# CARBON SEQUESTRATION MODEL OF TROPICAL RAINFOREST ECOSYSTEM USING SATELLITE REMOTE SENSING DATA

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*To my beloved family and parents*

*especially*

*Ummi Farihah, Muhammad Faris and Farah Aneesa*

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# ABSTRACT

Various measurements methods have been used to determine the validity of the information produced for carbon sequestration especially in tropical rainforests. Generally, these methods can be divided into two major categories which are the micrometeorological and biometric approaches. The former uses remote sensing and tower flux and the latter refers to field direct measurement of biomass. Presently, use of a single measurement approach has sometimes caused uncertainty in the accuracy of carbon sequestration in terms of the source or sink of carbon in these forests. Thus, this study proposed and developed a new model for carbon sequestration generated from the integration of remote sensing and biometric approach. This study was carried out in Pasoh Forest Reserve and the model was used for up-scaling to estimate the carbon concentration of the entire forest. Data for remote sensing were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data and the biometric approach was based on tree census and litterfall observations. The results for the years 2000 until 2009 based on the new model showed that the carbon sequestration was a carbon source with increments ranging between -1.421 t $ha^{-1}yr^{-1}$ to -16.573 t $ha^{-1}yr^{-1}$, a mean value of -8.526 t $ha^{-1}yr^{-1}$ and Root Mean Square Error (RMSE) 2.916. The use of the new model revealed that there is a 6% accuracy improvement in the results as compared to a single-based remote sensing model. As a conclusion, the integration of approaches for a new model for carbon sequestration is more efficient than the use of a single approach. Furthermore, the new model is suitable for validating and calibrating global automatic climate products.

# ABSTRAK

Pelbagai kaedah pengukuran telah digunakan untuk menentukan kesahihan maklumat yang dihasilkan untuk sekuestrasi karbon khususnya di hutan hujan tropika. Secara am, kaedah ini boleh dibahagikan kepada dua kategori utama iaitu pendekatan mikrometeorologikal dan pendekatan biometrik. Pertama menggunakan remote sensing dan menara fluks serta kedua merujuk kepada pengukuran langsung lapangan biojisim. Pada masa ini, penggunaan pendekatan pengukuran tunggal kadang-kadang menyebabkan terdapat ketidakpastian dalam ketepatan sekuestrasi karbon terhadap sumber atau serapan karbon di dalam hutan tersebut. Oleh itu, kajian ini mencadangkan dan membangunkan satu model baru untuk sekuestrasi karbon yang dijana daripada integrasi remote sensing dan pendekatan biometrik. Kajian ini telah dijalankan di Hutan Simpan Pasoh dan model ini telah digunakan untuk pengskalaan bagi menganggar ketumpatan keseluruhan karbon hutan. Data untuk remote sensing telah diperolehi daripada satelit Resolusi Sederhana Pengimejan Spektroradiometer (MODIS) dan pendekatan biometrik adalah berdasarkan bancian pokok dan cerapan daun dan ranting kayu yang gugur. Hasil kajian bagi tahun 2000 hingga 2009 berdasarkan model baru menunjukkan bahawa sekuestrasi karbon adalah merupakan sumber penghasilan karbon dengan peningkatan antara -1.421 t $ha^{-1}tahun^{-1}$ hingga -16.573 t $ha^{-1}tahun^{-1}$, nilai min -8.526 t $ha^{-1}tahun^{-1}$ dan ralat punca kuasa dua min (RMSE) 2.916. Penggunaan model baru mendedahkan terdapat penambahbaikan hasil ketepatan kajian ini sebanyak 6% berbanding model tunggal remote sensing. Sebagai kesimpulan, pendekatan integrasi untuk model baru sekuestrasi karbon adalah lebih efisien daripada penggunaan pendekatan tunggal. Selanjutnya, model baru ini sesuai untuk pengesahan dan kalibrasi produk iklim global automatik.

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| | | |
|---|---|---|
| AGB | - | Aboveground biomass |
| AMERIFLUX | - | American Flux Measurement Network |
| ANOVA | - | Analysis of Variance |
| ANPP | - | Above Ground Net Primary Production |
| AOI | - | Area of Interest |
| APAR | - | Absorbed Photosynthetic Active Radiation |
| $APAR_M$ | - | Absorbed Photosynthetic Active Radiation (MODIS-local scale) |
| ARD | - | Afforestation, Reforestation, and Deforestation |
| ASIAFLUX | - | Asia Flux Measurement Network |
| CFCs | - | Chlorofluorocarbons |
| $CH_4$ | - | Methane |
| CHINAFLUX | - | China Flux Measurement Network |
| $CO_2$ | - | Carbon Dioxide |
| COP3 | - | $3^{rd}$ Conference of the Parties |
| CTFS | - | Center Tropical Forest Science |
| CWD | - | Coarse Woody Debris |
| CZCS | - | Coastal Zone Color Scanner |
| DBH | - | Diameter at Breast Height |
| EDOS | - | EOS Data and Operating System |
| EOS | - | Earth Observing System |
| EPA | - | Environmental Protection Agency |
| EV | - | Earth view |
| EVI | - | Enhanced Vegetation Index |
| FAPAR | - | Fraction of Absorbed PAR |
| FLUXNET | - | Global network of Micrometeorological Tower |
| FOV | - | Field of View |
| fPAR | - | Fraction of Photosynthetically Active Radiation |

| | | |
|---|---|---|
| $fPAR_M$ | - | Fraction of Photosynthetically Active Radiation (MODIS-local scale) |
| FRIM | - | Forest Research Institute Malaysia |
| GDAAC | - | Goddard Space Flight Center Distributed Active Archive Center |
| GHGs | - | Greenhouse Gases |
| GLOPEM2 | - | Global Production Efficiency Model 2 |
| GPP | - | Gross Primary Production |
| H | - | Tree Heights |
| HDF | - | Hierachical Data Format |
| HFCs | - | Hydrofluorocarbons |
| $H_2O$ | - | Hidrogen |
| IBP | - | International Biological Programme |
| IPCC | - | Intergovernmental Panel on Climate Change |
| IRS | - | Indian *Remote Sensing* satellite |
| JERS | - | Japanese Environmental *Remote Sensing* |
| L | - | Litter production |
| LAI | - | Leaf area index |
| Landsat MSS | - | Multispectral scanner system |
| Landsat TM | - | Landsat Thematic Mapper |
| LSWI | - | Land surface water index |
| LUE | - | Light use efficiency |
| LUTs | - | Look-up tables |
| Meteosat | - | Meteorological Satellite |
| MODIS | - | Moderate-resolution Imaging Spectroradiometer |
| MODPRI | - | MODIS Photosynthesis Reflective Index |
| $MODPRI_M$ | - | MODIS Photosynthesis Reflective Index (MODIS-local scale) |
| MRSO | - | Malaysian Rectified Skew Orthomorphic |
| NASA | - | National Aeronautics and Space Administration |
| NASA CASA | - | National Aeronautics and Space Administration Carnegie-Ames-Stanford Approach |
| NBP | - | Net Biome Production |
| NCDC | - | National Climate Data Center |
| NDVI | - | Normalized Differential Vegetation Index |

| | | |
|---|---|---|
| $NDVI_M$ | - | Normalized Differential Vegetation Index (MODIS –local scale) |
| NEE | - | Net ecosystem exchange |
| NEP | - | Net ecosystem production |
| $NEP_B$ | - | Biometric Net Ecosystem Production |
| $NEP_{RS}$ | - | Net Ecosystem Production (Remote Sensing) |
| $NEP_{NM}$ | - | Net Ecosystem Production (New Model) |
| $NEP_M$ | - | Net Ecosystem Production (MODIS-local scale) |
| $NEP_P$ | - | Net Ecosystem Production (MODIS Product-based) |
| NIES | - | National Institute for Environmental Studies, Japan |
| NOAA AVHRR | - | National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer |
| NPP | - | Net Primary Production |
| $NPP_M$ | - | Net Primary Production (MODIS-local scale) |
| $NPP_B$ | - | Biometric net primary productivity |
| $NPP_{RS}$ | - | Remote sensing NPP |
| $N_2O$ | - | Nitrous oxide |
| OECD | - | Organization for Economic Co-operation and Development |
| PALSAR | - | L-band SAR |
| PAR | - | Photosynthetically Active Radiation |
| PFCs | - | Perfluorocarbons |
| PFR | - | Pasoh Forest Reserve |
| PRI | - | Photochemical Reflectance Index |
| $R_a$ | - | Autotrophic respiration |
| $R_h$ | - | Heterotrophic respiration |
| RMSE | - | Root mean square error |
| SAR | - | Synthetic Aperture Radar |
| SEBAL | - | Surface Energy Balance Algorithm for land |
| $SF_6$ | - | Sulfur hexafluoride |
| SPOT | - | Satellite Pour l'Observation de la Terre |
| STRI | - | Smithsonian Tropical Research Institute |
| TAGB | - | Total above-ground biomass |
| $TAGBY_1$ | - | total above ground biomass year 1 |
| $TAGBY_2$ | - | total above ground biomass year 2 |
| TBFRA-2000 | - | Temperate and Boreal Forest Resource Assessment - 2000 |

| | | |
|---|---|---|
| TDRSS | - | Tracking Data Relay Satellite System |
| UKCA | - | UK Chemistry Aerosol Community Model |
| UN | - | United Nations |
| UNFCCC | - | United Nations Framework Convention on Climate Change |
| UN-REDD | - | United Nations Collaborative Programme on Reducing Emissions From Deforestation and Degradation) |
| $W_B$ | - | Weight of branches; |
| $W_L$ | - | Weight of leaves |
| $W_S$ | - | Weight of stems |
| WGS84 | - | World Global Coordinate System 84 |
| Y | - | Growth increment |
| $\Delta L$ | - | Rate of litter fall |
| $\Delta G$ | - | Rate of grazing by herbivores |
| $\Delta Y$ | - | Rate of growth increments |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

Currently, climate change is one of the major global issues experienced in both developing and developed countries. Since the 19th century, scientists have begun to realize that the greenhouse gases in the atmosphere have shown an increase and this have led to an increase in the global temperature. The increase in global surface temperature which is also known as global warming has subsequently contributed to other environmental problems such as the rise in the sea-level due to the melting of the terrestrial pole ice, frequent flooding and drought and also various abnormal weather and climatic conditions. In the 1960s, scientists discovered carbon dioxide ($CO_2$) is one of the major greenhouse gases in the atmosphere and it is found to have increased tremendously and played a crucial role in causing global climate change (IPCC, 2007). Since then, many studies employing new technologies, including satellite imagery, have been undertaken in order to increase understanding regarding the effects of carbon dioxide on the environment. A recent research over large areas of forest has indicated that the tropical region is the biggest contributor of carbon source (Lewis, 2006). This is because, according to research findings, the natural resources in tropical regions such as forest, which could act as major global carbon pools, are poorly managed. For instance, Mygat (2006) has discovered that the Southeast Asia region had lost more than 14 million hectares of its forested area from 2000 to 2005 due to improper development activities. Meanwhile Zhang *et al.* (2001) predict the atmospheric temperature of the tropical region will increase from 2°C to 5°C during the next century due to the shortage of forest coverage. However, there are many uncertainties in most of the research findings due to the use of different techniques and scales to determine the carbon concentration in this low latitude of tropical forest. Among them is the research conducted by Miller *et al*., (2004) which has recognized that the conventional technique indicate moderate trends as compared to the micrometeorological technique which had shown drastic trends in carbon sink at Amazon forest during 2000.

Based on the above descriptions, the main aim of this study is to determine the current status of tropical rain forest with respect to its roles in regulating the global carbon budget. This study attempts to propose the new accurate method for the estimation of carbon sequestration through an integration of the plot scale contemporary classic measurement technique and moderate resolution multispectral remote sensing images. In addition to give a detailed explanation about the results of this study, it is also important to provide an appraisal of the theory and concepts and consider the significance of many of the previous studies. Thus, the following topics in this chapter will focus and consider in more detail on the greenhouse gases, climate change and carbon dioxide. This will then be followed by discussions on other topics specifically related to this study such as statement of problems, objectives of the study, scopes of the study, significance of the study and study area background. The structure of this thesis is highlighted in the last part of this chapter.

## 1.2 Greenhouse Gases

Greenhouse gases (GHGs) are gases in the Earth's atmosphere which can absorb and reflect long wave radiation. The presence of GHGs in the atmosphere is very important as it can act to regulate the temperature of the earth to avoid from being too cold or too hot. Four major GHGs are water vapor, carbon dioxide ($CO_2$), methane ($CH_4$) as well as ozone ($O_3$). They are categorized as GHGs that contribute to the climate chemistry. There is also another group of gases known as "lesser greenhouse gases" which is categorised as a minority group. This category of GHGs is normally caused by human activities such as chemical waste from plant fertilizers that also contribute to the grenhouse effect. Nitrous oxide ($N_2O$), sulfur hexafluoride ($SF_6$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) as well as chlorofluorocarbons (CFCs) are gases within this group (UKCA, 2009). GHGs react by trapping the long wave radiation discharged by the earth's surface. In some circumstances, about 90% of the reflected solar radiation is trapped in the atmosphere by GHGs and causes the earth's surface and its atmosphere to become heated.

Approximately a thousand years ago, the amount of GHGs in the atmosphere remained relatively constant. The GHGs have then begun to increase during the industrial revolution. The amount of GHGs particularly $CO_2$ has increased drastically at an estimated rate of more than 30% during the revolution period. This is mainly due to the loss of control of industrial activities and also the process of deforestation which resulted in the land use conversion. During 1850 to 1998, for instance, about 270 Gt $CO_2$ was emitted through industrial activities. Then, about 136 Gt $CO_2$ was released due to exploration of new land areas (IPCC, 2000). These occurrences have been continuing until the end of the 20th century. In the 1980s, the hottest years were recorded. Scientists have realized that the warming in the 1980s was caused primarily by an increase in the $CO_2$ concentration. Thus, the enhancement of the GHGs effects due to increased concentration of $CO_2$ subsequently is identified as an effect resulting from human activities causing global climate change. In addition, this circumstance contributes to the fluctuation of the climate conditions and leads to the vulnerability of the ecosystems. Due to the living things need, it is essential to take into account that $CO_2$ is one of the significant GHGs. Moreover, in the context of global warming, $CO_2$ is also regarded as a major source to any occurrences in climate change (NCDC, 2008).

Presently, the "Greenhouse Effect" is often reported in the media as a negative occurrence that is caused by human abuse of the environment. The truth is that it is a natural process and in its absence the Earth would actually be on average cooler (Berita Harian, 2007). As previously explained, the greenhouse effect is the result of the concentration of such foregoing major gases found in the atmosphere that allows incoming short wave solar radiation to enter the atmosphere. In another word, GHGs are said to be transparent to the short wave radiation. These gases only allow a portion of the energy reradiated from the Earth's surface to escape. When the concentrations of GHGs increased, greater amount of terrestrial radiation is held within this layer and consequently the earth's temperature is also increased. This is said to be the cause of global warming and climate change, resulting in the rise of the sea level as well as change in precipitation and other local climate conditions. Overall, the augmentation of $CO_2$ level results in the expected rise to the mean global temperatures due to the increased amount of solar radiation trapped by GHGs. Nevertheless, the $CO_2$ concentration in the atmosphere concerns the continuous flow of the carbon stores in the atmosphere, ocean and earth's ecosystem. Thus, as long as the $CO_2$ is consistently cycling from the atmosphere into living things and dissolved carbon are in balance, obviously the carbon level in the atmosphere is persistently constant.

## 1.3 Climate Change

Intense hurricanes, water shortages, soil erosion, droughts, rising sea level, biodiversity loss, extreme weather, changes in agricultural yields, change in trade routes, reduced summer stream flows, glacier retreat, species extinctions, deaths, displacements, economic losses as well as spread of diseases are among the effects due to climate change. Article 1 under United Nations Framework Convention on Climate Change or UNFCCC (1992) has defined that climate change is attributed directly or indirectly to human activities which alter the composition of the global atmosphere, in addition to natural climate variability observed over comparable time periods. Furthermore, climate, the earth’s weather as a whole is often analyzed as the synthesis of weather recorded over a long period of time. However, not all the changes in climate are caused by natural processes. Generally, effects due to the climate change are seen absolutely caused by human activities that significantly alter the world’s atmosphere. Those activities subsequently have been substantially increasing the atmospheric concentrations of GHGs that enhance the natural greenhouse effect, and normally resulting in added warming of the Earth’s surface. Since the GHGs concentrations are continuing to increase, the Earth’s surface warming is increasing as well.

Perceptibly, the relationship between the enhanced greenhouse effect and global climate change is very complex to understand because increased concentrations of GHGs also affects the oceans, soil as well as biosphere apart from the atmosphere. It is also the complex feedback mechanisms within the climate system that can act to amplify greenhouse-induced climate change, or even counteract it. However, generally the major causes influencing the patterns of climate change can be explained by various factors such as:

i. the radiation strength from the sun, which is to identify the present overall earth temperature;
ii. the spherical shape and axis of orientation of the earth;
iii. the water vapour effect and other radiatively active trace gases in the atmosphere-geospere;
iv. the various physical, chemical and biological processes within the atmosphere-geosphere biosphere climate system, particularly in energy balance, water cycle, carbon cycle and other related bio-geographical cycles; and
v. the distribution of land coverage and oceans.

Exploration of new land area or altering patterns of land use are able to cause climate change at the local scale. Since the mid 19th century industrial era, various activities as said before including accelerated usage of fossil fuels as well as large-scale deforestation for new development of industrial area have contributed to the enhancement of the natural greenhouse effect. The activities are also widely believed as responsible for the observed increase in global temperature through the next century (IPCC, 2001). In addition, climate change also influences other human activities and values. For example, it places stress on recreational capacities, thereby affecting tourism. Specifically, the predicament caused by climate change to the specific activities can be given as follows:

i. Agriculture

   Both temperature changes and changes in soil moisture from altered precipitation are likely to put pressure on agricultural activities at local scales. These changes are likely to alter the range of a number of major food crops. The result need not be global strains on food supply, especially if the fertilization effect of higher $CO_2$ levels in the atmosphere is taken into account.

ii. Water Resources

   A drier climate in many areas will only increase the technical and environmental challenges of providing adequate supplies to growing populations.

iii. Coastal settlements

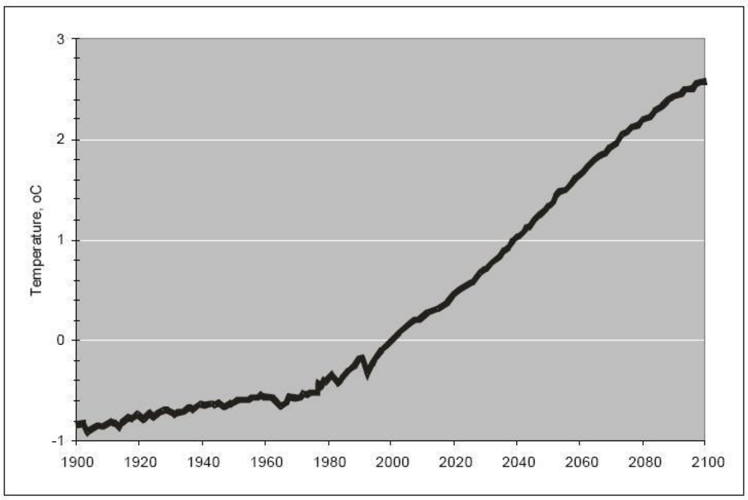
Coastal areas are obviously vulnerable to inundation from a rising sea level in a warmer world, as well as to any increase in the incidence of violent storms.

iv. Natural Ecosystems

Even if coastal human settlements can adapt, coastal wetlands and other natural features of importance may not meet the challenge of rising sea level, given the uncertanties about ecosystem dynamics and the barriers imposed by human infrastructure (e.g. highways). Inland wetlands also face serious challenges, as some wetlands could simply disappear in a drier climate. Policies that slow the ongoing loss of critical wetlands to development, reduce other human induced stresses (water pollution), and promote greater scientific understanding of wetland functions and how they can be restored are needed to address these problems.

Another component that plays a truly significant role which is correlated to the terrestrial climate change is the forest. Since the world has stated about 3,870 million hectares of forests account for 30 percent of the world land area, the mutual influence correlation of forest and climate change is important to be studied (TBFRA-2000, 2000). At the same time, climate also influences forest growth through two key variables which are temperature and precipitation. Increasing temperature as well as unchanged or reduced precipitation leads to the substantial decline in soil moisture, and subsequently limits plant growth while increasing the risk of fires. Forests also response to the long-term climate changes depending on the species ability to live in the new environment or by changing their geographical distributions. Then, changes in forest cover could generate feedback on the climate through modifications to surface temperatures, precipitation as well as altering the concentrations of $CO_2$ in the atmosphere. Forests have a lower albedo than other ecosystems and have more access to soil water compared to other types of vegetation, particularly through their extensive root systems. Thus, they absorb more solar energy, leading to either more surfaces heating or cooling through changes in evapotranspiration rates (Buermann *et al.*, 2001). In tropical zones, for instance, evaporation processes tend to dominate and the net effect of forests is to cool and moisten the atmosphere. Tropical forests response to climate changes depends mostly on changes in the rainfall regime. Where rainfall is reduced and temperature increases, reduced soil moisture is expected to be most significant threat (IPCC, 2001).

Based on the effects in the foregoing discussion, the occurrence of climate change is the most serious global issue presently faced by human. Over the past century, scientists claimed that the imbalance of carbon cycle emissions is making the climate warmer and more volatile. Then, the seasons are arriving at uncommon time, glaciers are retreating, and sea levels are rising (more than 3 millimetres a year since 1993) while extreme weather events are already getting more frequent as well as more severe. These are among the phenomena arising from a warmer climate. As the planet continues to heat, there will possibly be some rise in floods and droughts occurrence as well as seriousness in many regions. The scientists had subsequently decided on the most important indicator to track, as a kind of scorecard for climate change due to imbalance of carbon cycle emissions which can be determined by global surface temperature. Later, the established agency, the Intergovernmental Panel on Climate Change (IPCC) has determined that the average global surface temperature will continue to increase between 1.4°Celsius and 5.8°Celsius above the 1990 level, by year 2100. The following Figure 1.1 shows a simple standard prediction for the simulation of coming hundred years from the medium scenario of the 2007 conducted by IPCC.




Source: IPCC (2007)

**Figure 1.1**: Expected temperature increase from 2000-2100 in the business-as-usual scenario (with simulation of temperature increase from 1900-2000).

Since then, an international discussion of adaptive measures have carried a lot of efforts to investigate the sensitivity of resources to future climate change and assess their potential for successful adaption. In addition, enhancement of the awareness of potential irreversible or catastrophic climate changes by policymakers is very essential in order to identify and understand unfavorable trends that would make it more difficult to adapt to climate change in the future. Basically, policymakers must decide whether the steps taken should respond to climate change as it occurs, or steps should be taken to anticipate and mitigate the eventual effects. Policymakers must also evaluate whether the potential for natural adaptation or human intervention is low. Therefore, a series of organisations have been setup mainly and internationally to discuss the awareness of the impact of climate change. Generally, among these organisations are discussed as follows.

### 1.3.1 The United Nation Framework Convention on Climate Change

This convention has been set up since 1992 in Rio De Janeiro after series of world 'Earth Summit' meeting for climate concern that was previously known as the United Nation Framework Convention on Climate Change (UNFCCC). UNFCCC was one of the treaties that was agreed by world leaders during this meeting which formally decided on the stabilization of greenhouse gases (GHGs) as the ultimate objective of the whole multilateral climate policy process. Furthermore, the convention's priority objective is to achieve as well as ensure related world organisations adopt the effort in stabilizing GHGs' concentrations in the atmosphere at a level which is able to prevent dangerous anthropogenic interference with the climate system. The convention too is responsible for producing the timeframe sufficient for ecosystems to naturally adapt to climate change, ensuring food production is unthreatened as well as enabling sustainable economic development. Furthermore, UNFCCC has been set up also for the purpose of establishing a national greenhouse gas inventory which is significant for benchmarking any future actions toward climate stabilization. Nonetheless, most important is that the convention has subsequently proposed the 'protocols' which allow for mandatory emission limits, hence indirectly configuring UNFCCC as the umbrella treaty for all future actions related to climate change. The protocol yielded after is the Kyoto Protocol.

### 1.3.2 The Kyoto Protocol

The Kyoto Protocol was constituted five years after the UNFCCC. This is among most well known protocols at present, established as a priority to reduce the carbon emissions from industrial activities in developed countries by 5.2 percent below the 1990 levels by the year 2012. To realize the target, for instance, the United States of America and Japan as well as European Union countries have been forced by the protocol to reduce their emissions on average by 8 percent below the 1990 levels by the year 2012. Presently, the protocol agreed to exclude emission targets on developing countries. In the earlier results, a total of 175 countries have showed their commitments by reporting their emission levels to the protocol, including Brazil, India and China. Next, the protocol moved forward into the second step in awareness by broaching the issue of developing countries in their activities to prevent the climate change. Furthermore, the protocol agreed to implement important rules for a climate stabilization operating system including establishing the fundamentals for a standard emission trading system in developing countries. However, the protocol is agreed since to be more flexibile and reasonable. There is also a follow-up series of meeting to be conducted to highlight the related issues in carbon emission under developing countries after the expiry of the Kyoto Protocol.

### 1.3.3 Bali Roadmap

The Bali Roadmap was the most recent high-level event concerning climate change commitment made by UNFCCC and organised by UN Secretary-General Ban Ki-moon. This Bali Roadmap has been produced after the gathering of most world leaders from both developed and developing countries in Bali, Indonesia in December 2007. The main agenda for this meeting was to begin discussions earnestly on what should follow after the Kyoto Protocol’s first commitment period expires. Bali Roadmap is the result of these discussions which is an agreement to review the success of the Kyoto Protocol. In addition, it has been agreed that this Bali Roadmap will conclude on post-2012 actions at a climate change summit in Copenhagen in 2009. The main constraint has been solved during this Bali Roadmap by successfully convincing the United State of America and Australia to rejoin this international consensus after having stayed long outside the Kyoto Protocol. This meeting has shown the gayety after the reinvolvement of the world giant leaders. The Bali outcome was certainly a step forward, even though these were only talks about talks. Nonetheless, the true success of the Kyoto Protocol is expected to be revealed further in Copenhagen and able to show the world concern for the GHGs with $CO_2$ as priority.

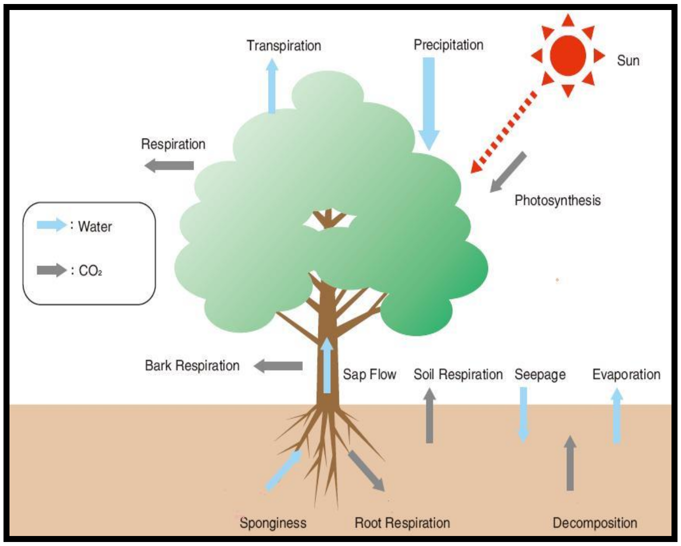
### 1.3.4 Copenhagen Summit 2009

Copenhagen Summit 2009 which was another United Nations Climate Change Conference was held at the Bella Center in Copenhagen, Denmark, between 7 and 18 December. The conference included the 15th Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 5th Meeting of the Parties (MOP 5) to the Kyoto Protocol. It was reported that the climate talks in the Copenhagen Summit 2009 were "in disarray" whereby only a "weak political statement" was expected as the conclusion of the conference. The Copenhagen Accord was drafted by the United States, China, India, Brazil and South Africa and judged a "meaningful agreement" by the United States government. The document which was produced during Copenhagen Summit 2009 recognises that climate change is one of the greatest challenges of the present day and that actions should be taken to keep any temperature increases to below 2 °C. However, the document is not legally binding and does not contain any legally binding commitments for reducing $CO_2$ emissions. Then, this issue has been identified due to sincerity by the biggest carbon emission country in the willingness or openness to overcome the global predicaments. As a result, United Nations Climate Change has decided to plan another summit conference in 2014 to discuss deeply on the feedback of the Kyoto Protocol which was not concluded during Copenhagen Summit 2009.

## 1.4 Carbon Dioxide

Basically, carbon dioxide ($CO_2$) is described as a chemical substance that is composed by two oxygen atoms covalently bonded to a single carbon atom (Drive, 2008). Naturally, $CO_2$ can be found at normal temperature and pressure under the atmosphere layer and able to spread under visible light but absorbs strongly in the infrared and near-infrared. Recently, the average concentration of $CO_2$ is stated at about 387 ppm by volume in the Earth's atmosphere and continues to increase subsequently at about 25 percent compared to in the 1990's (Nabuurs and Schelhaas, 2002). Nevertheless, this gas fluctuates in concentration according to seasons where it falls during the dry or hot seasons as plants desire $CO_2$, while it rises during the raining seasons when plants go dormant.

Carbon dioxide is a very important gas because all living things on this earth depend on it. They acquire $CO_2$ from their own surrounding environment such as air, water, soil and rock. Animals, plants, fungi as well as microorganisms produce $CO_2$ during respiration while plants use it for photosynthesis. The occurrences whereby carbon is released through the sources and taken up by the sinks is then interpreted as the carbon cycle. The carbon cycle in an ecosystem involves various complex chemical systems that influence the movement of $CO_2$ such as photosynthesis, respiration, evaporation and decomposition (Figure 1.2). Conceptually, under one ecosystem, plants act to absorb the $CO_2$ and release oxygen ($O_2$) to the atmosphere through the photosynthesis process. On the other hand, plants and ground soil under this ecosystem also release $CO_2$ through the respiration process. Thus, equilibrium in $CO_2$ is truthfully important under the carbon cycle system to avoid disturbance to the current climate condition.




(Source: Ono and Yamamoto , 2003)

**Figure 1.2**: Carbon circulation of plant ecosystem

Recently, scientists have shown that the earth's surface emission has seriously outweighs its ability to store carbon. They have investigated that, the major reasons for high level $CO_2$ emission lately are the burning of fossil fuel and the yield of industrial products. Various researches have shown that there is a correlation between the rise of industries and the increase of $GHG_S$ contained in the atmosphere, specifically $CO_2$. They also realized subsequently that this phenomenon sooner or later is disturbing the consistency of the average global temperature, which is commonly referred to as global warming. This circumstance affects both the weather and climate conditions as well as leads to the destruction of the ecosystems. Several researches that have been conducted have successfully outline the approaches in dealing with the carbon issues which are (i) increase the efficiency of the primary energy conversion as well as end use (less fossil fuel needed to generate the same energy service), (ii) invent carbon free energy sources such as natural gas and solar panel, and (iii) carbon sequestration: capture and storage where one keeps emissions from reaching the atmosphere, remove the overflow of carbon from the atmosphere (White *et al.*, 2000). Among these, however, carbon sequestration is the most potential method for reducing the net carbon emission by retaining or increasing the coverage of forest ecosystems.

In general, carbon sequestration in forest ecosystems provides the net removal of $CO_2$ from the atmosphere into the tree biomass (Pandey, 2002). In a forest ecosystem, trees utilize carbon as a source of energy to build the biomass by forming structures such as trunks, roots, stems, branches and leaves. Then it removes $CO_2$ from the air, converts it into the oxygen atoms, and returns them to the atmosphere. Generally, trees are an encirclement of 45% carbon, 50% water, and 5% minerals depending, however, on the species. In addition, trees have the potential to grow up to 50 percent faster in concentrations of 1,000 ppm $CO_2$, compared to ambient conditions. Besides utilizing the carbon, trees are also emitting $CO_2$ during respiration. Naturally, trees in a growing forest will absorb tons of $CO_2$ each year. In contrast, trees in a mature forest will produce as much $CO_2$ from respiration as well as decomposition of fallen structures such as leaves and branches. Nonetheless, the mature forests are still valuable carbon sinks, assisting in maintaining carbon cycle in the Earth's atmosphere.

## 1.5 Statement of Problem

Forests have been acknowledged to have major roles in combating climate change. Forests can act as sources and sinks of carbon or so-called as carbon sequestration. Scientifically, the accumulation of global carbon sequestration can be used as the global climate change indicator (FAO, 2005). Therefore, study on carbon sequestration is very important in all forest types in order to consistently provide the evidence and monitor the recent trends of carbon circulation under theirs ecosystems. For instance, tropical rainforests have been criticized by UNFCCC (United Nations Framework Convention on Climate Change) as acting as the largest contributor to terrestrial carbon emission recently. They quoted that the tropical rainforests are emitting about 50% of the global terrestrial carbon (Lewis *et al*., 2009). In the meantime, the above statement indicates that the tropical forests ecosystem has a low capability to sequester carbon compared to other terrestrial ecosystems. However, no concrete evidences have been provided which refer to the standard protocol measurement by avoiding any uncertainties (Kumagai *et al.*, 2005). Furthermore, there are also no related world carbon credit mechanisms enforcement bodies such as under UN-REDD (United Nations Collaborative Programme on Reducing Emissions from Deforestation and Degradation) that conduct direct on-ground forensic on the present carbon trends in the tropical forest ecosystem by their own organization. Most of their findings on the carbon trends in tropical forest are claimed based on the old method of global scale observation or regular observation from single established experimental plot (UNFCCC, 2005). In addition, previous attempts to reach an international agreement on the sustainability of tropical rain forests under the UNFCCC have mostly failed lately (LePrestre, 2005). Therefore, it is inevitable that every country under tropical rainforests must provide and conduct their own observations to validate any scientific results on carbon sequestration as those raised by world organizations which somehow show uncertainties. In addition, REDD is enforcing to implement an agreement in providing financial incentives to the tropical regions' developing countries that practice excellent monitoring of the forestry activities such as degradation and deforestation. Thus, adequate studies related to the carbon sequestration in tropical forests are needed in order to fulfill the REDD requirements. In addition, the increment in the number of carbon sequestration studies that indicate sources or sinks of carbon is able to produce consistent and more accurate information on the actual trends of present carbon emission in tropical forests regions as well as able to control the environment quality. Then carbon emissions reductions effort could simultaneously combat climate change, conserve biodiversity and protect other ecosystem goods and services

As known, forests represent approximately 3 billion hectares of earth coverage or 20% of the world's total terrestrial area, whereby approximately more than 19% are natural forests and less than 1% are forest plantations. In the meantime, poverty, expanding populations, weak institutions, incomplete scientific knowledge as well as climate change itself are problems that will challenge the world's capability to enhance the use of the forests as part of a global carbon control strategy. Even though carbon sequestering in the forests may be quite low, lately the need for actual measurement of the increment in carbon sequestration in the forest ecosystem is more important with emphasis to the tropical rain forests (Liao *et al.,* 2010). At present, there are numerous successfully developed techniques available to enhance the estimation of the forest's ability to sequester as well as store carbon, such as the ordinary inventory based on ground measurement. However, the different methods in the estimation of carbon, such as from ground measurement, tower flux and satellite imagery, are creating uncertainty in the accuracy carbon estimation. Moreover, researchers have recently found that there are imbalances in the results or techniques to determine the exact information on carbon sequestration because different technique shows different result under appropriate ecosystem (Chave *et al.,* 2005). Therefore, the researcher have decided that some further studies from numerous techniques have to be adequately conducted at different scales, as well as for different forest types. Furthermore, the idea to take into account the integration between various methods is very significant to be enhanced in order to get better justification of the carbon values in a particular area. Moreover, advanced and low cost technology has recently been intensively developed for global carbon monitoring with rapid measurement such as from moderate resolution images, hyperspectral and high angle field of view (FOV) instruments that could assist in determining high impact accuracy of local carbon. Under this particular reason, the lacking of a new advanced technique seems to be another critical concern in carbon sequestration and climate change studies in tropical rain forests. Thus, this study offers a new technique by integrating two different approaches namely from biometric data and remote sensing images in order to obtain better accuracy of carbon trends in tropical rainforests. In addition, the integration of biometric and remote sensing methods is expected to overcome the limited number of flux towers which are ordinarily used as complement validation to the remote sensing data in carbon sequestration studies. Furthermore, several studies have proposed that the integration of biometric and remote sensing approaches is potential to identify the ecosystem behavior and capable to improve the accuracy of carbon measurements (Muraoka and Koizumi, 2009).

Modeling is a method adequately used in the processes involved in terrestrial carbon sequestration. In fact, rigorously modeling techniques are very useful tools in monitoring the carbon sequestration potential of an ecosystem through complex dynamical system. Even now, the modeling method is very important in the light of climate change, where it becomes essential to have an understanding of the future role of terrestrial ecosystem as potential sinks or sources in the context of global carbon sequestration (Kennan *et al.*, 2008). Models allow for the evaluation of many alternative strategies and the effectiveness of each can thus be tested based on the requirements. Scientifically, those models are classified into two approaches which are empirical approach and process based approach. Empirical approach is mainly statistical based with faster execution times, while process based approach, in contrast, connects to the processing of mathematical description into large number of parameters which needs detail and longer field work activities and lab experiments as well as high-cost of sophisticated instruments. Even though it seems that empirical model has not been giving most high impact scientific outcome, it is very useful and easy to build simple and produce accurate description of the ecosystem with very few parameters. Study on the effects of climate change on tropical terrestrial ecosystems requires the use an effective model which is able to focus on the response of forests to climate change.

Carbon sequestration studies have not been much explored especially in tropical rain forests due to some of the researches showing the complicated modeling methods and field parameters involved for example using the process based approach from biogeochemical model. At present, most of the carbon sequestration studies conducted have only emphasized on the meteorological parameters obtained from insufficient number of high-cost flux tower data observations. Moreover, most of the tropical rainforests region countries are not capable in establishing and monitoring the flux instruments as it has been recorded that threre is no flux tower in the Africa continent (Fluxnet, 2006). Therefore, this study is believed able to overcome the predicament faced by tropical countries by creating a new low cost carbon sequestration model by using series of field data observation and free access geophysical remote sensing imageries such as MODIS. In addition, the success of this study is aimed to contribute in transformation of the existing high order complicated carbon sequestration model and hoped to be adopted by IPCC as a new platform of carbon sequestration measurement for the developing countries (IPCC, 2006).

The recent issues on carbon sequestration studies in tropical forests is in up-scaling and the transformation process from plot scale to other different sizes of scale such as the local or landscape scale as well as regional scale. However, the most challenging is the up-scaling process which concern difficulties in determining the suitable spatial and temporal data in improving the frameworks for monitoring, reporting and verification (MRV) during the implementation of UN-REDD (Herold *et al.,* 2011). REDD has identifed the critical information during evaluation practices while obtaining uncertainties from upscaling plot data across the landscape, region and nations. Until now, REDD claims there are no practical scaling-up techniques to directly measure forest carbon across multi-scale and multi-method approaches. Therefore, this problem has caused to the failure in establishing accurate baseline scenarios that can be used to accurately estimate up-scale carbon emission especially across forested landscape (Vergas *et al.,* 2013). Thus, historical data from forest inventories which provide high quality information and satellite images, respectively have been investigated as one of the great solution in order to establish the accurate baseline on carbon emission for the up-scaling purposes according to the spatial and temporal concern under low uncertainties (Gibbs *et al.,* 2007). Furthermore, both data are the most practical sources that are relevant to the tropical rainforests region whereby some of them have established forest inventories field data from biometric approach since longer period as well as the availability of different specifications of satellite images (Clark, 2004). Therefore, this study is to investigate the potential of using series of forest inventory data at plot scale size for up-scaling to local scale forest coverage using low resolution MODIS satellite images in tropical rain forest. It is hoped that the outcome from this study is able to give the better solution to any uncertainties in the up-scaling process from plot up to national level in carbon studies of tropical rain forests.

At present, the status of the research which is primarily related to carbon sequestration in Malaysia is at the commencement level. Malaysia, which is under the tropical rainforest zone with forested coverage of approximately 62% of land area has been drastically exorbitant in annual carbon emission ranging from 1.3 metric tonne per capita in 1970 to 7.3 metric tonne per capita in 2007 (World Bank, 2011). Particularly, Malaysia signed the United Nations Framework Convention on Climate Change (UNFCCC) in June 1993 and has ratified the convention since 1994. Then, more commitments have been continued to engage with the UNFCCC process and two reports were submitted in 2011 on financing and methodological guidance for REDD. Malaysia had also previously made a pledge to maintain at least 50 per cent of perpetual forest and tree cover, and this commitment was reiterated at the Conference of the Parties (COP15) in Copenhagen in 2009. Malaysia has also made a pledge to voluntarily reduce carbon intensity by 40 per cent by the year 2020 compared to the 2005 level (NRE, 2011). Thus, it is inevitable that research related to carbon sources and sinks is to be developed rapidly in Malaysia concurrent with the advancement of technology such as remote sensing satellite imageries in order to achieve the 2020 targets. In addition, Tthe recent success from previous studies of forest biomass extraction using Landsat TM, NOAA AVHRR and synthetic aperture radar-SAR (i.e. Foody *et al.,* 2001; Hashim *et al.*, 2003; Hashim *et al.*, 2005), supported by the new discovery of remote sensing technique from this study, perhaps can be used as the baseline to manage carbon emission based on the COP15 agreements. However, as stated above, the present achievement in research related to the carbon sources and sinks in Malaysia is still at the beginning mode. Subsequently, nearly no publication on the forest carbon sequestration topics have been highlighted whereby most of them are only related to the extraction of tree biomass. Therefore, this study is able to support our National Steering Committee On Climate Change (NSCCC) in formulating and implementing climate change practices including mitigation of GHG emissions and adaptation to climate change as well as intensifying national scale carbon study.

## 1.6 Objectives of the Study

The main objective of this present study is to produce a new carbon sequestration model in tropical rain forest by integrating satellite remote sensing data and direct field measurements. This study intensively emphasizes on two major carbon flux parameters in the establishment of a new carbon sequestration model which are net primary productivity (NPP) and net ecosystem productivity (NEP). In this regard, both are the most important and fundamental parameters in the evaluation of the ecosystem function in any carbon cycling study in a forested area. Carbon sequestration is indicated by NEP, while NPP is an essential variable that can be used to estimate NEP. In addition, two measurement methods namely from the biometric approach and remote sensing techniques will be investigated to calculate NPP in this study. Apart from the accomplishment of the main objective, there are also a number of essential objectives that have been included as follows:

i. to estimate NPP in tropical rainforest ecosystem based on direct field measurements called as the biometric approach;
ii. to estimate NPP in tropical rainforest ecosystem from MODIS satellite data by adopting the micrometerological approach;
iii. to estimate NEP in tropical rainforest ecosystem using the biometric approach and remote sensing techniques, respectively based on contemporary classic equation of carbon sequestration.
iv. to produce a new carbon sequestration model in tropical rainforest ecosystem from the integration of biometric NEP and remote sensing NEP;
v. to assess the accuracy of the new MODIS carbon sequestration model using appropriate statistical method; and
vi. to evaluate and map carbon sequestration using the new carbon sequestration model in order to show the capability of this study in monitoring the spatial heterogeneity and temporal dynamics of carbon sequestration in a tropical rain forest by up-scaling from plot scale to local scale.

## 1.7 Scope of the Study

Most studies throughout the world have discussed various issues regarding carbon, particularly its impact on global climate changes. However, none of the studies have emphasized the use of MODIS satellite data particularly with respect to its relationship with the integration of biometric approaches and remote sensing technique in order to estimate the carbon sequestration at local scale. Thus, this study will be focusing on analyses and enhancements of MODIS satellite data to establish the relationship between spectral properties and the measurement of vegetation characteristics. Subsequently, the scope of this study can be quoted as follows:

i. Only satellite image from MODIS (12 bit) will be used for modeling carbon sequestration in this study. MODIS satellite data consists of 36 spectral bands which range from 620nm to 14385nm. However, only four bands will be employed for the purpose of this study which are band 1 (620 – 670 nm ), band 2 (841 – 876 nm), band 11 (526 – 536 nm) and band 12 (546 – 556 nm), respectively at spatial range of 250 to 500 m. Furthermore, this study attempts to utilize only a single image of MODIS satellite data during the optimum tree growth season to represent annual carbon product (October only). Further analysis will be carried out in order to justify the appropriateness of using this single MODIS image.

ii. Two techniques of field data collection involved in this study are as follows:

   a) Biometric approach

   Biometric approach is direct field measurements at experimental plot which involves parameters that have been used to calculate aboveground NPP or ANPP such as: i) Diameter at breast height (DBH) for only DBH > 10 cm; ii) tree heights (H); iii) weight of stems ($W_S$); iv) weight of branches ($W_B$); v) weight of leaves ($W_L$); vi) growth increment (Y); and vii) litter production (L). Meanwhile soil respiration data will be acquired to calculate NEP.

   b) Remote Sensing technique

A micrometerological approach will be adopted to estimate remote sensing NPP in this study, based on two main micrometerological parameters namely absorbed photosynthetically active radiation (APAR) as well as light use efficiency (LUE). Meanwhile, climatic variables such as solar radiation, temperature and precipitation will be used as primary data in order to calculate APAR and LUE, respectively.

iii. Only six years field measurements data from 2000 until 2005 that have been acquired after interpolation of series annual observation since 1990 to 2005 will be used to determine the carbon sequestration based on the biometric approach. While, since MODIS was first launched in 1999, thus six MODIS images from 2000 to 2005 will be acquired to be used for estimation of NPP and NEP, respectively in this study as well as producing the new local scale carbon sequestration model. However, data of 2009 will also be acquired to be used in the quantitative analysis.

iv. Establishment of the new carbon sequestration model generated by using the ecophysiological concept (correlation of vegetation's function and its environment – precipitation, temperature, growth increment, PAR and LUE) which will then be correlated to the MODIS satellite data using regression analysis method. This correlation is also quoted as a hybrid model whereby to be subsequently extended from plot scale to local scale.

v. Accuracy of the new carbon sequestration model derived from satellite remote sensing data will be analyzed using an appropriate statistical method analysis such as root mean square error (RMSE) and t-test.

vi A series of existing global MODIS products such as MOD15 (fraction of photosynthetically active radiation and leaf area index), MOD17 (gross primary productivity as well as net primary productivity) and meteorological data (rainfall and temperature) wil be used in the qualitative analysis.

## 1.8 Significance of the Study

Tropical rainforest has been defined frequently by most researchers as involving improper management of the ARD (Afforestation, Reforestation, and Deforestation) activities especially in biomass inventories. Houghton (2005) in his research has found that recent estimates of carbon emissions in tropical rain forest have shown underestimates due to the inadequate data used for the biomass. In addition, Pandey (2002) claims that the tropical rain forest contributed high risks to climate change due to the foregoing reasons. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) has quoted that future worldwide temperature will increase up to 6ºC in the year 2100 as a result of improper management of the global ARD activities. Meanwhile, some investigations have determined that an increase of 2ºC of global temperature could subject up to two billion people to water shortages by 2050, and threaten the extinction of 20 percent to 30 percent of the world's species (New Straits Times, 2007). Therefore, the new carbon sequestration model using moderate resolution climate satellite such as MODIS in this study is very important in supporting good management of forest activities and indirectly in the determination of the exact conditions of carbon balance in the tropical rain forest. The results from this study can provide better understanding on the status of tropical rain forests especially in terms of the contribution to the world climate change. Most importantly, the outcomes from this study is useful to be used as indicators to the UN-REDD (The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) programme. This UN-REDD programme which has been established since 2008 is aimed as a mechanism designed to prevent $CO_2$ emissions by developing countries such as Malaysia whereby their forested areas are paid to avoid forest degradation and deforestation activities. However, the programme determines that the success in monitoring forest degradation and deforestation will depend on the accuracy in the measuring of the forest biomass as a proxy for $CO_2$ stocks.

MODIS NPP products such as MOD17 are designed to provide an accurate, regular information related to the production activity or growth of terrestrial vegetation and carbon sequestration at global scale (Running *et al.,* 1999). Current approaches which adopt micrometeorological measurements are inadequate to present better accuracy of carbon sequestration because of the limited number of flux towers to validate the NPP results. In addition, another crucial issue of MODIS NPP is the inability to link field data to the satellite images due to the spatial scale mismatch between the coarse resolution satellite pixels and the coverage of ground measurements

(Turner *et al.*, 2004b). Thus, by employing the biometric measurements and linking them with MODIS satellite data at the local scale, the accuracy of current NPP products from MODIS satellite data is able to be improved. At the same time, this study highlights another alternative source of ground measurements data for MODIS products to complement the limited number of flux towers.

Most important, this study will overcome the uncertainty in carbon study from single distinct methods that frequently occurs even at the same experimental plot and the same period as well. This is due to some researchers having claimed that their findings are indicative of a carbon sink and some others showing the contradictory. For instance, NPP measured from two different methods such as based on utilizing tree biomass census and photosynthesis rate estimation shows different result for the same experimental plot even though completely applying the conversion factor from carbon to biomass. This uncertainty is also included in the patterns of long-term series of carbon observation while comparison was made from both method. However, sources and sinks of carbon associated with forests depend strongly on the management regime and spatial patterns in potential productivity (Turner *et al.*, 2004a). Therefore, adaption through the integration of satellite images and ground measurement is the potential solution that will be able to rapidly show the carbon results in spatial patterns. This integration and new modeling hence produce spatially explicit carbon storage and flux information that can be used significantly to respond to any uncertainty in carbon status at single experimental plot and up-scale to the large coverage area.

The Kyoto Protocol was planned to be implemented for the five years commitment period from 2008 until 2012. During this period, the Kyoto Protocol is to be emphasized only on heavy industrial countries such as France, United State of America, etc. In addition, the protocol is included in their enactments with enforcement on the ARD activities especially in the tropical forest. Since Malaysia is moving to be an industrial country and also in the tropical rain forest region with more than half of the terrestrial area are forests (63%), the implementation of the protocol in Malaysia in the future is inevitable. Thus, any research related to carbon using the latest and advanced technologies must be developed adequately in order to deliver any monetary reward for carbon sequestration from the Protocol in future. In addition, the development of this new technique of modeling carbon sequestration is very essential as a complement to the present ways of dealing with carbon sequestration by responsible agencies in Malaysia such as FRIM. This study is also parallel with FRIM's mission to "develop appropriate knowledge and technology for the conservation, management, development and utilization of forestry resources; and shall pursue excellence in scientific research, development and technology transfer in the forestry sector" (http://www.frim.gov.my).

Generally, this study can be beneficial to the government for the future planning in analyzing of econometric-process model which is designed to evaluate the cost of agroforestry reserves as well as being used to assess the economic feasibility of carbon sequestration (Antle *et al.,* 2007). Consequently, the potential for carbon sequestration and the value of carbon price depend on both the rates of carbon accumulation associated with agroforestry practices and the productivity of the carbon sequestering practices. Furthermore, one of the protective forests' roles well acknowledged by the global community is in reducing carbon release and sequestering carbon until the climax stage is reached where the net carbon sequestered is zero. Therefore, the value of carbon will probably become low while the forested area which has been managed to protect the biodiversity and its ecosystem will continue to fulfil its functions without interference even as agroforestry activities are being executed. Hence, effective management and accurate information to achieve the goal as above is necessary. Carbon study using advanced technology like the one conducted in this study is very useful to help in designing the economic model. Furthermore, advanced technologies of carbon study are useful to the government in attracting investors from abroad for industrial development purposes considering the enforcement by the international community of policies like UNFCCC. Thus, it should also be possible to improve the present technology especially in forest conservation and logging system as there are drastic changes in the tropics over the last two decades. Finally, the most important is that this study can assist in policy formulation and identifying constraint which can be determined by the government in order to highlight the regulation for forestry activities with direct impact on global climate change.

## 1.9 Study Area Background

The Pasoh Forest Reserve (PFR) which is known as a virgin jungle reserve is one of 124 permanently reserved forests that were established in Peninsular Malaysia and Sabah in 1984 (Chape *et al.*, 2003). Located in the State of Negeri Sembilan, Peninsular Malaysia (Figure 1.3), it is also known as one of the oldest tropical rainforests and an old-growth tropical evergreen broad-leaved forest. The core area of PFR is a primary lowland mixed dipterocarp forest with terrain type stated as gentle hill slope. With its floristically rich forest being the key attraction, the 50 hectares area has recorded a total of 335,256 stems $\geq$ 1 cm DBH belonging to 814 species, 294 genera and 78 families. The dominant vegetation types in this reserve are tree species such as *Dipterocarpaceae*, *Leguminosae*, *Burseraceae* as well as *Euphorbiaceae*, and *Annonaceae* for understory species. Meanwhile, the dominant upper canopy are red meranti, *Shorea* section Muticae, especially *S. leprosula* Miq. *S. acuminata* Dyer, and *S. macroptera* Dyer. Other significant canopy emergent include keruing, *Dipterocarpus cornutus* Dyer, balau, *Shorea maxwelliana* King, and chengal, *Neobalanocarpus heimii* (King) Ashton. In addition, while lacking wild animals like tigers and tapirs, there are elephants and a good combination of small mammals, primates and birds where many bird species regarded as rare in other forests can be found here.

From 1970 until 1978, PFR was the site of intensive research on lowland rain forest ecology and dynamics under a collaboration project between University of Malaya (UM) and the International Biological Programme (IBP), the Man and Biosphere (MAB) Programme as well as the joint Rain Forest Research Project of UM and the University of Aberdeen, United Kingdom. PFR was in fact declared as an International Biosphere Reserve under the MAB Programme. In December 1977, the Forest Research Institute (FRI) through collaboration with the Negeri Sembilan State Forest Department took over PFR management from UM. The area has since become a field research station of the Forest Research Institute of Malaysia (FRIM).

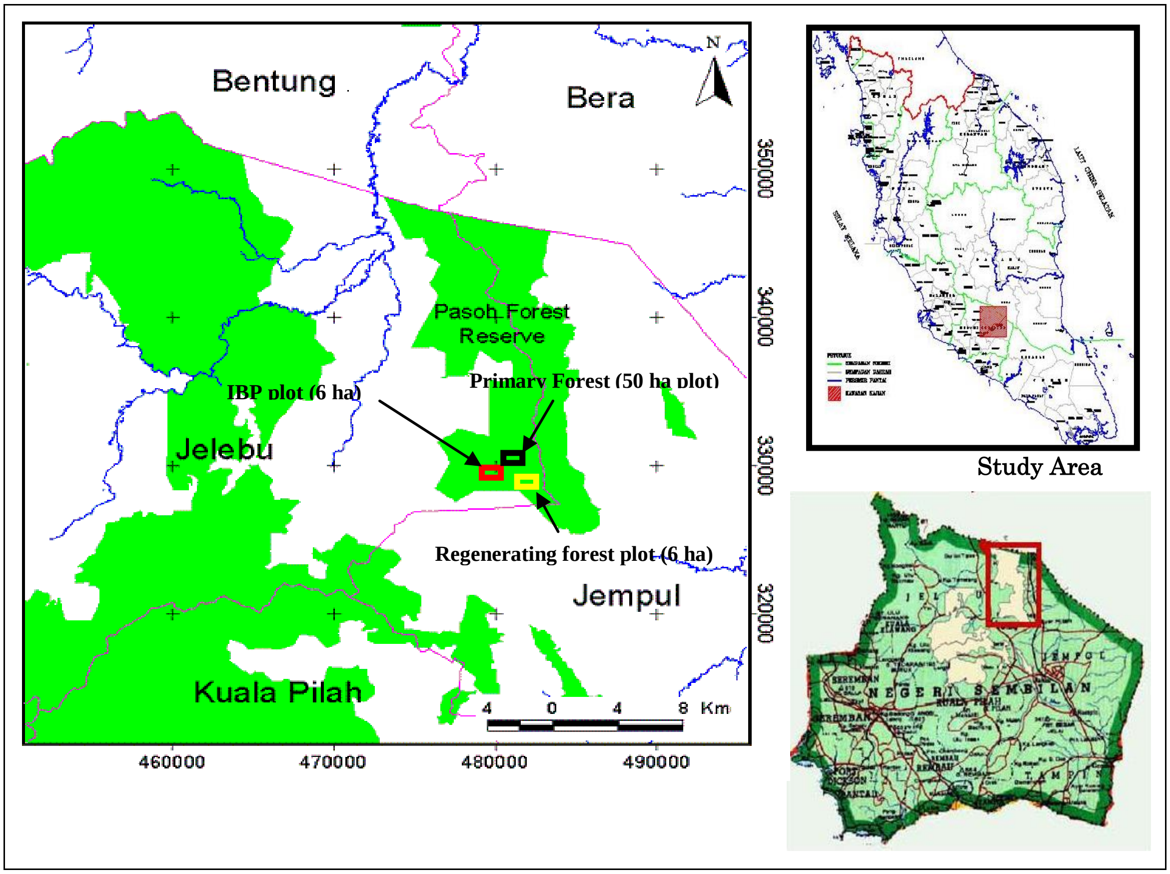



**Figure 1.3**: Study area (Pasoh Forest Reserve)

Pasoh Forest Reserve comprises three experimental plots which have been widely utilized for primary productivity study of tropical rainforest using various techniques since 1978 (Kira, 1978a). The biggest plot is an area of approximately 50 hectares called a primary forest plot and located toward the centre core area of PFR, which was jointly established by FRIM and the National Science Foundation and the Smithsonian Tropical Research Institute (STRI). A series of five years interval tree censuses have been conducted since 1990 from this permanent plot where all tree species ≥ 1 cm DBH were tagged, identified and mapped. These tree censuses will be used in the calculation of total above-ground biomass (TAGB) for the present study. Meanwhile, the most southwestern plot which covers an area of about 6 hectares and is known as the IBP (International Biological Program) plot had pro-actively been used in many forest ecological studies since 1970s. In this plot, an aluminium alloy tree tower-canopy walkway system was constructed within a collaborative project between FRIM and the National Institute of Environmental Sciences (NIES), Japan. The system which was funded by the Government of Japan comprises three 40 m tall free standing towers that facilitate microclimatic and physiological studies at various forest canopy heights, with each station having individual stairways. Meanwhile, the walkways offer convenient access to the canopy for phenological observations and faunal studies. Some sophisticated instruments are also currently placed at the top of towers in this oldest experimental plot including LI190 (LICOR, USA) for observing PAR and LUE, HMP45 (VAISALA, Finland) for recording air temperature and RT-5 (Ikeda keiki, Japan) for observing precipitation (http://asiaflux.net). The third plot called the regenerating forest plot covers an area of about 6 hectares which is adequate to be studied for logging impacts and its vicinity since early 1990s. In addition, PFR also contain several sign posted trails including the Nature Trail which is the most interesting to be taken on a short day visit. The easy circular trail starts and ends opposite the Arboretum which functions as a botanical tree garden for research and education besides the PFR's base station. Various interesting features of the reserve can be seen as the trail first passes through the selectively logged forest before entering a section of the virgin forest and looping back to the starting point.

## 1.10 Thesis Structure

A total of six chapters are included in this thesis. To summarize, chapter one presents an introduction to the study covering the background of the study, statement ofproblem , objectives of the study, scope of study, significance of the study, study area background and brief for thesis structure. Meanwhile, chapter two comprises the literature review of this study. This chapter discusses comprehensively previous related studies from fundamental research through current technologies in carbon topic such as carbon studies using biometric approach until the new era in the development of carbon satellite imageries such as MODIS satellite. In addition, three methods of carbon measurements and study comparisons under two different forest types will be discussed further in chapter two. Lastly, previous related carbon researches which have successfully been conducted at Pasoh Forest Reserve will be elaborated in this chapter as well. Chapter three subsequently focuses on the detail in theory and concept of carbon sequestration studies in three different methods whereby from tree biomass, tower flux and remote sensing data, respectively. Meanwhile, chapter four elaborates the methodology of the research. Two major processing works are presented in this chapter based on the remote sensing technique and biometric approach. Then, chapter five presents the output of the study and analysis. New carbon sequestration model from the integration of the biometric approach and remote sensing technique will be showed as the final output of the study in this chapter. Whilst, analysis will be carried out in order to identify the suitability of the new carbon sequestration model that has been produced whereby focusing on appropriate statistical analysis such as root mean square, correlation coefficient and t-test. The last chapter, which is chapter six, will discuss the achievement of the study by reviewing the objectives of study. Subsequently, a strong conclusion is produced in order to determine the significance of the study. Last but not least, the recommendation section will show the best encouraging solution to improve any uncertainty in related future carbon studies.

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