfying, and the example of the classification results are depicted in **Figure 7** for the year 2020. The classification results in pixels form were converted to vector format

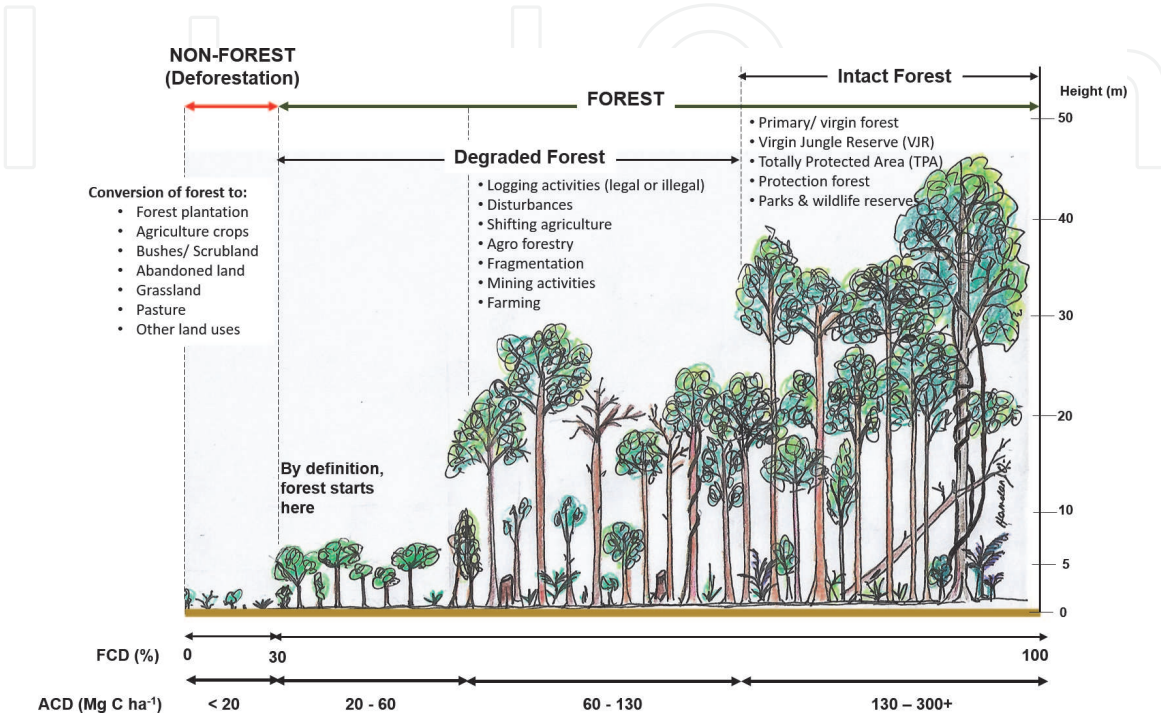


Figure 6.
Common structure of forests in Malaysia.

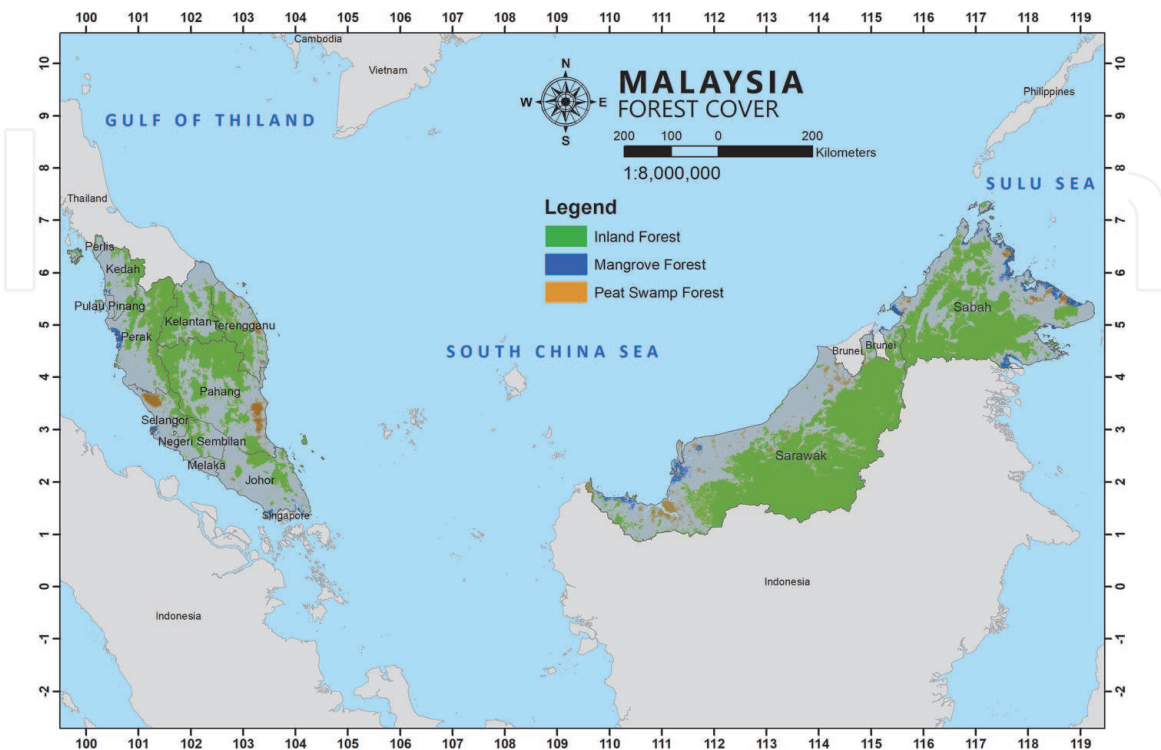


Figure 7.
Forests in Malaysia classified from the images.

Region	Forest Cover (ha)			Total Forest Cover (ha) (d) = (a) + (b) + (c)	Land Area* (ha) (e)	Percentage (%) (f) = (d)/ (e)*100
	Inland Forest (a)	Peat Swamp Forest (b)	Mangrove Forest (c)			
Peninsular Malaysia	5,338,082	243,504	110,953	5,692,539	13,100,367	43.5
Sarawak	7,328,029	320,207	139,890	7,788,126	12,444,951	62.6
Sabah	4,273,536	97,276	378,195	4,749,007	7,390,224	64.3
Total	16,939,647	660,987	629,038	18,229,673	32,935,542	55.3

**Sources: Department of Survey and Mapping Malaysia, Lands and Surveys Department, Sabah and Department of Land and Survey, Sarawak.*

Table 4.
 Composition of forest cover in Malaysia (2020).

(.shp) for further analysis and post-classification detection process. From the vector data, the areas for each forest type classified from the images were determined. Example forest area statistics derived from the vector data is summarized in **Table 4** for the year 2020.

2.4 CO₂ emissions calculation

Carbon dioxide (CO₂) is the main greenhouse gas that plays critical roles in regulating the earth's climate. According to IPCC, there are two basic approach to estimate CO₂ emissions/removals, which is Gain-Loss Method (GLM) and Stock-Difference Method (SDM). Calculation methods for this study are determined by SDM at Tier-2 level by using CO₂ based on [16]. The result is then multiplied by 44/12 or equal to 3.67 unit of carbon (C). Since the emission from the forestry activities are considered, the CO₂ in this study is attributed only from the forest carbon stock, and it is not equivalent to emission from other gases. Therefore, the reported emission is in carbon dioxide (CO₂) and not carbon dioxide equivalent (CO₂e).

2006 IPCC Guidelines offer a default methodology that includes default emission factors for Tier-1 [14]. Tier-1 level is designed to be the simplest to use, for which equations and default parameter values (e.g., emission and stock change factors) are provided by 2006 IPCC Guidelines. The emission factor is derived from readily available statistical information, which often globally available sources of activity data estimates (e.g., deforestation rates, global forest cover maps, etc.) although these data are usually spatially coarse.

Meanwhile, Tier-2 level use the same or similar activity data to Tier-1 level but applies emission and stock change factors that are based on country- or region-specific data. Country-defined emission factors are more appropriate for the local climatic regions and land use system. In many cases the Tier-2 could also be applied at a higher level of temporal and spatial resolution and more disaggregated activity data, where the activity statistics are further split into sub-categories.

Higher-order approaches are utilized at the Tier-3 level, such as models and inventory measurement systems suited to national circumstances, repeated over time, and driven by high-resolution activity data disaggregated at the subnational level. Higher-order approaches produce more accurate estimations than lower-tier approaches.

Estimated carbon stock (Mg C) in the stock change method is obtained by multiplying the forest area (ha) by the carbon stock per unit area (Mg C ha⁻¹). The

carbon stocks of the entire project area at a given time are obtained by calculating the products of the carbon stocks per unit area for each forest type and the area occupied by that type and then summing the results over all forest types.

$$C_t = \sum_{i=1}^n (A_i \times C_i) \quad (1)$$

Where:

C_t = total carbon stock at a certain time t (Mg C)

A_i = area occupied by forest type i (ha)

C_i = carbon stock per unit area of type i (Mg C ha⁻¹)

The emission is calculated as the difference of carbon stocks for a given forest area at two points of time, which is expressed as

$$\Delta C = (C_{t2} - C_{t1}) / (t_2 - t_1) \quad (2)$$

Where:

ΔC = annual carbon stock change in biomass (Mg C yr.⁻¹)

C_{t1} = carbon stock at time 1 (Mg C)

C_{t2} = carbon stock at time 2 (Mg C)

3. Results and discussion

3.1 Changes of forest cover

Deforestation is defined as human induced permanent conversion of forest land to non-forest, i.e., all the forest stands are cut, and the land is cleared and used for another purpose. Temporary change in land use, like one rotation tree crop (up to 25 years) within forest reserves are not considered as deforestation [17]. In a broader term, deforestation converts forest land to alternative, permanent, non-forested land to be used in agriculture, grazing or urban development or clearing of any area of its natural vegetation cover, which normally leads to a decrease in plant population, resulting in a loss of plant biodiversity [18]. Deforestation is caused by multiple drivers and pressures, including conversion for agricultural uses, infrastructure development, wood extraction, agricultural product prices, and a complex set of additional instructional and location-specific factors [7], which can be extremely important in certain localities.

A crude estimate showed that the total forest loss in Malaysia during years 2000–2012 amounted to 14.4% of its year 2000 forest cover [19]. Oil palm expansion was the major reason that contributed to the figure. The oil palm plantation area in Malaysia increased from 5.59 to 11.56 Mil. ha from 2000 to 2018, an increase of 5.98 Mil ha with a growth rate of 106.96%. The area of oil palm plantations in West Malaysia increased by 2.53 Mil ha, with a growth rate of 82.77%; in East Malaysia, the area increased by 3.45 Mil ha, with a growth rate of 136.14% [20]. The growth of oil palm accelerated between years 2000–2010 and become decelerated starting from 2010 onwards. In addition to that, the deforestation was caused by rubber plantation, construction of hydro-electric dam reservoirs, mining activities, forest fire, illegal logging, shifting cultivation, and natural disasters such as tsunami and erosion.

In contrast, the study found that the deforestation from 2005 to 2020 was amounted to the loss only of 1,087,030 ha (5.6%) of its year 2005 forest cover, with

the annual rate of deforestation at $0.37\% \text{ yr.}^{-1}$. Hence the study proved that the reported rate by [19] was not right. The forest cover has reduced from 19,316,702 ha in 2005 to 18,229,672 ha in year 2020 (**Table 5**). This was attributed to reduction in about 3.4% of total forest extents in Malaysia due to the conversion of forest to agricultural lands and settlement, which were mainly under the stateland forest that are designated for development purposes.

3.2 Carbon stock of forests in Malaysia

Aboveground biomass (AGB) comprises all living aboveground vegetation including stems, branches, twigs, and leaves. It is the most important pool of carbon forest types. In this study, a published allometric equation was used to calculate AGB for inland forests [21]. This equation was calibrated based on trees sampled in lowland and hill forests in west Peninsular Malaysia. Wood densities were obtained from the Global Wood Density Database [22]. A biomass expansion factor of 0.47 was used to convert the biomass into carbon stock. Previous study indicated that the average values for carbon stock from all carbon pools in major types of forest in Malaysia as summarized in **Table 6** [16]. A comprehensive review of carbon stock in various forest types and conditions in Malaysia was also made by [23, 24]. However, only the aboveground component of carbon stock is used for the emission calculation in this study.

The most important parameters that play roles that produce variations in carbon stock estimations are (i) the use of different allometric equations in the estimations, (ii) application of different sampling design/protocols, (iii) levels of disturbances in the forest, (iv) harvesting/ logging practices in production forest, and (iv) the selection of study sites. These influence the process of selecting project sites for carbon offset project.

Year	Forest cover (ha)				Percentage cover (%)
	Inland forest	Peat swamp forest	Mangrove forest	Total	
2005	17,949,753	700,401	666,547	19,316,702	58.7
2010	17,329,165	676,186	643,502	18,648,853	56.6
2015	17,088,338	666,789	634,559	18,389,686	55.8
2020	16,939,647	660,987	629,038	18,229,672	55.3

**Given the landmass of Malaysia was at 32,935,542 ha.
 Source: https://www.data.gov.my/data/ms_MY/dataset/keluasan-malaysia.*

Table 5.
 Forest cover in Malaysia (ha).

Forest type	Carbon stock (Mg C ha^{-1})					
	Above-ground	Below-ground	Dead-wood	Litter	Soil	Total
Inland forest	174.49	35.22	4.92	1.29	48.40	264.32
Peat swamp forest	168.63	35.95	21.40	2.19	188.10	416.27
Mangrove forest	135.45	48.57	22.12	3.88	54.87	264.89

Table 6.
 Carbon stock in all carbon pools in major types of forests in Malaysia (Mg C ha^{-1}).

3.3 CO₂ emission from deforestation

Assuming the CO₂ emission occurred was a result from the changes of forest cover, the emission from year 2005 to 2020 was about 689.26 Mil. Mg CO₂, with an annual rate of emission at 45.95 Mil. Mg CO₂ yr.⁻¹. This was equal to carbon loss of about 12.53 Mil. Mg C. **Table 7** summarizes the trend of CO₂ emission that occurred between years 2005 and 2020. The trend indicates that the deforestation accelerated between years 2005 and 2010 and slowed down between year 2010 and 2020. This was mainly due to awareness and mitigation action among government towards REDD+ interventions and enhancement of management practices towards various conservation efforts.

Although there are a few assumptions and generalizations were included in the estimations, the reported figures can present an overall scenario of CO₂ emission resulted from deforestation activities in Malaysia.

3.4 CO₂ emission in forest land remaining forest land

Although deforestation attributed much to the CO₂ emission in LULUCF sector, the remaining forests are still playing roles in CO₂ sequestration while they regrow. However, the rate of CO₂ sequestration is very slow and is greatly depending on the overall management practices applied within the forests. This is also typically occurred within the PRFs where some areas are designated for production purpose with sustainable forest management (SFM) practices. The average rate of sequestration for the major types of forests in Malaysia is summarized in **Table 8**.

Analysis of CO₂ emission and removals from LULUCF sector in Malaysia evidenced that the activity data used are very important to determine the emission and removals within the forest land remaining forest land category. In this case, data such as logging history records, net production (timber volume), and annual allowable coupe (AAC) acquired from the respective forestry departments were used estimate emission from upstream forest operations. Peninsular has contributed net removal from the category was about -0.14 Mil. Mg CO₂ within 5 years from 2005 to 2010. Then, it was followed by net emissions at 14.31 Mil. Mg CO₂ which occurred between year 2010 to 2015 as compared to year 2015 to 2020, which

Time Series	CO ₂ emission (Mil. Mg CO ₂)			Total
	Inland forest	Peat swamp forest	Mangrove forest	
2005–2010	397.05	14.97	11.45	423.47
2010–2015	154.08	5.81	4.44	164.33
2015–2020	95.13	3.59	2.74	101.46

Table 7.
CO₂ emission resulted from deforestation Malaysia (2005–2020).

Forest type	Growth rate AGB (Mg ha ⁻¹ yr. ⁻¹)	Carbon sequestration* (Mg C ha ⁻¹ yr. ⁻¹)
Inland	9.3	4.37
Peat swamp	9.2	4.23
Mangrove	11	5.17

*Carbon conversion factor: 0.47.

Table 8.
Rate of carbon sequestration in major forest types in Malaysia [17].

Year	Net (Mil. Mg CO ₂)			
	Peninsular Malaysia	Sabah	Sarawak	Total (entire Malaysia)
2005–2010	–0.14	–16.22	–11.83	–28.19
2010–2015	14.31	–0.49	–90.44	–76.62
2015–2020	23.53	–72.62	48.87	–0.22

Note: -ve sign is net removal and + ve sign is net emission.

Table 9.
 Summary of CO₂ emission for forest land remaining forest land.

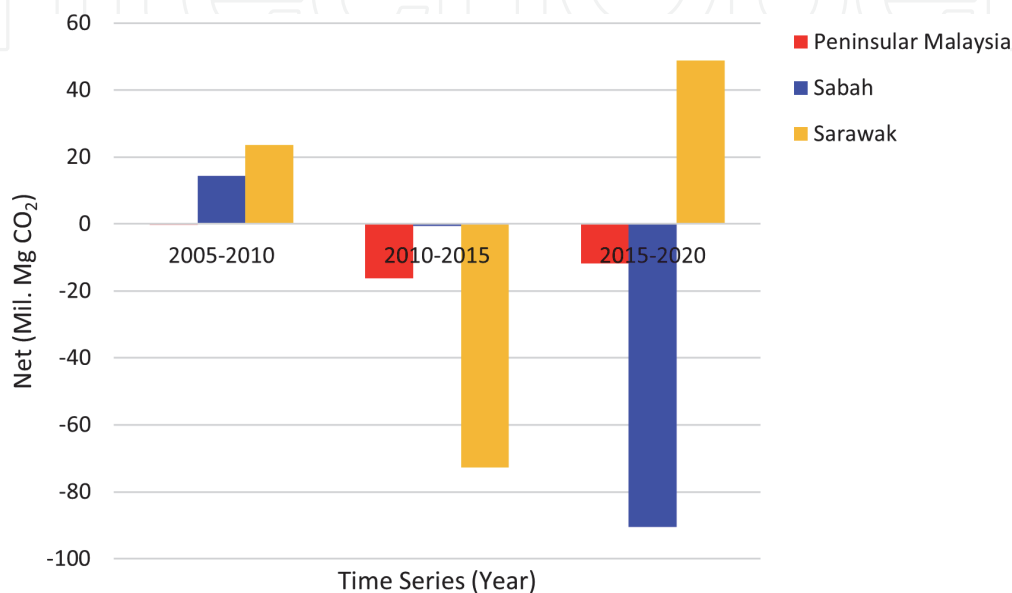


Figure 8.
 Net CO₂ emission/removal in Malaysia.

accounted net emissions for 23.53 Mil. Mg CO₂. Meanwhile, Sabah has contributed net removal from forest land remaining forest land about –16.22 Mil. Mg CO₂ within 5 years from 2005 to 2010. Then, it continued to remove emission at –0.49 Mil. Mg CO₂ between years 2010 and 2015, and even much greater between years 2015 and 2020, with the accounted net removal of –72.62 Mil. Mg CO₂. Sarawak has contributed net removal of about –11.83 Mil. Mg CO₂ in 5 years between 2005 and 2010 and continued to the years between 2010 and 2015 with a net removal at –90.44 Mil. Mg CO₂. However, it emitted back within the years 2015–2020 with the net emission of 48.87 Mil. Mg CO₂. **Table 9** and **Figure 8** summarize the fluctuations in the net emission and removal that have occurred within years 2005 to 2020.

Principally there is not fix trend in the net emission and removal within the category of forest land remaining forest land in each region in Malaysia. This indicates that the activities within the forests are dynamic and unpredictable. Some areas could produce emission, but some other areas sequester carbon and thus resulting in removals. However, taking Malaysia as a whole, there is a trend of continuous removals from year 2005 to 2020 that has been produced by the remaining forests in Malaysia (**Figure 9**).

4. Requirements to offset the emission

It is concluded that the rapid logging operations within the forest can be very dynamic, thus the forests in Malaysia not only remove CO₂ but also produce

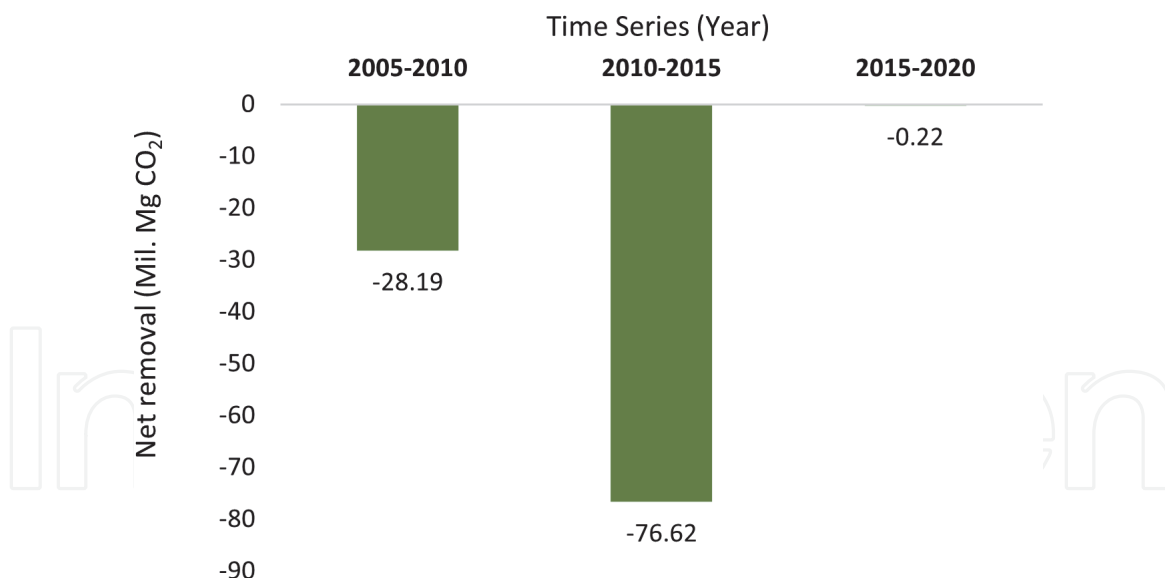


Figure 9.
Net CO₂ removal in Malaysia.

Time Series	Net CO ₂ emission/removal (Mil. Mg CO ₂)		
	Net CO ₂ emission from deforestation	Net CO ₂ removal in forest land remaining forest land	Net CO ₂ emission
2005–2010	423.47	–28.19	395.28
2010–2015	164.33	–76.62	87.71
2015–2020	101.46	–0.22	101.24

Table 10.
Summary of CO₂ emission for forest land remaining forest land.

emissions. These indicated that the forest areas that have been serving for timber production and logging are continuously fluctuating in terms of emission and removals. This area is worth for a carbon offset program because the intervention can stand on all pillars of SFM; ecological, economic, and socio-cultural. The forests' ability to attract investment and support commercially sustainable forest uses is unaffected in the present and future.

Analysis indicated that the LULUCF sector in Malaysia is still producing the net emission at 101.24 Mil. Mg CO₂ at the end series of year 2020 (Table 10). Based on this figure, Malaysia needs to stop completely deforestation activities and restore about 27.6 Mil. Mg C, which is equal to 158,240 ha of natural forest to offset the emission from LULUCF sector in the country. Otherwise, Malaysia must limit logging activities and retain about 631,838 ha of the logging areas to regrow naturally for at least 10 years. This is almost impossible since Malaysia is a developing country and still depending much on the forests for timber productions [25]. While the remaining stateland forests can be demolished at any time for development purposes. Therefore, the finding of this study suggesting that the project types that have potentially suitable for carbon offset program are (i) avoided planned deforestation, (ii) conversion of logged forests to protected forests, (iii) extending the rotation age of evenly aged managed forests, and (iv) avoided deforestation on wetlands (conservation).

The continuing removals indicated that the forest sector contributed greatly to the sinks through forest land remaining forest land. In this case, there are activities

occurred within the forestland that attributed to the CO₂ removals, which could be driven by the good of management practices, such as Forest Stewardship Council (FSC) Certification Scheme. The FSC will conduct an independent review of forest management methods in order to ensure sustainable management practises, sustainable management of Malaysia's natural forest, and to meet demand for certified timber products.

Forest enrichment activities are being made by the forest industry between 2016 and 2020 to rehabilitate degraded forests. Ongoing projects such as the Central Forest Spine (CFS) in Peninsular Malaysia and the Heart of Borneo (HoB) in Sabah and Sarawak serve as facilitators for improving forest connectivity, reducing fragmentation, and improving natural resource management. The forestry sector implemented a REDD+ strategy in 2017 to ensure that at least 50% of Malaysia's land mass is forested, which was accomplished by improving sustainable forest management, conservation activities, and seeking synergies with activities under the National Policy on Biological Diversity 2016–2025 [17].

Nonetheless, the current net removals are still not sufficient to offset the emission that has been produced by the deforestation activities in Malaysia. While the LULUCF sector is producing emission, the other sectors such as energy, transportation, agriculture, solid waste, and others are also emitting CO₂ to the atmosphere at even greater amount. Therefore, carbon offset can not only depend on forests. Appropriate mitigation actions need to put in proper place within the individual sector so that the climate change mitigation can be achieved, and the targeted reduction of global temperature is materialized.

5. Conclusion

The study demonstrated that the use of remote sensing data, coupled with the other supporting data are viable for assessing forest carbon and emissions in forestry sector in Malaysia. Although there were technical issues regarding the data, with appropriate image processing methods, the issues have been well addressed. Landsat satellite images that have been acquired between years 2005 and 2020 with 5-year intervals were processed to produce seamless, wall to wall images over Malaysia. Forests have been identified from the image classification and then classified into three major types, which are dry-inland forest, peat swamp and mangroves. Post-classification change detection technique was used to determine areas that have been undergoing conversions from forests to other land uses.

Forest areas were found to have declined from about 19.3 Mil. ha (in 2005) to 18.2 Mil. ha in year 2020. The study found that the deforestation from 2005 to 2020 was amounted to the loss of 1,087,030 ha (5.6%) of its year 2005 forest cover, with the annual rate of deforestation at 0.37% yr.⁻¹. This has contributed to the total CO₂ emission of 101.46 Mil. Mg CO₂. The study also estimated the total CO₂ emission and removals within the forest land remaining forest land. It was revealed that the forests also produced emission in terms of timber production activities. However, the overall estimates showed that this category is still able to sequester carbon and provide removals at a sum of 105.03 Mil. Mg CO₂ for the period of 15 years (2005–2020).

The study exposed suggested that Malaysia must stop completely deforestation activities and restore about 27.6 Mil. Mg C to achieve the net-zero emission. This is equal to 158,240 ha of natural forest or 631,838 ha of the logging areas to need to be left regrown naturally for at least 10 years. The study also suggested that the project types that have potentially suitable for carbon offset program in Malaysia are (i) avoided planned deforestation, (ii) conversion of logged forests to protected

forests, (iii) extending the rotation age of evenly aged managed forests, and (iv) avoided deforestation on wetlands (conservation).

The study proved that the use of a series satellite images from optical sensors are the most appropriate sensors to be used for monitoring deforestation in Malaysia. Although cloud covers are the major issue for optical imagery datasets, current development in remote sensing, computer technologies and processing algorithms for images analysis can provide solutions for the issues.

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Conflict of interest

The authors declare no conflict of interest.

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