Modelling carbon stock in oil palm using system's approach

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by

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Abstract

Oil palm is one of the most productive oilseeds. The demand for products of oil palm is increasing, thus more land is planted under oil palm. Indonesia is the major crude palm oil producing country with the highest growth in area under oil palm plantations. However expansion of the plantations in the tropical forests and peat lands has been a cause of concern. Literature showed contradicting values for carbon stock of oil palm in comparison to forest; leaving the picture of carbon emissions due to expansion of oil palm incomplete. This study aims to estimate carbon stock of oil palm for the complete lifecycle of oil palm tree for Riau province in Indonesia. Field study was conducted in Riau province and parameters such as height, age, transpiration rate; photosynthetic rate, stomatal conductance, and air and leaf temperature were estimated. 90 samples were collected for oil palm in mineral soil and 60 samples were collected for peat soil. Productivity model, TURC, was used to estimate carbon stock of oil palm. Syahrinudin, Henson and Khalid published three different allometric equations for oil palm that was also used to estimate carbon stock. The photosynthetic capacity in leaves of oil palm is found to decrease with age of oil palm. Mean carbon stock estimated from TURC and allometric equation of Khalid was found significantly close to each other. The estimated carbon stock is approximately 40, 80, 140 and 170 tonnes per hectare by methods of Henson, Syahrinudin, Khalid and TURC for 25 years old oil palm, respectively. The sensitivity analysis of TURC model showed TURC is most sensitive to incident solar radiation, photosynthetic efficiency and fAPAR. The maintenance respiration estimated by TURC was found unrealistic and thus, it overestimated carbon stock for mature oil palm. Carbon stock estimated from allometric equation of Syahrinudin is found most accurate for the oil palm growing in Riau province. The carbon stock of the oil palm growing in the mineral soil was much higher in comparison to carbon stock of the oil palm on peat soil.

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List of Acronyms

AGB	Above Ground Biomass
APAR	Absorbed Photosynthetically Active Radiation
CASA	Carnagie Ames Stanford Approach
CO_2	Carbon dioxide
CPO	Crude Palm Oil
fAPAR	fraction of Absorbed Photosynthetically Active Radiation
GaAsP	Gallium Arsenide Phosphide
GHG	Green House Gases
GJ	Giga Joules
GLO-PEM	Global Production Efficiency Model
GPP	Gross Primary Productivity
Gt	Giga tonnes
Ha	hectares
IPCC	Inter-governmental Panel of Climate Change
Kg	Kilogram
MODIS	Moderate Resolution Imaging Spectrometer
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Productivity
PAR	Photosynthetically Active Radiation
PKO	Palm Kernel Oil
Ra	Respiration
RH	Relative Humidity
RSPO	Realizing Sustainable Palm Oil Production
SDBM	Simple Diagnostic Biosphere Model
SiB2	Simple Interactive Biosphere Model
SPOT	Système Pour l'Observation de la Terre
STELLA	Systems Thinking for Education and Research
TURC	Terrestrial Uptake and Release of Carbon

1. Introduction

'Deforestation and burning for land clearance are huge problems for the world in terms of the carbon emissions. Indonesia is the third largest emitter, largely the result of deforestation and peat fires.'

- Lord Nicholas Stern
  Former chief economist of World Bank and
  Climate Change Expert

Annual global emissions of carbon dioxide (CO_2) have grown from 21 to 38 gigatons (Gt) in last 34 years (1970-2000) and contributed to 77% of total anthropogenic Green House Gas (GHG) emissions in 2004 [*IPCC*, 2007]. GHG gases include water vapour, methane, carbon dioxide and nitrous oxide. CO_2 is the most important green house gas as its concentration is highest in the atmosphere in comparison to other GHG. GHG in the atmosphere trap incoming infrared radiation and make earth habitable by making it warm. Due to increased anthropogenic GHG emissions, increased warming of the earth is taking place. The average global temperature has increased over 0.74 degree Celsius in the last 100 years (1901-2005) [*IPCC*, 2007]. Though the number seems quite small but the impact of the rise of temperature is already visible. Increase in sea level, decrease in glaciers, increased incidences of flood and droughts, increased incidences of cyclones and hurricanes are reported across the world [*Cowie*, 2007; *Jager and Ferguson*, 1991; *Kondratyev and Cracknell*, 1995; *Lamb*, 1966; *O'Neill and Oppenheimer*, 2002; *Pittock*, 2005; *UNEP and GRID-Ardenal*, 2005]. If the temperature continues to increase at a current trend, by the end of this century the temperature could rise to more than 2 °C [*IPCC*, 2007] and could lead to a devastating effect.

Carbon dioxide is one of the forms in which carbon exists in atmosphere. Carbon moves in its various forms between ocean, land, earth's crust and atmosphere. This exchange of carbon between ocean, land, atmosphere and earth's crust is called carbon cycle which is shown in Figure 1-1. The major stocks of carbon are atmosphere, plants, soils, oceans and earth crust as shown in the carbon cycle. Before human intervention, carbon cycle was in equilibrium. In Figure 1-1, if emissions from burning fossil fuels and deforestation and land use change are excluded, emissions are almost in equilibrium with the assimilation of carbon. Due to human intervention, equilibrium of carbon cycle is getting disrupted and carbon dioxide concentration in atmosphere is increasing. Deforestation contributes to

17.3% of the total Green House Gas (GHG) emissions [*IPCC*, 2007]. Total deforestation rate is estimated to be 13 million hectares per year [*FAO*, 2007]. Such high deforestation rate is alarming because forests represent a significant carbon stock as it is estimated to be approximately 560 Gt. The annual uptake from photosynthesis accounts for 10-20% of the total carbon stored in the atmosphere [*Sabine*, 2005]. Conversion of these forests into agriculture and commercial plantations is one of the major sources of CO_2 in atmosphere.

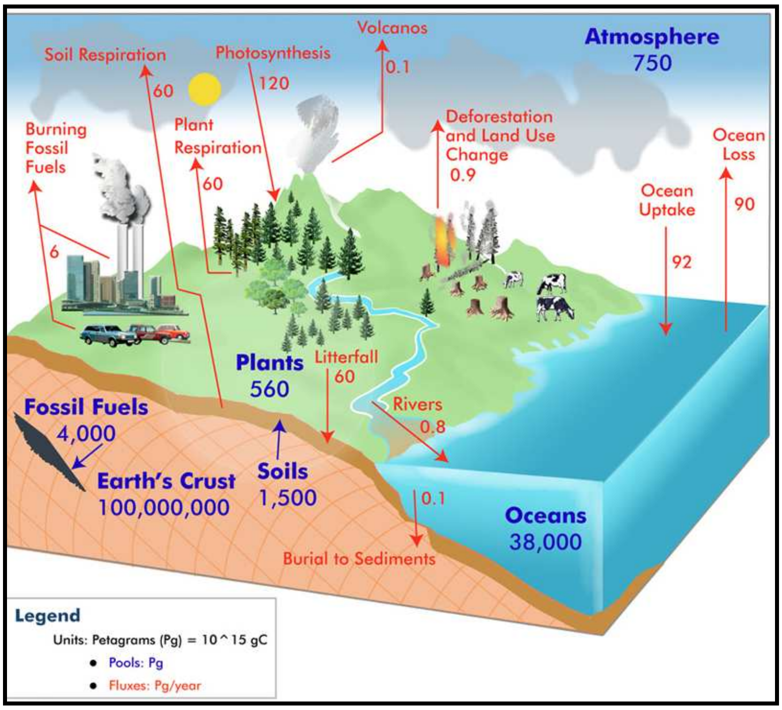


Figure 1-1 Global Carbon Cycle showing pools and fluxes of carbon in Petograms and Petograms/year, respectively
(Source: http://www.globe.gov/fsl/eventsimages/CCdiagram-Print.jpg).

Indonesia is the largest contributor of emissions due to deforestation and land use change [*Houghton*, 2003]. Indonesia has 100 million hectares of tropical forests that account for 10% of the global tropical forests [*Palmer*, 2001; *Sunderlin and Resosudarmo*, 1996]. Tropical forests have the highest carbon pool both in plant biomass and soil when compared to other forest types [*Sabine*, 2005]. Deforestation rate in Indonesia from 2000 to 2005 is 1.9 million hectares per year, highest in South-east Asia [*FAO*, 2007]. The forest in Indonesia store approximately 3.5 million tonnes of carbon. Apart from carbon stock in forest, peat soil of Indonesia also store huge amount of carbon. Peat is formed by the dead and decomposing plant material that gets accumulated for many years in the water logged conditions. The waterlogged conditions lack oxygen and thus, the organic material of plants do not get decomposed and stores huge amount of carbon [*Jaenicke et al.*, 2008]. Due to land use change and drainage of peat soil, the organic matter of peat starts oxidizing and release huge amounts of CO_2 [*Hirano et al.*, 2007]. Land use change and drainage also makes peatland very prone to fires [*Zakaria et al.*, 2007]. Fires in degraded peat land have become common in Indonesia. In some cases, plantation owners set fire on clear felled peat swamp forests to burn the wood residues and to drain the peat soil [*Sargeant*, 2001; *Zakaria et al.*, 2007]. In the fires on peat lands in Indonesia between 1997 and 1998, estimated carbon emissions are 0.8 to 2.5 Gt which accounts for 13 to 40% of the annual global carbon emissions from fossil fuels [*Jaenicke et al.*, 2008; *WWF*, 2007].

Deforestation in Indonesia is largely caused due to expansion of commercial oil palm plantations [*Casson*, 2003; *Erwidodo and Astana*, 2004; *Rhee et al.*, 2004; *Wakker*, 2004]. Crude Palm Oil (CPO) produced from oil palm (*Elaeis guineensis*) has the highest energy content amongst all other possible sources of biodiesel and is estimated to be 150 GJ/ha. This energy content is 6 times more than soybean and approximately 3 times more than *Jatropha* [*RS*, 2008]. Oil palm is considered to be the most productive oil crop as a single hectare of oil palm can produce 6000 litres of crude palm oil (CPO). Its nearest competitor, soybean, has 3 to 8 times less productivity [*Wahid*, 2005]. It means oil palm would require much less land to produce the same amount of oil than soybean. Due to these advantages, global palm oil production increased by 55% in 5 years from 2001 to 2006 [*Fitzherbert et al.*, 2008] and thus, more land area is converted into oil palm plantations. Conversion of forest to oil palm emits CO_2 due to loss of plant biomass, soil decomposition and increased fire incidences. However, since the forested area is converted to plantations which is considered as 'alternative productive use' [*FWI/GFW*, 2002], some claims that carbon stock within oil palm is considerable and neutralizes the emissions due to deforestation [*Lamade and Bouillet*, 2005].

The carbon stock in oil palm tree has two major components: soil carbon and oil palm standing biomass as shown in Figure 1-2. Photosynthesis, respiration and decomposition of organic materials are the main flows of the system. Emissions due to deforestation is also included in this system however it is excluded if the expansion of oil palm takes place in wasteland or in non-forested land. Emissions from palm oil production include emission due to burning of fossil fuel while transportation and producing electricity for various machineries used in palm oil mill. Increase in the demand of palm oil in market directly influences the emissions from oil palm plantations. Oil palm management affects the emissions from oil palm plantation system, for e.g. management choice of burning the wood residues for site preparation may lead to huge emissions from oil palm plantation system. Policy implementation like zero burn policy and Realizing Sustainable Palm Oil Production (RSPO) can affect oil palm management by enforcing restrictions on management activities emitting huge amounts of carbon in the atmosphere. Policy restrictions such as export taxes can also restrain the market and lead to decrease in demand. Before aiming for reduced demand for palm oil, there is a need to know why oil palm is so important to the world, when was it introduced in Indonesia and why did it expand so unsustainably.

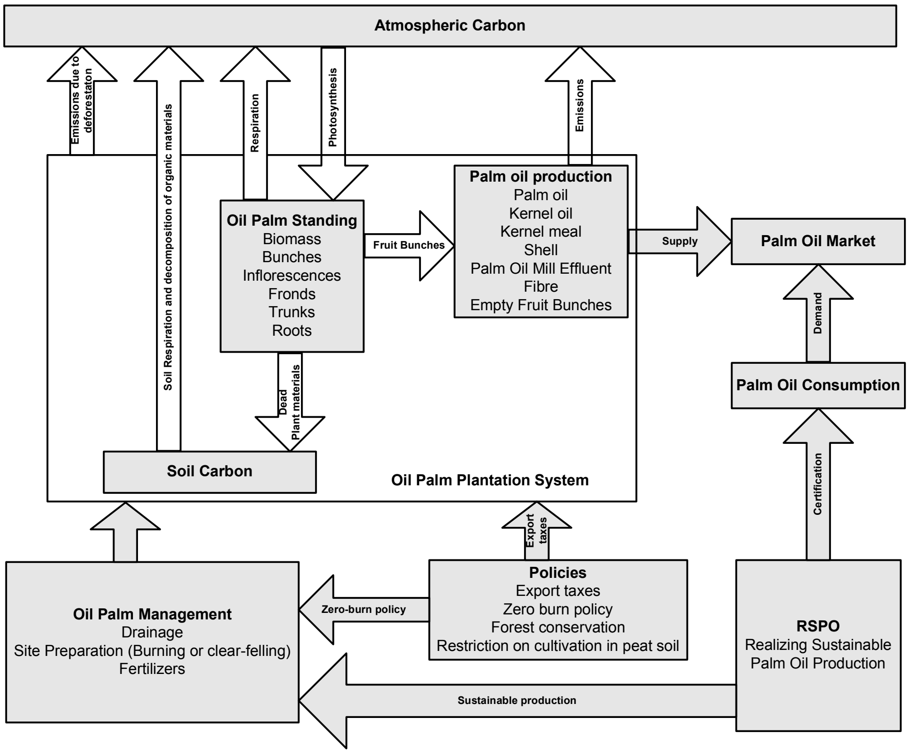


Figure 1-2 Carbon stocks and flows in the oil palm plantation system and external systems affecting the plantation system

Importance of oil palm

Oil palm, *Elaeis guineensis*, was known to the world even in 3,000 B.C. In Egypt, evidence of oil palm has been found in archaeological digs. Fruits of oil palm became an important part of the food for sailors since Portuguese discovered this crop in West Africa in the 15th century [*van Gelder*, 2004]. As the nutritional value of palm oil was realized, its consumption increased and it was introduced in more countries to meet the demand. Oil palm is native to the tropical region of West African coast [*van Gelder*, 2004]. There are two economically important products of oil palm: Crude Palm Oil (CPO) and Palm Kernel Oil (PKO). CPO is derived from the red fruits of oil palm and it has equal amount of saturated (oleic) and unsaturated (palmitic) fatty acid [*Casson*, 2003; *van Gelder*, 2004]. Palm Kernel Oil (PKO) is derived after crushing palm kernel and has 82% saturated fatty acid (lauric acid). The application of products of oil palm in industries is listed in Table 1-1.

Table 1-1 Products of oil palm and its use in various industries [*van Gelder*, 2004]

	Oil palm product used	*Purpose*
Food industry	CPO (low cholesterol)	Cooking oil and many more
Soap and detergent industry	PKO (lauric acid)	Quick lathering
Cosmetics industry	Oleochemical ingredients of CPO and PKO	Easily absorbed by skin
Leather and textile industry	CPO	Lubricant/ greasing and softening leather
Metal industry	CPO	Rolling, polishing metals
Chemical industry	CPO and PKO	Paints, coatings
Energy industry	CPO	Biofuel

Oil palm in Indonesia: Historical development and present status

The first oil palm plantations in Indonesia at a commercial scale were established by Dutch colonial government in 1911 [*Casson*, 1999; *van Gelder*, 2004]. After gaining independence in 1945, these plantations were owned by State government. The optimum conditions for the growth of oil palm requires humid tropical lowland climate, evenly distributed rainfall throughout the year with the mean of 2000 mm or more and minimum temperature of 18°C [*Moll*, 1987]. Location of Indonesia and its climate made it a favourable place for oil palm growth. Due to investment opportunity by Indonesian government through assistance of World Bank, oil palm plantations started to expand since 1968. International investment opportunities in Indonesia increased as it was cheap to grow oil palm in Indonesia [*Larson*, 1996]. Due to government intervention and World Bank assistance, smallholder estates started to expand in 1979 whereas private estates expanded after 1986 [*Casson*, 1999; *Larson*, 1996; *van Gelder*, 2004]. Due to low cost of palm oil production, area under oil palm plantations increased by 36 times between mid 1960s and 1999. Indonesian government aimed at outcompeting Malaysia and wanted to increase its share in palm oil production. To achieve it they approved of converting 7 million hectares of forest land to plantations by the end of 1997 [*Casson*, 1999; *Larson*, 1996]. Indonesia succeeded in 2005 and become the largest palm oil producing country [*Falk*, 2008].

Carbon stock in oil palm

The area of oil palm plantations has increased from 200,000 hectares in 1967 to 5.6 million hectares in 2005 [*FWI/GFW*, 2002]. This has come at the cost of 20 million of tropical forest and this loss continues at a rate of 1.9 million hectare per year [*Erwidodo and Astana*, 2004; *FAO*, 2007; *FWI/GFW*, 2002]. There are some studies that claim that oil palm can store 4 times more carbon than forest ecosystems [*Lamade and Bouillet*, 2005]. However, some studies state that carbon stock in oil palm is much smaller than forests [*WWF*, 2008a]. Such contrasting results give an insight into the errors and uncertainties involved with estimation of carbon stock [*DeFries et al.*, 2002; *Hese et al.*, 2005; *Houghton et al.*, 1999; *Houghton*, 2003; *Lu*, 2006]. In tropical countries such as Indonesia, estimation of carbon can have a possible uncertainty of ±50 % [*Houghton*, 2003; *Watson*, 2008]. For a clear picture of carbon emissions from oil palm expansion, carbon stocks within oil palm should be estimated with accuracy.

For estimation of carbon stock in oil palm, first biomass is estimated and then, standard carbon content (%) in biomass is used to convert it to carbon stock. However, there are uncertainties in estimation of biomass and carbon content in the biomass. Henson [2004] has attempted to model carbon sequestration in oil palm and stated the high uncertainty in carbon content in the biomass of oil palm. The rate of biomass production for the oil palm is generally taken constant throughout the life cycle of 25-30 years [*Thenkabail et al.*, 2004; *WWF*, 2008a]. According to National GHG inventory of Indonesia, the annual biomass production of oil palm is 10.00 tonnes per hectare [*Lasco*, 2002]. Whereas another study by Wahid et al [2004] states that 'non-oil equivalent' biomass production of oil palm is over 44 tonnes per hectare. However, constant biomass production may not be representative for the whole life cycle. In order to model the carbon stock of oil palm accurately, it is important to asses the rate of biomass production accurately. For the accurate assessment of biomass production, it is important to be familiar with the physiological properties of oil palm.

Oil palm is a monocotyledonous perennial crop with a C3 photosynthetic pathway. It is the most productive of all oil crops. If water deficits are minimal, the yields of oil palm are high because [*Wahid*, 2004; 2005]:

1) Its photosynthetic capacity is high,
2) At spacing of 130-150 palms per hectare, it attains full canopy cover by 5th to 6th year of planting.
3) By the 10th year, 96% of Photosynthetically Active Radiation (PAR) is intercepted whereas the mean interception for the whole life cycle of oil palm is also quite high, i.e. 88%.

The photosynthetic activity of oil palm is quite high but respiration of oil palm is also estimated to be much higher than the dicotyledonous plants. The respiration is higher because all the vegetative tissues (trunks and rachises) are living and thus, must be respiring [*Corley et al.*, 1971] unlike dicotyledonous that have non-living secondary thickening. Thus, it could be that its uptake of CO_2 is much higher than normal forest species but due to high respiration rate the net carbon stocks are much less in comparison to carbon stocks in tropical forests. However, in literature considerable difference was found in the estimates of carbon stock in oil palm as can be seen in Table 1-2. This difference in the carbon stock could be due to difference in the age of oil palm for which the carbon stock is measured. In some studies, it is mentioned that the rate of carbon assimilation changes with age of the oil palm crop. Lasco [2002], Henson [1992] and Syahrinudin [2005] covered different age groups but there was no in depth discussion of how carbon assimilation changes throughout the lifecycle of oil palm. It is important to know how oil palm stores carbon and how this rate changes with age.

Table 1-2 Estimates of carbon assimilation in oil palm available in literature

Reference	*Parameter estimated*
[*Lamade and Bouillet*, 2005]	CO_2 fixation = 26 tonnes/hectare/year Estimates given by IOPRI*
[*Lasco*, 2002]	Carbon stock = 30 to 100 tonnes/hectare
[*Syahrinudin*, 2005]	Carbon stock = 10 to 60 tonnes/hectare
[*Henson*, 1992]	Carbon stock = 5 to 7 tonnes/hectare/year

*IOPRI: Indonesia Oil Palm Research Institute

Methods to estimate carbon stocks

Carbon stocks estimation in the field is done mostly through biomass estimation. It is established that carbon content of a tree is almost 50% of its oven dry biomass[*Brown*, 1997]. Biomass here is understood as the weight of the tree including both aboveground (trunk, fronds) and belowground organs (roots) in a given area. Dry biomass is the weight of the tree after drying it in oven at a temperature of approximately 105 °C [*de Gier*, 2003]. Due to difficulty of measuring belowground biomass, most research focuses on above ground biomass (AGB) [*Brown and Lugo*, 1984; *Brown et al.*, 1991; *Chave et al.*, 2005; *Lamade and Bouillet*, 2005; *Lasco*, 2002; *Ludang and Jaya*, 2007; *Michelsena et al.*, 2004; *Richards*, 2002]. There are different techniques available to measure biomass which can be broadly classified into two categories as shown in Table 1-3: a) Field based methods, and b) remote sensing based methods [*Lu*, 2006]. Field based measurements are the most accurate and majority of the work done to calculate carbon stocks are based on such methods. Remote sensing based measurements have recently gained popularity due to easy repetitiveness, more spatial coverage and good correlation between biophysical parameters (such as NDVI, fAPAR, etc.) and spectral bands [*Cramer et al.*, 1999; *Lu*, 2006].

Field based estimation of biomass generally involves cutting the tree, determining fresh and dry (oven dry at 105 °C) weight. Carbon content can also be accurately measured by burning the dry matter and determining the weight of ash left after burning. This method is called destructive method and is impractical to implement on trees or crops with a stem diameter of 30 cm or more [*Hairiah et al.*, 2001]. As oil palm reaches a height of 10m and a diameter of about 40 to 60 cm, it is impractical to implement destructive method. Another field based method to estimate biomass is to use allometric equations derived for the same site or atleast for the similar conditions. Allometric equations available in literature estimate wet and dry biomass from parameters such as height and diameter of trunk but for oil palm generally height is used to estimate biomass. This is because oil palm is monocotyledonous and there is no secondary thickening in the trunk. It is believed that the width of trunk of oil palm increases till three years after planting but later vertical growth predominates [*Henson*, 2006]. There are various allometric equations available for oil palm based on height and age of plantations. However for conditions comparable to Indonesia there were only three allometric equations which are summarized in Table 1-4.

Field methods described above are impractical to estimate biomass for large oil palm plantations. The cheapest and easiest method to meet the objective of estimating biomass for large plantations is to use the technology of remote sensing. The red and near infrared bands of remote sensing images obtained from satellites can derive fraction of Absorbed Photosynthetically Active Radiation (fAPAR). fAPAR measures the proportion of available radiation in the specific photosynthetically active wavelengths of the spectrum 0.4 - 0.7 μm that a canopy absorbs. This fAPAR have linear relationship with the photosynthetic capacity. Moderate Resolution Imaging Spectrometer (MODIS) is a sensor on board satellites TERRA and AQUA.

MODIS land science team provide 8 day composites of derived fAPAR, MOD 15A. It is one of the most widely used product.

Table 1-3 Techniques available for measurements of biomass

Technique	*Sub-classes*	*Source*
Field measurement	Destructive sampling	[*de Gier*, 1989; 2003; *Ludang and Jaya*, 2007]
	Allometric equations	[*Chave et al.*, 2004; *Chave et al.*, 2005; *de Gier*, 1989; 2003; *Ketterings et al.*, 2001; *Woomer and Palm*, 1998]
Remote sensing based methods	Using high resolution images (e.g. IKONOS)	[*Thenkabail et al.*, 2004]
	Using medium resolution images (e.g. LANDSAT, SPOT)	[*de Gier and Sakouhi*, 1995; *WWF*, 2008a]
	Using low resolution images	[*Lefsky et al.*, 2005; *Veroustraete et al.*, 2004]

Table 1-4 Allometric equations available for Malaysia and Indonesia

Source	*Equation*	*x*	*Site*
[*Syahrinudin*, 2005]	Total biomass(tonnes ha^{-1}) $= 68.2\ln(x) - 36.7$ R^2 = 0.99, p not available, density not available	Age	Loam to clay in Sumatra, Indonesia
[*Henson*, 2003]	Mean standing biomass (tonnes ha^{-1}) = $\left[-\left(0.00020823 * x^4\right) + \left(0.000153744 * x^3\right) - \left(0.011636 * x^2\right) + (7.3219 * x) - 6.3934 \right]$ R^2=0.85, p not available, density not available	Age	Malaysia
[*Khalid*, 1999]	Total fresh biomass (kg) = $725 + (197 \times x)$ R^2 = 0.96, p=0.001 density = 136 palms ha^{-1}	Height (m)	23 year old in Malaysia

There are empirical models available that use fAPAR as input to estimate Net Primary Productivity [*Cramer et al.*, 1999; *Ruimy et al.*, 1996; *Ruimy et al.*, 1999]. Net Primary Productivity (NPP) can be defined as 'the rate of atmospheric carbon uptake' [*Ruimy et al.*, 1996]. NPP is measured by the two main processes:

1) Gross Primary Productivity (GPP): Rate of uptake of CO_2 for the process of photosynthesis. Photosynthesis consumes energy and combines carbon and water to form CH_2O compounds. These compounds form the plant tissues.
2) Respiration (Ra): Rate of release of atmospheric carbon. This process breaks down CH_2O compounds to release energy, CO_2 and H_2O. Energy released in this process is used by plants for growth and maintenance of plant tissues. CO_2 and H_2O are released back in the atmosphere.

NPP is the difference between GPP and Respiration and can be estimated by models using remote sensing data. However these models are used mostly for dicotyledonous plants and have not been studied much for monocotyledonous C3 plants such as oil palm.

The models considered for this study were taken from a review study by Cramer et al [1999]. Cramer et al [1999] divided the models estimating NPP into three categories:

1) models that use remote sensing input,
2) models for seasonal biogeochemical fluxes,
3) models for seasonal biogeochemical fluxes and vegetation structure.

The models under consideration are the remote sensing based models that included CASA, GLO-PEM, SDBM, TURC and SiB2 as described in Table 1-5. Terrestrial Uptake and Release of Carbon (TURC) was chosen because of three advantages:

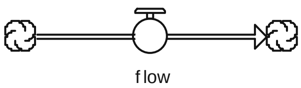
1) It produces both GPP and Respiration as output unlike CASA, SDBM that give NPP directly. Thus, it would help in understanding the process of carbon uptake in a better way.
2) It is the simplest model of all as it requires least parameters to estimate the carbon uptake and still is widely used.
3) Its temporal resolution is 1 month and it is not specific to any ecosystem.

Table 1-5 Models reviewed for the study that uses remote sensing as input
Source: [*Cramer et al.*, 1999]

Model	*Acronym*	*Temporal resolution*	*Output*
CASA	Carnagie Ames Stanford Approach	1 month	NPP
GLO-PEM	Global Production Efficiency Model	10 days	GPP, Ra
SDBM	Simple Diagnostic Biosphere Model	1 month	NPP
TURC	Terrestrial Uptake and Release of Carbon	1 month	GPP, Ra
SiB2	Simple Interactive Biosphere Model	12 min	GPP, Ra

TURC model is a simplified set of mathematical equations to estimate Net Primary Productivity (NPP). System's approach is a way of representing the model such that its behaviour is more explicit. For example if TURC is understood by system's approach; the system that is modelled is tonnes of carbon in oil palm plantation per hectare. The carbon stock is the accumulation of NPP over time. However, GPP and respiration are the flows, i.e. the movement of carbon into the system or out of the system. Apart from stocks and flows, there are convertors that are constants or external or internal factors affecting the flows. In TURC, convertors for GPP would be fAPAR and incoming solar radiation. Both these factors are external and still affect the system of carbon in oil palm. However, convertors or factors affecting the flow of respiration would be biomass and temperature where biomass is an internal factor and temperature is external. TURC can be simply represented by the system dynamics flow diagram with stocks and flows. The symbol of stocks and flows are given in Table 1-6. In order to understand the system's behaviour over time, system's approach is very useful. The software such as STELLA (Systems Thinking for Education and Research) provide a user-friendly interface to build a model by defining stocks and flows of the system.

Table 1-6 Symbols used in the system dynamics flow diagram and its definition in the TURC model

Symbol	*Represent*	*TURC definition*
	Stocks	Carbon stock in oil palm
	Flow	GPP and Respiration
	Convertor, i.e. components modifying flows	fAPAR, incoming solar radiation, biomass, temperature.

Research Objectives

The main objective of this study is to estimate carbon stock in oil palm plantations and to explore different methods to estimate carbon stock. Another minor objective of this study is to compare the carbon stock in oil palm growing on mineral and peat soil.

Specific Objectives

1) To assess the age related changes in photosynthetic capacity of leaves of oil palm.
2) To estimate carbon stock in oil palm from available allometric equations mentioned in Table 1-4.
3) To estimate carbon stock in oil palm by TURC.
4) To assess the difference of carbon stock in oil palm when estimated from allometric equations and by TURC.
5) To assess the sensitivity of input parameters for the model TURC.
6) To validate the carbon stock estimated from four different methods.
7) To assess the difference between carbon stock in oil palm growing on mineral soil and peat soil.

Research Questions

Related to Objective 1

1. How does the photosynthetic capacity of leaves change with the age of oil palm?

Related to Objective 2

2. What is the carbon stock in oil palm estimated from allometric equations?

Related to Objective 3

3. What is the carbon stock in oil palm estimated by TURC?

Related to Objective 4

4. Are the estimated carbon stocks estimated from allometric equations different from carbon stock estimated by TURC?

Related to Objective 5

5. How sensitive is TURC to the various input parameters?

Related to Objective 6

6. Which is the most accurate method to estimate carbon stock in oil palm for Riau province?

Related to Objective 7

7. Are the estimated carbon stocks in oil palm growing on mineral soil different from estimated carbon stock in oil palm growing on peat soil?

Hypothesis

Research Question 4: Are the estimated carbon stocks estimated from allometric equations different from carbon stock estimated by TURC? ($p=0.05$)

Hypothesis 1

H_o: Mean carbon stocks in the oil palm by four different methods are equal.

H_1: Mean carbon stocks in the oil palm by four different methods are not equal.

Research Question 7: Are the estimated carbon stocks in oil palm growing on mineral soil different from estimated carbon stock in oil palm growing on peat soil? ($p=0.05$)

H_o: Carbon stock in the oil palm growing on mineral soil is equal to or less than the carbon stock in the oil palm growing on peat soil.

H_1: Carbon stock in the oil palm growing on mineral soil is more than the carbon stock in the oil palm growing on peat soil.

2. Study Area

Location

The study area chosen for this study is Riau province in Sumatra island of Indonesia. Its latitudinal and longitudinal extent is 1° S to 2°30' N and 100° E to 103° 50' E, respectively (Figure 2-1). Sumatra is the largest island of Indonesia and sixth largest in the world [*WWF*, 2007]. Forest cover is approximately 20% of Sumatran land mass [*Sunderlin and Resosudarmo*, 1996] and can be divided broadly into: lowland forests and peat swamp forests. Sumatra has the majority of existing oil palm plantations of Indonesia, mainly located in four provinces: North Sumatra, Riau, South Sumatra and Jambi [*Erwidodo and Astana*, 2004]. Riau was chosen as the study area because the expansion was the highest amongst all the provinces in Indonesia [*Casson*, 2003] and also because of the good background dataset allowing comparison and better interpretation of results. Riau lost 65% of its forest cover in last 25 years from 1982-2007 [*WWF*, 2008a]. Out of this total forest lost, 29% was replaced by industrial and 7.2 % by the smallholder oil palm plantations. The peat swamp forests of Riau store 16.9 million tonnes of carbon which is the highest in Indonesia [*WWF*, 2008b].

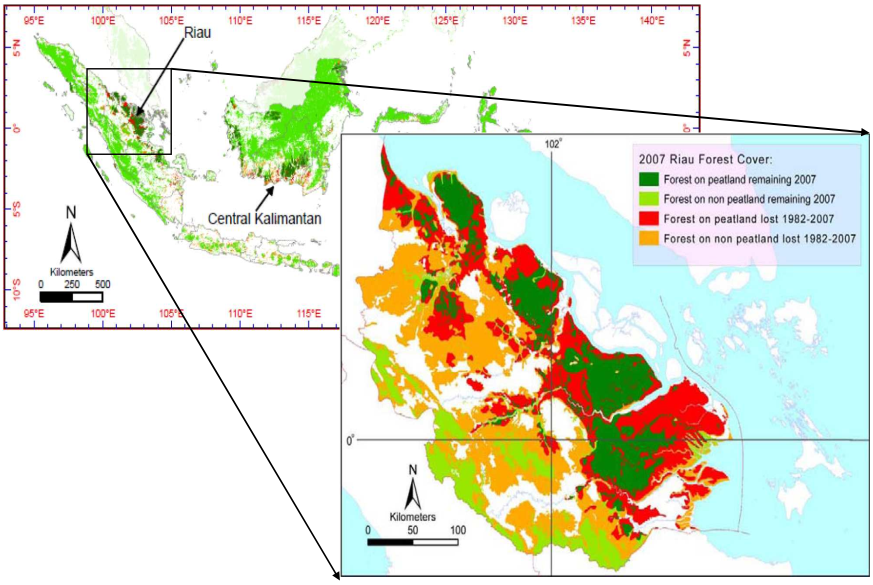


Figure 2-1 Location of Riau province and its forest cover for the year 2007

Climate

The climate of Riau is tropical with dry (June to September) and rainy seasons (October to May). The precipitation ranges from 2000 to 3000 mm per year with approximately 160 days of rain. The average temperature remains around 28 °C throughout the year with the minimum of 23°C to 34°C. Thus, the climate of Riau is very suitable for the growth of oil palm.

Land Use

Land use of Riau can be divided into: natural forest, pulpwood plantations, estate plantations, small holder plantations, wasteland and water body. The area of the various land use and its percentage is given in Table 2-1.

Table 2-1 : Area in hectares and percentage of various land cover found in Riau (Source: WWF, Riau)

Land cover	*Area (hectares)*	*Area (%)*
Acacia Plantation	1104073	10
Cleared land	260234	2
Natural forest	3618164	32
Oil palm plantations	1675698	15
Other land cover	1847751	17
Small holder oil palm plantations	488389	4
Wasteland	1195178	11
Water body	1002538	9

3. Materials and Methods

General methodology

Simplified methodology followed to achieve the answers to research questions laid down in this study is shown in Figure 3-1. It comprised of both field sampling and implementation of an empirical model in system dynamic based software, STELLA. Every component of approach is discussed in detail later in this chapter.

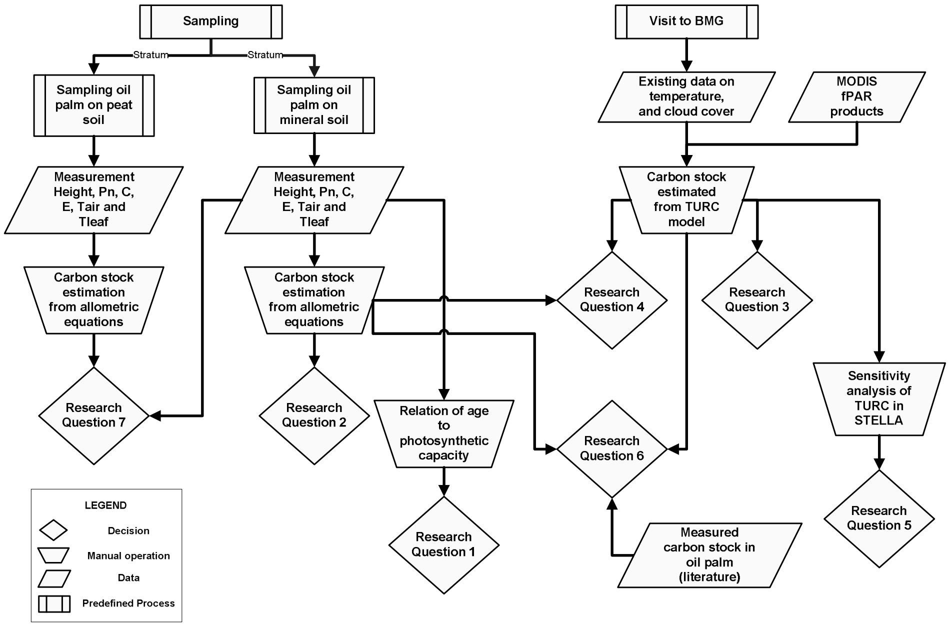


Figure 3-1 General approach to attain answers to the research questions

Field data

The oil palm plantations were divided into two strata: those growing on peat and on mineral soil. For every age sampled in each stratum, 10 repetitive samples were taken in order to assess how the photosynthetic capacity varies for the same soil, same conditions, same location and same age. Earlier stratified random sampling was planned though random sampling could not be performed because of the following reasons:

a) Earlier it was planned to take samples from big plantations companies. But these companies were apprehensive to allow research on carbon stocks in their premises. Thus, samples were taken from smallholder plantations. The shapefiles of these plantations were not available and thus random points could not be established before going to the field.

b) Access to smallholder plantations also was restricted. Therefore, every opportunity to enter an oil palm plantation was taken. Due to the good contacts of WWF with various small holders in the area and talking to plantation owners it was possible to visit sufficient different farms with oil palm of different age classes.

Thus the samples taken were representative of only the small holder plantations in Riau province. Instead of a plot of a certain size, a single tree was taken as sampling unit as measurement of all parameters in a single tree was taking a minimum of 15 minutes. Spacing between the oil palm trees was found to be 9m X 8.5 m in the field. The density of oil palm in Riau was found to be 131 trees per hectare. The area of the sampled plantations ranged from 0.5 to 15 hectares. Oil palm plantations on peat soil were relatively young and no samples were found in the mature age, i.e. between 21-25 years. The total number of samples collected is 150; 90 for the mineral soil and 60 for the peat soil. The details of the sample are given in Table 3-1. The parameters that were measured in the field and its purpose are given in Table 3-2. Height was measured by meter tape and for old trees the dried fronds of oil palm were used to measure height. Height was measured from the growing point of oil palm which is at the top of the stem. For older palms, standard method to measure height is to measure distance from ground to frond 33 as it can be easily located. Though frond 33 may likely to fall below growing point and thus, may underestimate the height [*Henson*, 2006]. The plantation owners shared that true height is the distance from ground to frond 17. Thus all the height measurements for this study were taken as a distance from ground to frond 17.

This study aimed to assess the age related changes in the photosynthetic capacity of leaves of oil palm. Three parameters characterizing photosynthetic capacity were measured in the field, namely: photosynthetic rate, stomatal conductance and transpiration rate. Photosynthetic rate is the rate with which carbon is assimilated in the plants. Stomatal conductance determines 'rate of diffusion of CO_2 into the intercellular air spaces of leaves' and is linearly related to the photosynthetic capacity [*Henson*, 1991]. Transpiration rate here is defined the rate of loss of water vapour through stomata. As transpiration rate is also dependant on stomata, it is always associated with diffusion of CO_2 for photosynthesis. CI-340 portable photosynthesis system was used to measure photosynthetic rate, stomatal conductance and transpiration rate. All these parameters were estimated per square meter of leaf area by CI-340. CI-340 has CO_2/H_2O gas analyzer to measure photosynthetic rate, stomatal conductance and transpiration rate along with PAR, air and leaf temperature. The specification of these analyzers and sensors are given in Table 3-3. Due to high sensitivity of the PAR sensor to variability of light conditions and high cloud cover during the fieldwork period; reliable data on PAR could not be collected.

Table 3-1 Age and total number of the samples taken for the two stratum

Sub-strata	*Strata*			
	Mineral Soil		*Peat Soil*	
	Age sampled	*No. of samples*	*Age sampled*	*No. of samples*
Young stage (1-3 years)	2	10	2,3	20
Intermediate stage (4-10 years)	4,6,10	30	8,9	20
Productive stage (11-20 years)	11,15,17	30	12,18	20
Mature stage (21-25)	22,24	20		
Total no. of samples		*90*		*60*

Table 3-2 Parameters estimated in the field for oil palm

S.No.	*Parameters*	*Purpose*	*Research Question*
1	Age	Biomass estimation from allometric equation	Research Question 2
2	Height	Biomass estimation from allometric equation	Research Question 2
3	Photosynthetically Active Radiation (PAR)	Extra dataset	
4	Air temperature	Extra dataset	
5.	Photosynthetic rate	To assess age related changes in photosynthetic capacity of leaves of oil palm	Research Question 1
6.	Leaf temperature	Extra dataset	
7.	Leaf stomatal conductance	To assess age related changes in photosynthetic capacity of leaves of oil palm	Research Question 1
8.	Transpiration rate	To assess age related changes in photosynthetic capacity of leaves of oil palm	Research Question 1

Table 3-3 Specifications of CI-340 portable photosynthesis system Source:[*CID Inc.*, 2005]

S.No.	*Type*	*Sensor*	*Accuracy*	*Range*
1.	Stable analyzer for accurate CO_2 and H_2O measurements	Low power infrared detector	±2 %	
2.	Highly stable analyzer for accurate H_2O measurements	Humidity sensitive capacitor	±2 % at 10% RH and ±3.5 % at 90% RH	0 – 100 % R.H.
3.	PAR sensor	Filtered GaAsP photodiode	5 mmol $m^{-2}s^{-1}$	0 ~ 2500 mmol $m^{-2}s^{-1}$
4.	Air temperature sensor	Thermocouple	±0.1 °C	-15 ~ 50 °C
5.	Leaf temperature sensor	Infrared	±0.3 °C	-10 ~ 50 °C

Method to assess age-related changes in photosynthetic capacity of leaves of oil palm

The data estimated in the field for photosynthetic rate, transpiration rate and stomatal conductance of leaves of oil palm in mineral soil was used for this analysis. Out of the 90 samples taken for oil palm; only for 33 samples these three parameters could be estimated. This was mainly because the instrument CI-340 couldn't stabilize for the rest of the 57 samples. The reason for the inability of instrument to stabilize could be attributed to high humidity as the Relative Humidity (R.H.) in Riau was always above 50%. The performance of CI-340 is affected by humidity as can be seen in Table 3-3 that its accuracy reduces with increase in R.H. The 10 samples for 4 year old palm were removed from analysis as the height of palm in this plantation was almost equal to 10 year old oil palm sampled in the field. The inclusion of these samples would increase the bias in the data due to changing conditions and thus were not used at all in the analysis. Therefore, out of 33 samples only 23 could be used finally. For these 23 samples, descriptive statistics of the three parameters were performed as given in the Table 3-4. Outliers were defined below the lower flag and above the upper flag. By this criterion, 6 outliers were found for Photosynthetic rate; 1 outlier for stomatal conductance and none for transpiration rate. The data after removing outliers was regressed with age of oil palm plantation to assess the relationship of age and the photosynthetic capacity of leaves of oil palm which is represented by three parameters.

Table 3-4 Descriptive statistics for photosynthetic rate, stomatal conductance and transpiration rate

Parameters	*Lower flag*	*1st quartile*	*Median*	*3rd quartile*	*Upper flag*
Photosynthetic rate	-13.5	-3.3	0.9	3.4	13.6
Stomatal conductance	-146.6	70	99.7	214.4	431
Transpiration rate	-0.9	0.6	0.8	1.7	3.2

Method to estimate carbon stock in oil palm from allometric equations

The field data used here was also for oil palm in mineral soil in order to avoid bias due to difference in soil type. However, differences due to maintenance, management and location could not be avoided. Three allometric equations listed in Table 1-4 were used to first estimate biomass of the oil palm. Then the biomass was converted to carbon stock by assuming the carbon content in the biomass to be 45% [*Henson*, 2004]. One of the allometric equation used height of oil palm plantation whereas other two equations used age of oil palm plantation as an independent variable to estimate biomass. For the equation that used height i.e. Khalid et al [1999], each age had 10 estimates for biomass which was averaged to estimate the mean biomass. The biomass estimated from Khalid et al [1999] was estimated in kg/tree whereas the rest were estimated in tonnes/hectare. The carbon estimated by Khalid et al [1999] was thus, converted to tonnes/hectare by assuming the tree density of 131 trees/hectare (as discovered while sampling in the field). The equation applied to convert kg/tree to tonnes/hectare is as follows:

$$Biomass\ (tonne/hectare) = \frac{Biomass\ (kg/tree) \times 131\,(trees/hectare)}{1000\,(kg/ton)}$$

Terrestrial Uptake and Release of Carbon (TURC)

It is essential to know the model TURC before describing the data required for the study. TURC is a remote sensing based model to estimate the Net Primary Productivity (NPP) of vegetation. This model makes an attempt to estimate NPP as simply as possible without need of calibration. It calculates NPP as a difference of GPP and respiration where:

1. *GPP* is dependent on incoming solar radiation, fAPAR and photosynthetic efficiency.
2. Respiration is divided into two components: maintenance respiration and growth respiration. *Maintenance respiration* is dependent on air temperature and biomass. *Growth respiration* is dependent on carbon available for growth.

GPP is calculated by *Equation 3.1*:

$$Pg = \varepsilon \times f \times S \times c$$

P_g = Gross Primary Productivity in tonnes (C) per hectare per annum

ε = Photosynthetic efficiency tonnes (C) per MJ of light energy

S = Incoming Solar Radiation MJ per hectare per annum

f = fraction of radiation absorbed by canopy (remote sensing derived product)

c = ratio of incident PAR to incident solar radiation

Maintenance respiration calculated by *Equation 3.2*

$$M = \sum_i \left(M_{20,\,i} \times \left(x + \left(y \times T \right) \right) \right) \times W_i$$

Where,

M = Maintenance Respiration in tonnes per hectare per annum

$M_{20,\,i}$ = Maintenance respiration coefficient at 20 °C in tonnes per ton (dry matter) per hectare

x, y = constants explaining dependence of maintenance respiration on temperature.

T = Air temperature in °C

W = Biomass in tonnes (dry matter) per hectare

i = various parts of oil palm (roots, leaflets, trunk, petioles and rachises, fruit bunches

Growth respiration is calculated by *Equation 3.3*

$$G = g\left(P_g - M\right)$$

G = Growth respiration in tonnes per hectare per annum

g = growth coefficient

This model is implemented in the system dynamics model STELLA 9.0.1(Systems Thinking for Education and Research). This software can be used for dynamic modelling and is fairly easy to use. There was a single stock in the system, carbon assimilating in the oil palm whereas there were two flows in the system (Figure 3-2):

1) Gross Primary Productivity: Flow adding to the carbon stock
2) Respiration: flow removing carbon from the stock

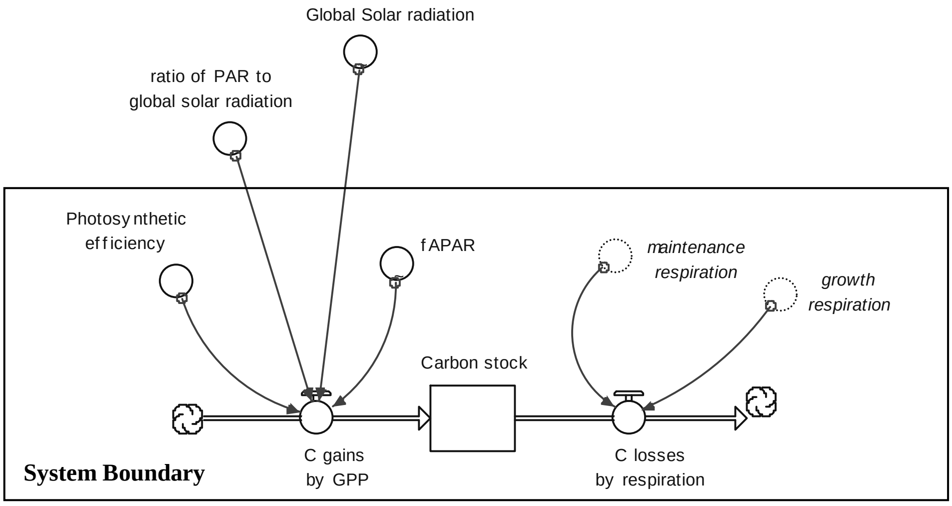


Figure 3-2 Stocks and flows in the estimation of carbon stock in oil palm by TURC

Meteorological data

Daily minimum, maximum and average temperature for Pekanbaru station was taken from the Meteorological and Geophysical Agency in Jakarta. The average temperature was found in the range of 23°C to 35°C throughout the year. The temperature data is collected from September 2007 to August 2008 (Figure 3-3). Data on cloud cover is also collected from BMG to assess the reliability of remote sensing data.

Global solar radiation was taken from the NCEP/NCAR reanalysis project available free on the website http://www.cdc.noaa.gov. National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR) have global dataset on daily solar radiation flux from 1948 to the present. NCEP/NCAR reanalysis project uses a global data assimilation system and a spectral model. Solar radiation flux was completely determined by the model and forced to remain as close as possible to the observations in the data assimilation. Thus, daily data may not be very reliable though annual variation of the data contains useful information [*Kanamitsu et al.*, 2002]. The spatial resolution of the data is also quite coarse, i.e. 2.5 degree. Unit of solar radiation data is Watt per square meter (W/m^2). From 1984 to 2008, annual averaged solar radiation flux was downloaded such that we had 25 raster images representative of the life cycle of an oil palm 25 years of age in 2008.

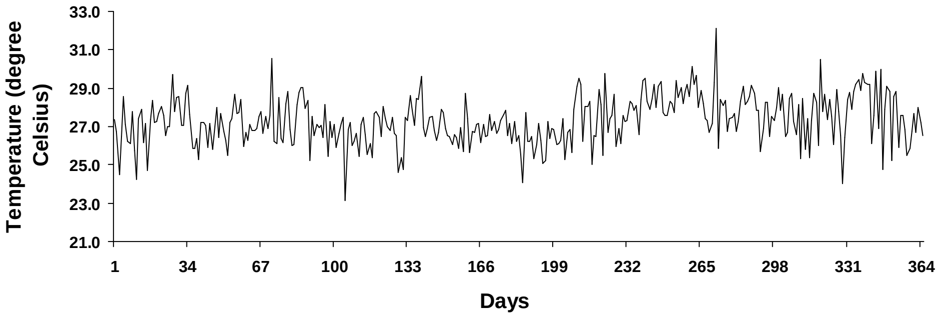


Figure 3-3 Average temperature for Pekanbaru station from September 2007 to August 2008

MODIS data

Moderate Resolution Imaging Spectrometer (MODIS) derived product, MOD 15A, 8 day composites of fAPAR (fraction of Photosynthetically Active Radiation) was used as an input variable in the model. 'fAPAR measures the proportion of available radiation in the specific photosynthetically active wavelengths of the spectrum 0.4 - 0.7 µm that a canopy absorbs' [*Knyazikhin et al.*, 1999; *Steinberg and Goetz*, 2009]. MODIS land science team derives fAPAR by a canopy radiation model that requires information on a) architecture of individual plant and the entire canopy, b) optical properties of vegetation and soil, and c) atmospheric properties such as aerosol optical thickness, etc. The information on canopy structure and optical properties is available in the Look Up Table (LUT) for the six biomes classified in MODIS Land Cover Product (MOD12). MOD12 is used as an input to the canopy radiation model and information for canopy is taken from LUT. The modelled canopy reflectance is compared with the observed reflectance obtained from the MODIS reflectance product values (MOD09). If the difference between modelled and observed reflectance is lower than the uncertainities in the observed reflectances, then the canopy structural values taken as an input are taken as possible solution. fAPAR values are the mean of all possible solution. But if the difference between modelled and observed reflectance is higher than the uncertainities in the observed reflectances, then backup algorithm is used to calculate the fAPAR values (Figure 3-4). Backup algorithm uses biome specific non-linear relationship between NDVI (Normalized Difference Vegetation Index) and fAPAR.

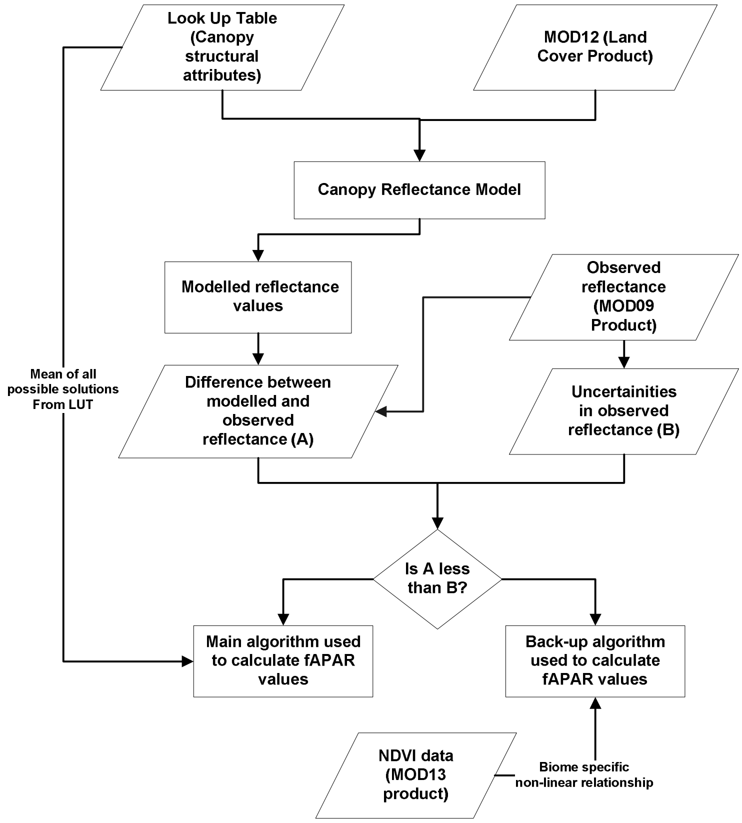


Figure 3-4 Input and algorithm used to calculate MOD 15A product

Quality check of input data

The input data taken from the remote sensing required quality check as meteorological data showed that all the days from September 2007 to August 2008 had cloud cover raging from 50 % to 100 %. In 365 days, approximately 110 days had 100% cloud cover. If the clouds are present, problem in remote sensing data due to atmospheric attenuation is even higher. Thus, remote sensing data should be used with great caution. There are two remote sensing based input data in this study: a) incoming solar radiation, and b) fAPAR. Quality check on incoming solar radiation could not be performed due to lack of validation data and information on the algorithm. In the source of incoming solar radiation data, it is mentioned that monthly or seasonal data may not be reliable but yearly data contains useful information. Therefore the carbon stock is calculated per year in this study.

Information on the algorithm to calculate fAPAR in MOD 15 product gives a useful insight on the possible errors in the data. MOD12 used to define the vegetation characteristics for canopy radiation model can differentiate only in six biomes: a)grass and cereal crops, b) shrubs, c) broadleaf crops, d) savannas, e) broadleaf forests, and f) needle forests. Thus errors in fAPAR values would be high for landcover that do not have similar vegetation characterisitcs to any of the six biomes. Cloud cover add to the sources of error and uncertainty. MOD 15 product also give useful information on the quality of the data in the layer FparLai_QC. This layer contains 8 bit data with information on various aspects of quality assigned with each bitfields. Bitfields of the 8-bit quality control data of MOD15 product is shown in Figure 3-5. Table 3-5 contains descripion of the 8-bit data in the layer FparLai_QC. Cloud state and algorithm used to calculate fAPAR is studied in detail to assess its affect on fAPAR values.

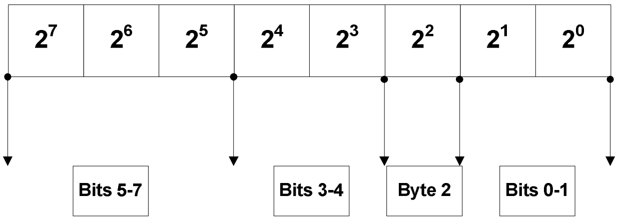


Figure 3-5 Bit fields in 8-bit quality control data of MOD15 product

To assess the error in data, information on quality of data was extracted along with fAPAR values from the GPS points taken in the field for oil palm plantations. The value in the QC_fPARLAI is in integer and thus, need to be converted to bit value to get detailed information on the quality. Once converted in bit, Table 3-5 was used to see the detail on cloud state and algorithm used to derive the fAPAR value for the given date. Regression was performed for fAPAR values and cloud state (taken as a dummy variable 0-clouds present; 1-clouds not present) to assess how clouds affect the fAPAR values. Similarly, another regression analysis was performed between fAPAR and SCF_QC (0-main algorith used; 1-back-up algorithm used). Figure 3-6 shows the steps followed to perform the analysis. From the regression analysis, it was established that slope of the linear trendline is negative for both cloud cover and SCF_QC. The regression coefficients are given in Table 3-6. With regression analysis, it can be claimed that cloud cover causes the derived fAPAR values to be lower. Similarly back-up algorithm also estimate lower fAPAR values in comparison to main algorithm derived fAPAR. It should be noted that this findings are only applicable for oil palm plantations and may differ with other land cover. For this study area, 75% of the data was affected by cloud cover and 70% of the retrieved fAPAR values were calculated by back-up algorithm, thus, it is expected that fAPAR values are lower than the actual fAPAR values. In order to overcome that problem, descriptive statistics was performed for the data. 1st quartile, median and 3rd quartile were plotted and for input in TURC (Figure 3-7), 3rd quartile is taken as it would decrease the probability of the fAPAR values to be affected by cloud and thus, quality of the data is assured.

Table 3-5 Description of the bit fields in the MODIS quality assessment definitions

Bitfields	*Information*	*Values*	*Description*
0-1	MODLAND (Overall quality)	00	Best possible
		01	OK, but not the best
		10	Not produced, due to cloud
2	DEAD DETECTOR	0	Detectors OK for upto 50% channels
		1	Detectors forced >50%
3-4	CLOUD STATE (Algorithm used)	00	Significant clouds not present
		01	Significant couds were present
		10	Mixed cloud present on pixel
5-7	SCF_QC (Algorithm used)	000	Main algorithm used with best results
		001	Main algorithm used with saturation
		010	Main algorithm failed due to geometry, Back-up algorithm used
		011	Main algorithm failed due to other reason, Back-up algorithm used

Table 3-6 Regression analysis for different age of oil palm plantations with fAPAR for n=42 and p=0.05

Regression coefficient	*Age of oil palm plantations*						
	2	*4*	*6*	*11*	*15*	*17*	*24*
Slope for cloud state	-0.25	-0.3	-0.21	-0.24	-0.36	-0.21	-0.24
Intercept for cloud state	0.77	0.85	0.73	0.75	0.88	0.42	0.75
R^2 for cloud stae	0.2	0.3	0.1	0.2	0.3	0.3	0.2
Slope for SCF_QC	-0.43	-0.41	-0.42	-0.43	-0.39	-0.15	-0.43
Intercept for SCF_QCe	0.81	0.85	0.79	0.80	0.87	0.51	0.80
R^2 for SCF_QC	0.7	0.6	0.6	0.7	0.4	0.2	0.7

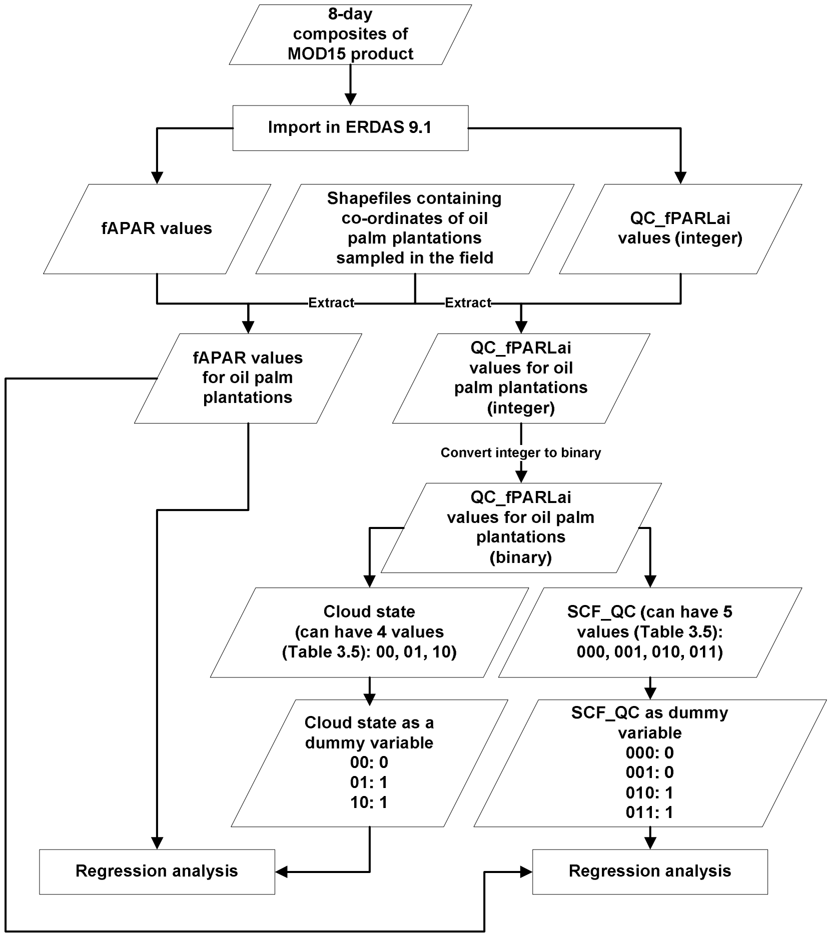


Figure 3-6 Approach to perform quality check on MODIS data

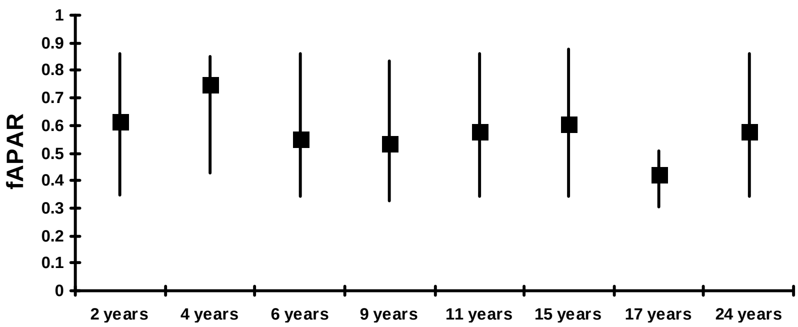


Figure 3-7 1st quartile, median and 3rd quartile of fAPAR values

Method to estimate carbon stock in oil palm by TURC

The inputs of the model are photosynthetic efficiency, fAPAR, incoming solar radiation, ratio of incident PAR to incident radiation (c), biomass, temperature, maintenance respiration at 20°C and growth coefficient (Table 3-7). The assumptions taken for the input data are as follows:

1. The time period of the model is from 1984 to 2008, i.e. for the 25 years of oil palm life cycle. But the air temperature data is collected only from September 2007 to August 2008. This year value is assumed to be representative for the 25 years of oil palm lifecycle.
2. For constants such as ratio of incident PAR to incident global radiation (c), growth coefficient (g) and x, y (that define relationship of maintenance respiration with temperature) are taken from the default values of TURC model. These default values are assumed to be applicable for oil palm.

Table 3-7 Input parameters required to run TURC

S.No.	*Parameters*	*Units*	*Source*
1	Photosynthetic efficiency	tonnes (C) MJ^{-1}	[*Henson*, 2003]
2	Incoming solar radiation	MJ ha^{-1} $year^{-1}$	http://www.cdc.noaa.gov
3	fAPAR	Ratio	MOD 15A product
4	c as in Equation 3.1	Ratio	[*Ruimy et al.*, 1996]
5	Maintenance coefficient at 20°C	tonnes (C) ton^{-1} (dry matter) $year^{-1}$	[*Henson*, 1992]
6	x, y as in Equation 3.2	Constants	[*Ruimy et al.*, 1996]
7	Biomass	Tonnes ha^{-1}	[*Syahrinudin*, 2005]
8	Temperature	°C	Meteorological station
9	Growth respiration coefficient	Constant	[*Ruimy et al.*, 1996]

The maintenance coefficient at 20 °C was taken from a study by Henson [1992]. The coefficient was given for leaflets, petioles, trunk, roots and fruit separately, which was added to represent total respiration coefficient. These coefficients were measured for young oil palm at different temperatures and then averaged to give a value used in the model. Thus, the maintenance coefficient taken for analysis was not measured at 20 °C. Some of the input parameters were not in the same unit as required and thus was converted into the required unit. The conversion factors are mentioned in Table 3-8. The values after conversion into required units were used as an input to the model TURC described above.

Table 3-8 Conversion factors used to bring input parameters of TURC to required units

Parameters	*Value given*	*Unit required*	*Conversion factor*
Photosynthetic efficiency	0.89 g (dry matter) MJ^{-1}	tonnes (C) MJ^{-1}	4.5 X 10^{-7}*
Solar radiation	J m^{-2} s^{-1}	MJ ha^{-1} $year^{-1}$	3.15 X 10^{5}**
Biomass	tonnes (dry matter) ha^{-1}	tonnes (dry matter) ha^{-1}	-
Maintenance coefficient at 20 °C	132 g (CO_2) kg^{-1} (dry matter) day^{-1}	tonnes (C) ton^{-1} (dry matter) $year^{-1}$	0.0995***

* taking 45% as the value for carbon content in dry matter

** 1 MJ = 10^6 Joules; 1 ha = 10^4 m^{-2}; 1 year = 3.15 X 10^7

*** 1 ton = 10^6 g; 1 ton = 10^3 kg; 1 year = 365 days; 1 g (CO_2) = 0.27 g (C)

Method to compare carbon stock estimates from allometric equations and TURC

The carbon estimates in oil palm from allometric equations were compared by two statistical tests: one way Analysis of Variance (ANOVA) and two-tailed paired t-test. ANOVA would reflect if the mean carbon stock throughout the lifecycle of oil palm is same for four different methods. The difference in paired values was taken into consideration by paired t-test for each combination of methods. Two assumptions were made before applying ANOVA and paired t-test and these include:

a) Carbon estimated from all four methods is normally distributed.
b) Estimated carbon stocks from four methods have equal variances.

Method for sensitivity analysis of TURC

The parameters for which sensitivity of TURC is performed are listed in Table 3-9 along with their base values. The model output was first generated for the base values of all input parameters. Then each input parameter was varied (taking the base values for all other inputs) in a range of ± 50% of the base values, taking 10 successive intervals (±10%, ±20%, ±30%, ±40% and ±50%). Each time the model output is recorded, such that we have 10 outputs for each input. As there are 8 input parameters for which sensitivity was performed, 80 outputs were generated. Then, for each input parameter, the sensitivity is calculated by following equation:

$$\textit{Change in output}\,(\%) = \left(\frac{Q_{x_i} - Q_B}{Q_B}\right) \times 100\%$$

Where,

Q_{xi}: Output of model when x input variable is varied by i %

Q_B: Output of model when base values for all input variables are used

Table 3-9 Input parameters and the base values used in sensitivity analysis

S.No.	*Parameters*	*Base value*
1	Photosynthetic efficiency	0.486 g (dry matter) MJ^{-1}*
2	Incoming solar radiation	200 J m^{-2} s^{-1}*
3	fAPAR	0.66
4	c as in Equation 3.1	0.5
5	Maintenance coefficient at 20°C	79.5 g (CO_2) kg^{-1} (dry matter) day^{-1}*
6	Biomass	100 tonnes (dry matter) ha^{-1}
7	Temperature	27 °C
8	Growth respiration coefficient	0.4

* These values were converted to required unit by applying conversion factors in the equations used to calculate GPP and respiration.

Method to validate carbon estimates by field measurements

Syahrinudin [2005] measured the carbon stock for 3, 10, 20 and 30 years old oil palm in his Ph.D. thesis. He used destructive method to measure carbon stock, i.e. he harvested oil palm and then measured the dry weight and carbon content. His study area was Jambi and North Sumatra provinces in Sumatra island. Since Riau province, the study area for this study is also located in Sumatra island; the measured values by Syahrinudin were taken as validation data to estimate the accuracy of estimated carbon stocks by four different methods. To determine the accuracy, Root Mean Square Error (R.M.S.E.) was calculated. Carbon estimated by Khalid et al [1999] were not validated as the height samples were not taken for 3, 20 and 30 years old and thus, no estimates were available for these age classes. TURC also estimated carbon stock from 1 to 25 years and thus, could be validated for only 3, 10 and 20 years.

Method to compare carbon estimates in oil palm growing on mineral and peat soil

The carbon stock for this objective was estimated by the allometric equation of Khalid et al [1999]. The other two allometric equations use age (mentioned in Table 1-4) and thus, can not differentiate between soil types. The allometric equation from Khalid et al [1999] used height to estimate biomass and the height measured in the field showed variation due to difference in soil type. After estimating biomass from Khalid et al in kg/tree, it was converted to tonnes/ hectare by taking palm density as 131 trees/ hectare. The biomass was converted to carbon stock by multiplying with 0.45 as carbon content in biomass of oil palm is assumed to be 45%.

4. Results

General results

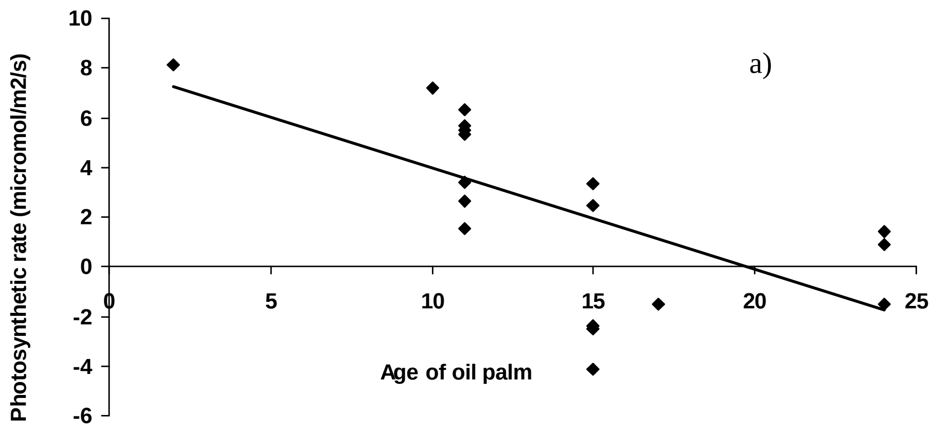
The descriptive statistics for height of oil palm is shown in Table 4-1. Height is given in meters. Standard deviation was ranging from 0.17 to 0.91 m. Standard error was found high for 4, 6, 11, 15, 17 and 22 years old palm.

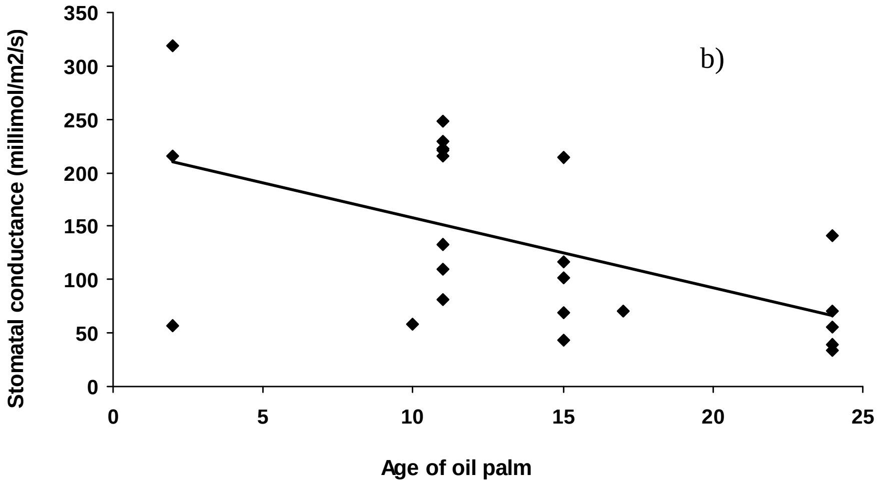
Table 4-1 Descriptive statistics for height of oil palm growing on mineral soil in each age sampled (n=10)

Sample statistics for height (m)	*Age of oil palm plantation*								
	2	*4*	*6*	*10*	*11*	*15*	*17*	*22*	*24*
Mean	0.95	3.33	1.61	3.03	5.34	5.51	7.21	7.25	8.09
Standard Deviation	0.17	0.63	0.38	0.25	0.89	0.56	0.91	0.27	0.70
Standard error	0.05	0.20	0.12	0.08	0.28	0.18	0.29	0.09	0.22

Age-related changes in photosynthetic capacity of leaves of oil palm

The photosynthetic rate, stomatal conductance and transpiration rate of leaves of oil palm was found to have negative relationship with age as shown in Figure 4-1. Table 4-2 shows the output of regression analysis between the above-mentioned three biophysical parameters and age of oil palm.





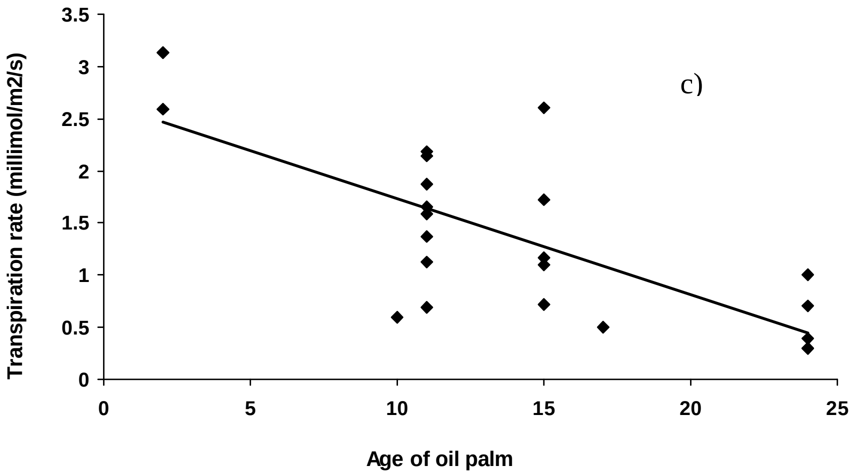


Figure 4-1 Scatter plot for age of oil palm with a) Photosynthetic rate , b) Leaf stomatal conductance and c) Transpiration rate

Table 4-2 Regression analysis with age of oil palm and three parameters characterizing photosynthetic capacity in leaves of oil palm (p=0.05)

Regression analysis of age with	*Slope*	*Intercept*	R^2
Photosynthetic rate (n=18)	-0.41	8.08	0.40
Leaf stomatal conductance (n=23)	-6.55	223.41	0.29
Transpiration rate (n=22)	-0.09	2.65	0.53

Estimation of carbon stock in oil palm from allometric equations

Carbon stocks estimated from allometric equations by Syahrinudin (2005), Henson (2003) and Khalid et al (1999) are given in Figure 4-2. From 10 to 11 years, a sudden increase in carbon stock was seen for all three allometric equations.

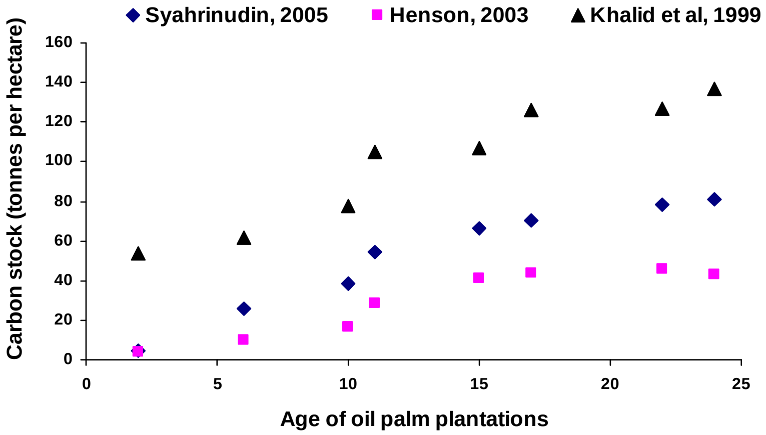


Figure 4-2 Carbon stock in oil palm as estimated from allometric equations of Syahrinudin, Henson and Khalid et al.

Estimation of carbon stock in oil palm by TURC

Carbon stock estimated by TURC is shown in Figure 4-3 along with the carbon losses by respiration and carbon gains by GPP. Carbon stock increases almost linearly from 1 to 25 years of age. Whereas, the carbon losses and gains grows almost exponentially till 2 years of age and then increases slowly. There were two sudden peaks and valleys starting from 15th year after planting. The drop in the values of estimated carbon stocks was the lowest at approximately 18 and 23 years.

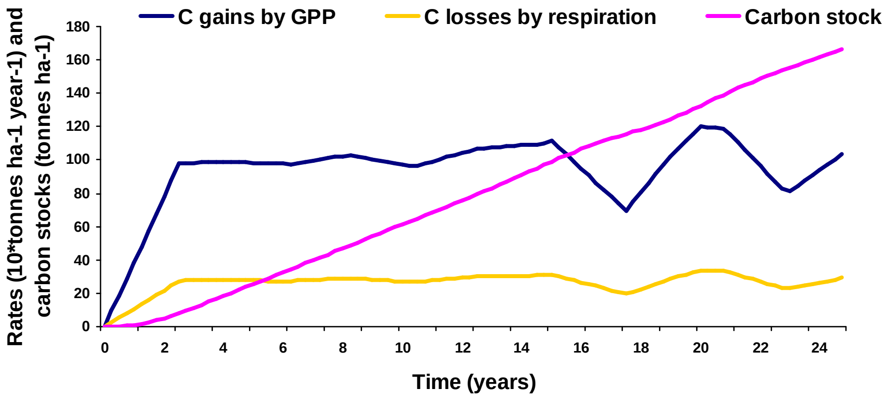


Figure 4-3 Estimated carbon stock, respiration and GPP by TURC

Comparison of carbon stock estimates from allometric equations and TURC

Comparison of the mean of carbon stocks estimated by three allometric equations and TURC by Analysis of Variance test (ANOVA) is given in Table 4-3. F value calculated for the test was higher than the F critical and thus mean of one or more pairs of estimated carbon stocks are not equal. Comparison of the difference in the estimated carbon stocks for all the four methods were tested for every combination by paired two tailed t-test. The output of the test is given in Table 4-4. If the probability (p-value) of t-test value is higher than the level of significance, i.e. 0.05 then it means that there is enough evidence that null hypothesis is correct (i.e. the mean difference in the estimated carbon stock for the two methods is equal to zero). The paired t-test showed that estimated carbon stock by TURC and Khalid et al, 1999 are significantly close to each other as whereas all other combinations are found statistically insignificant. The difference in the estimated carbon stock by all four methods is shown in Figure 4-4.

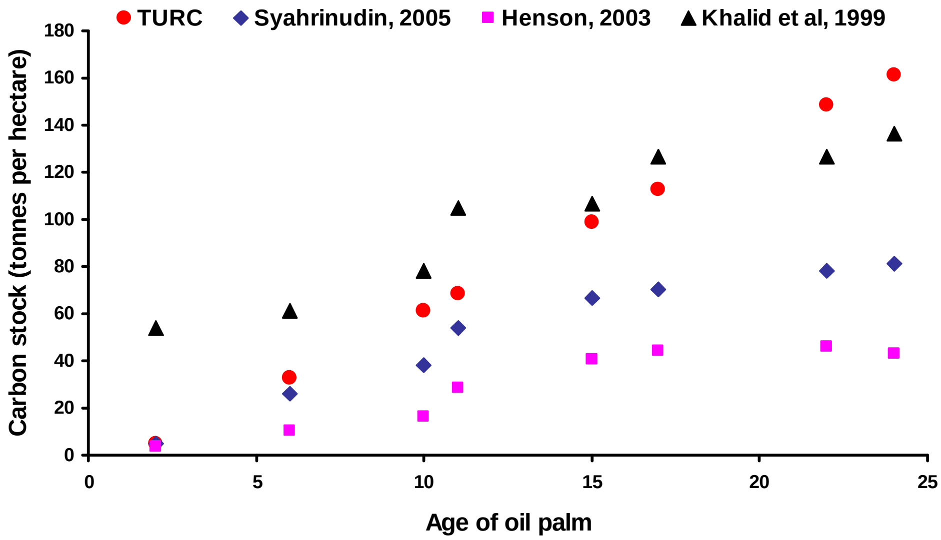


Figure 4-4 Carbon stock estimated by TURC and from three allometric equations

Table 4-3 One-way ANOVA test for estimated carbon stock by four different methods

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between methods	24435.4	7	4122.8	3.24	0.015	2.42
Within methods	34981.6	24	1273.23			
Total	*59417.1*	*31*				

Table 4-4 Two-tailed paired t-test to compare estimated carbon in oil palm for every combination of methods

Comparison of carbon stock estimates between methods	*Mean difference*	*t-statistic*	*t-critical, two-tailed*	*p,two-tailed*
TURC and Syahrinudin, 2005	34	3.26	2.37	0.01
TURC and Henson, 2003	57	4.11	2.37	0.005
TURC and Khalid et al, 1999	-13	-1.43	2.37	0.19
Syahrinudin, 2005 and Henson, 2003	23	5.92	2.37	0.001
Syahrinudin, 2005 and Khalid et al, 1999	-47	-17.26	2.37	< 0.001
Henson, 2003 and Khalid et al, 1999	-70	-12.71	2.37	< 0.001

Sensitivity analysis of TURC

Sensitivity analysis showed high sensitivity of TURC to photosynthetic efficiency, solar radiation, ratio of incident PAR to incident solar radiation (c) and fraction of photosynthetically active radiation (fAPAR); medium sensitivity to growth coefficient; and very low sensitivity to maintenance respiration at 20 °C (Rm20), biomass and temperature as shown in Figure 4-5.

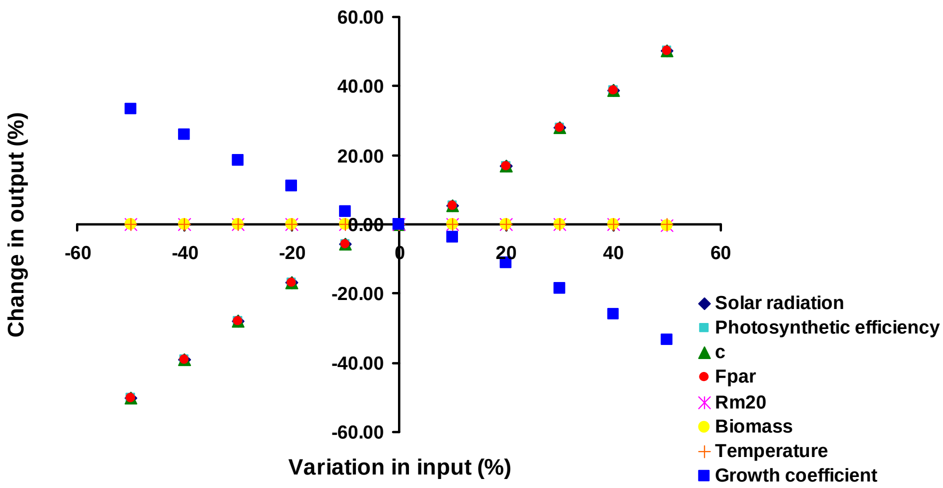


Figure 4-5 Sensitivity analysis of TURC for all the input parameters

Validation of the carbon stock estimates by field measurements

The Root Mean Square Error (R.M.S.E.) was calculated for carbon estimated by TURC and from allometric equations by Syahrinudin [2005] and Henson[2003]. The

R.M.S.E is given in Table 4-5. The R.M.S.E is least for carbon estimated from Syahrinudin [2005] and highest for carbon estimated by TURC.

Table 4-5 Validation data and estimated carbon stock with associated Root Mean Square Error (R.M.S.E.) for estimated carbon (Values in tonnes per hectare)

Age of oil palm	*Validation data*	*Estimation by Syahrinudin [2005]*	*Estimation by Henson [2003]*	*Estimation by Khalid et al [1999]*	*Estimation by TURC*
3	17	17	7	-	11
10	49	54	29	78	61
20	65	75	47	-	132
30	85	88	17	-	-
R.M.S.E		*6*	*37*	-	*54*

Comparison of carbon stock estimates in oil palm growing on mineral and peat soil

The estimated carbon stock for each age sampled in oil palm growing on peat and mineral soil is shown in Table 4-6. For oil palm of 10 years, mean carbon stock in oil palm growing on mineral soil is less than mean carbon stock in 9 years old oil palm growing on peat soil. The mean of difference in estimated carbon stocks for mineral soil and peat soil is compared by paired one tailed t-test. The null hypothesis for the t-test is rejected which claims that carbon stock in oil palm growing on mineral soil is equal to or less than carbon stock in oil palm growing on peat soil. The result of the paired t-test is summarized in Table 4-7.

Table 4-6 Mean and Standard Error (S.E.) of carbon stock estimated in tonnes/hectare for oil palm growing on mineral and peat soil

Age for samples in mineral soil	*Mean and S.E. of carbon stock in mineral soil*	*Age for samples in peat soil*	*Carbon stock in peat soil*
2	54 ± 0.6	2	44 ± 0
4	81 ± 2.3	3	49 ± 0
6	61 ± 1.4	8	71 ± 1.0
10	78 ± 0.9	9	90 ± 1.4
11	105 ± 3.3	12	89 ± 1.9
17	127 ± 3.3	18	89 ± 4.5

Table 4-7 One-tailed paired t-test to compare carbon stock in oil palm growing on mineral and peat soil

	Values	*Units*
Mean of the difference in carbon stock	12.38	Tonnes/hectare
t-statistic	4.50	
t-critical, one-tailed (df=59, p=0.05)	1.65	
p, one-tailed	< 0.005	

5. Discussion

Characteristics of height of oil palm

The descriptive statistics for samples of height reflects a lot on the variation of the height for the same age and same location. The standard error for height represents standard deviation among sample means was found to be high for 4, 6, 11, 15, 17 and 22 years. This is explained by varying conditions for light, topography and soil nutrient content as can be seen in the notes collected in the field (Appendix 7). It was observed in the field that slope varied a lot within the same plantations. The moisture content of soil also varied as some samples were taken near the drainage and ponds whereas for other samples, soil was drier.

Age-related changes in photosynthetic capacity of leaves of oil palm

This study reveals that photosynthetic capacity of leaves of oil palm decreases with age. The explanation of the decrease in photosynthetic capacity with age was found in the study by Henson [1991]. Henson found a decrease in ratio of abaxial (upper leaf surface) stomata to total stomatal numbers with age. Abaxial stomata were found very rarely in the mature leaves of oil palm. However, stomatal density increases till it reaches its peak by the end of approximately 2 years after planting. The samples taken in the field does not cover the palms below the age of 2 years thus; the increase in photosynthetic capacity till 2 years could not be picked up in the results of this study. Another finding of the study by Henson revealed the bias in the samples taken for this study. Henson found large variations in the stomatal densities between fronds and between leaflets along a frond. This variation is larger in mature palm than in younger palms. The leaflets at the base of the frond have much lower stomatal density than the leaflets at the apex. However during the sampling of mature oil palms in this study, the young fronds were not accessible and leaflet sampled along a frond was also inconsistent. Thus, there is an expected bias in the samples taken for this study. Figure 5-1 shows the fronds and leaflets of oil palm. However there is a need to know the standard frond and leaflet from which measurements of physiological parameters should be taken for future studies. Suresh and Nagamani [2006] studied variation of photosynthetic rate and associated parameters with age of oil palm fronds. They found the photosynthetic rate, transpiration rate and stomatal conductance was highest in the 9^{th} frond and progressively declines with age. However variation of these parameters between leaflets of a frond was not discussed. Corley [1971] studied the productivity of oil palm and in order to avoid bias in the samples, he took samples from fronds 1, 9, 17, 25 and 33 and from every 10th leaflets on one side of the frond. He later averaged these sample statistics to find an unbiased estimation of the productivity of oil palm. Further studies to estimate photosynthetic capacity in leaves of oil palm should consider the bias in the samples if only one frond is measured or should sample more than one fronds representative of both young and old fronds. Another possibility of bias in the study is due to the heterogeneous management and other environmental conditions. For future studies, age related variations in photosynthetic capacity in leaves of oil palm should be measured in more homogeneous conditions. It is also worth mentioning that in this study the age related variation of photosynthetic capacity is assessed at the leaf scale. At a palm scale, the photosynthetic capacity may increase until it reaches its full canopy cover which is attained by 5th to 6th years after planting under favourable conditions [*Wahid*, 2004]. At a stand scale, this variation may differ based on the density of palm trees.

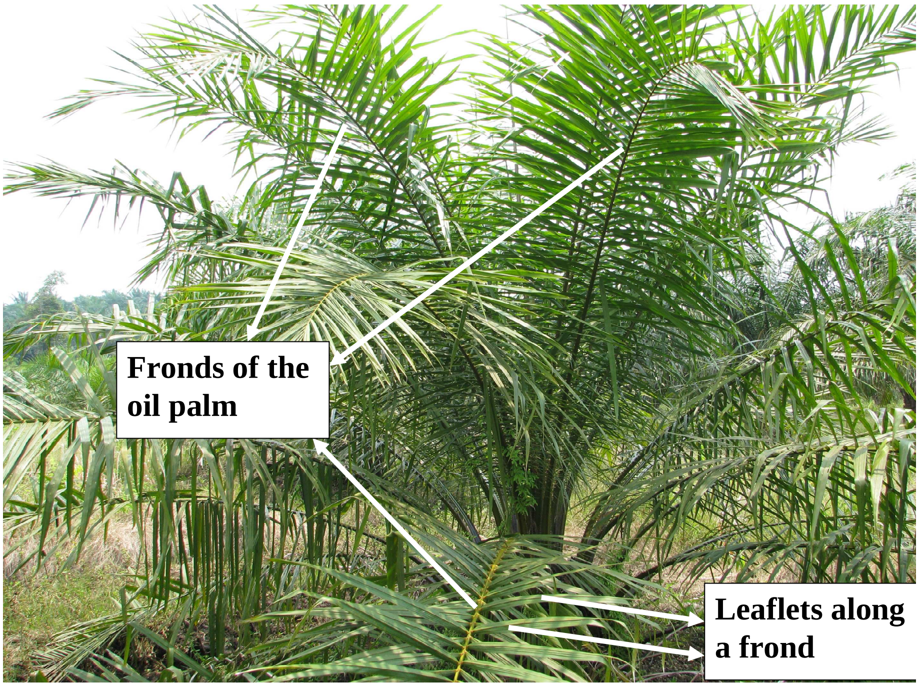


Figure 5-1 Fronds and leaflets along frond of an oil palm crop

Estimation of carbon stock in oil palm from allometric equations

The estimated carbon stock from the three allometric equations is very different from each other. Allometric equations by Syahrinudin and Henson estimate carbon stock from age of plantations and thus the estimated carbon stocks are relatively closer to each other in comparison to estimation from Khalid et al, 1999 that uses height to estimate carbon stock. Estimation of carbon stock from allometric equation by Khalid et al shows very high carbon stocks in young oil palm. This overestimation of carbon stock for young age could be attributed to its formulation. This allometric equation was formulated for 23 year old stand of oil palm in Malaysia and thus, may not accurately estimate the carbon stock of younger stands. Estimation of carbon stock from allometric equation by Henson uses a third order polynomial equation and thus, Henson stated that a fall in standing biomass is expected after 20 years. He attributed this decrease in biomass to the lower rate of frond production, abscission of mature fronds, etc. However, the estimation of carbon stock in this study shows a decrease at around 23 years (Figure 4-2). Though there is a gap of information from 18 to 22 years. It is possible that between these time steps, the carbon stock gets to its peak and then starts decreasing. Estimation of carbon stock from Syahrinudin, 2005 uses a logarithmic equation to estimate carbon stock and thus, the carbon stock increases almost linearly till 10 years and after that gets relatively flattened. All three allometric equations show a sudden increase from 10 to 11 years. The productive stage of oil palm also starts from 11 years, based on the stages defined by Nordin [2002]. These stages are defined based on the yield of the plant. As the yield of the plant increases, more fruit bunches are produced. However equation by Syahrinudin was established for carbon stock in crop, trunk, root and litter and does not include the stocks in fruits. But still the increase from 10 to 11 is seen from carbon estimates by this method. The equations by Henson and Khalid et al do not define whether stocks in fruits are included in the total carbon stock estimated by equations. Thus, it could not be established whether the increase in carbon stock from 10 to 11 years is due to increased fruit production.

The equations by Syahrinudin and Henson lack some crucial information such as for what density of oil palm, the equation was established. The density in Riau province is 131 palms per hectare. If these allometric equations are established for density much higher or lower than 131 palms per hectare, these equations are not applicable for the study area. The equations established by Syahrinudin and Henson estimate carbon stock based on information of age of plantation. Thus, these equations may give very accurate results for the oil palm located in the same conditions for which it was established. But if these equations are applied to plantation growing in slightly different conditions, it may give huge bias. The allometric equation by Khalid et al uses height and thus, variation in conditions may be reflected by height. Even in the same plantations, different palm tree have different height as can be seen in Table 4-1 and thus, also the carbon stock. Thus it can be used more extensively than other two equations based on age. However equation by Khalid et al was developed specifically for 23 year old palm stand. Thus, its application to assess carbon stock for the whole lifecycle can lead to bias in the estimates for younger and older palm. Therefore there is a need to establish an improved allometric equation that estimates carbon stock based on height and is established after measuring palms of all age.

Estimation of carbon stock in oil palm by TURC

The estimated carbon stocks by TURC show linear increase with age of oil palm. The carbon gains due to GPP interestingly increased exponentially till 2 years which is expected as the stomatal density, one of the determinants of photosynthetic capacity increases till 2 years where it reaches its peak. This trend is correctly picked up by the model. But it doesn't show a sudden increase between 10 and 11 years old as shown by other three methods. The carbon losses by respiration follow the same trend as that of carbon gains by GPP. This can be explained by the formulation of the respiration in the model. Respiration is a sum of maintenance respiration and growth respiration. Growth respiration is calculated by multiplying growth coefficient with the difference between carbon assimilated by GPP and carbon lost by maintenance respiration. Therefore, the trends in GPP are also seen in respiration and the increase in carbon stock is linear.

The GPP shows a sudden drop at approximately 18 and 22 years. When this is traced back to the input parameters, the fAPAR data shows a drop at approximately 18 years and solar radiation data at 22 years. Since GPP is determined in TURC as a product of these two parameters, both the drops were picked up in the output of the model. The drop in fAPAR at 18 years is attributed to the bad quality of the data as 74% of the data was severely affected by clouds for the pixel. Most of the fAPAR estimated by MODIS land science team for the Riau was found to be calculated by back-up algorithm which also reduces the quality of the data. Another possibility is a mixed pixel as the samples are taken from smallholder plantations which covered an area of maximum 15 hectares however the spatial resolution of fAPAR data is 1 km^2 i.e. 1000 hectares. Therefore, there is a possibility that landcover adjacent to the plantations also affect the fAPAR value. However the drop in the solar radiation at 22 years could just be explained by the low quality of data. This also reveals that the errors in the input data propagate in the output of the model. The cloud cover is a problem when remote sensing data is used. Chasmer et al [2008] recently used airborne lidar sensor to estimate fAPAR and revealed that lidar based estimates of fAPAR is realistic. These estimates can be coupled with productivity models to see whether they provide more realistic carbon stock estimation. Lidar based estimates have a clear advantage over MODIS land product of fAPAR as Lidar is unaffected by cloud cover. For areas such as Indonesia that have cloud cover for all the days in a year, Lidar based fAPAR estimates may lead to improvement in the output of productivity model.

Soil water deficit is one of the limiting factors in the productivity of the oil palm as it has C3 photosynthetic pathway [*Wahid*, 2004]. The plants with C4 photosynthetic pathway can adapt to drought conditions by closing their stomata to reduce transpiration rate. However, plants with C3 photosynthetic pathway cannot adapt in drought conditions and thus, soil moisture deficits can critically affect their photosynthetic capacity. TURC does not use soil water deficit to estimate GPP and thus, may overestimate for dry areas where soil water deficits affects the photosynthetic capacity of oil palm. However, soil water deficit is not such a big problem in Riau but with increased incidences of drought across the globe, it could become an issue in coming years. Therefore model such as GLO-PEM and SiB2 that uses soil water to estimate GPP may provide better estimate for carbon stock of oil palm especially in the water limiting conditions.

Comparison of carbon stock estimates from allometric equations and TURC

ANOVA test reveals that mean of estimated carbon stocks from one or more pair of methods is not equal. The two tailed paired t-test shows that mean of estimated carbon stock by TURC and allometric equation by Khalid et al are significantly equal as seen in Figure 4-4. However the estimation of carbon stock by TURC for oil palm below 10 years is much lower than the Khalid et al. Since, allometric equation by Khalid is expected to overestimate for young oil palm; TURC is more reliable in comparison to allometric equation by Khalid et al, for estimating carbon stocks in oil palm younger than 23 years old. No other two methods produced carbon stocks significantly close to each other. This again reflects on the uncertainty involved in estimating carbon stocks with different methods. TURC showed almost a linear increase in carbon stock from 1 to 25 years whereas the carbon stock estimated by other three equations flattened relatively during the mature stage, which is expected as the maintenance respiration is not estimated accurately in TURC as discussed in detail in the sensitivity analysis of TURC.

Sensitivity analysis of TURC

The input parameters that determine GPP are found to affect the output of the model, the most. It is because GPP not only determines the inflow of the carbon stock but also affects the growth respiration. Therefore as fAPAR, incoming solar radiation, photosynthetic efficiency and ratio of incident PAR to incoming radiation increases, the estimated carbon stock also increases. All the parameters determining maintenance respiration did not affect the output of the model much as in comparison to growth respiration, it was much lower in value. Thus, biomass, temperature and maintenance respiration at 20 °C do not affect the carbon stocks at all. Overall the maintenance respiration in oil palm is not found significant according to estimates by TURC. However this is not realistic as maintenance respiration is a major component atleast for the mature oil palm. Thus, it is expected that the performance of TURC will not be good for the estimation of carbon stocks in mature oil palm. Coefficient for growth respiration also affects the model significantly. With increase in the coefficient for growth respiration the value of carbon stock decreases. This can be explained by the fact that coefficient for growth respiration determines the growth respiration which is the outflow from the model.

Sensitivity analysis also provides insight into what could be the possible errors in the carbon stock estimates. Coefficient for growth respiration is taken as default. However if it is not applicable for oil palm, the errors in the carbon estimates may be huge as the output from the model is sensitive to coefficient for growth respiration. Thus, more information on the coefficient for growth respiration is required to improve the output. Similarly fAPAR, solar radiation and photosynthetic efficiency are crucial for the model and should be error free to get a reliable output. For this study, temperature for one year is considered to be representative for the 25 years of life cycle of oil palm. Even if it is not representative, it does not affect the output of the model. This reflects problem with the model. If the impact of global warming needs to be evaluated on productivity; TURC cannot be used.

Validation of the carbon stock estimates by field measurements

Since the measurements done by Syahrinudin [2005] is taken as validation data, allometric equation by Syahrinudin (which was established on the same dataset) is found to be the most accurate. However, it cannot be denied that this method is only accurate for estimation of carbon stocks in Sumatra. TURC is found to be overestimating by approximately 60 tonnes per hectare which is possible because the quality of some of the main inputs in the model is questionable like fAPAR and incoming solar radiation. The errors in carbon stock estimated by TURC are more for the mature age. As the oil palm matures the maintenance respiration in the plant increases. However in TURC, maintenance respiration does not affect the model very much as found in sensitivity analysis. Thus, the error in estimated carbon stock for mature age can be explained by the problems in the model. Allometric equation by Henson also overestimated by approximately 40 tonnes per hectare which is expected as the allometric equation was established for oil palm in Malaysia. Since it is based on age of oil palm, it is expected to produce huge errors for oil palm growing in different conditions, as discussed before.

Comparison of carbon stock estimates in oil palm growing on mineral and peat soil

The descriptive statistics of estimated carbon stock in oil palm growing on mineral and peat soil (Table 4-6) shows the carbon stock in oil palm of 10 years growing on mineral soil is less than mean carbon stock in 9 years old oil palm growing on peat soil. However for all other combinations, carbon stock in oil palm growing on mineral soil is more than mean carbon stock in oil palm growing on peat soil. The decrease in carbon stock in oil palm of 10 years growing on mineral soil could be attributed to unfavourable conditions. From the field observations, it is realized that slope and soil moisture conditions vary a lot for the 10 year old oil palm on mineral soil. However, one-tailed t-test shows that carbon stock in oil palm growing on mineral soil is significantly higher than the carbon stock in oil palm growing on peat soil. The peat soils are unfavourable for the growth of oil palm due to water logged conditions and thus unfavourable soil condition can be accounted for reduced carbon stocks in oil palm. Cultivation on peat requires high maintenance due to extra efforts of water drainage of the soil [*Moll*, 1987]. Thus economically, growing oil palm on peat soil may be far less profitable than growing on mineral soil. However expansion of oil palm on peat soil is still taking place and is a clear indication of bad land use planning. The samples taken for peat soil could only be taken for plantations younger than 18 years. This reflected that replacing tropical peat swamp forests is relatively recent in comparison to replacement of lowland forests.

Comparison of carbon stock estimates in oil palm with forest

According to the allometric equation by Syahrinudin; at the end of 25 years, carbon stock of oil palm is 90 tonnes per hectare. However, the carbon stock of tropical forest could be as high as 340 tonnes per hectare as found by Ludang and Jaya [*Ludang and Jaya*, 2007]. Therefore, total carbon stock in forest is almost four times to that of oil palm. Therefore, replacing tropical forests with oil palm can not be justified. Expansion of oil palm should be carefully planned. The oil palm plantation is also considered a “biological desert” as it can support only 15% of the species recorded in primary forest [*Brown and Jacobson*, 2005; *Fitzherbert et al.*, 2008]. Strict regulations should be implemented to restrict expansion of oil palm in tropical forests.

Mapping carbon stocks in oil palm with remote sensing data

McMorrow [2001] studied the possibility of estimating age of oil palm stand from radiance values of Landsat Thematic Mapper (TM) at pixel level. He found that Infrared Index (IRI) of Landsat TM can be used to estimate age of oil palm with the Root mean square error (RMSE) of 0.58 years. Productivity model like TURC gives an estimate of carbon stock for each age class with an R.M.S.E. of 60 tonnes per hectare. Models such as TURC can be coupled with the study conducted by McMorrow to map the carbon stock from the radiance values of Landsat TM image. But before using models like TURC, sensitivity analysis should be performed to understand the limitations of the model. Similarly, before using map produced from this method in policy development, accuracy of such maps should be determined by reliable validation data. Every model simplifies the reality and in this process, the estimates of carbon stock provided from model can have huge deviation from the real carbon stock. In such cases if the accuracy estimates are not provided, poor estimates can be used for important assessments.

6. Conclusions and Recommendations

The specific conclusions of this study can be summarized in the following points:

- The photosynthetic capacity of leaves of oil palm decreases with age of oil palm.
- Total carbon stock (including trunk, fronds, frond bases and roots) estimated from allometric equations of Syahrinudin, Henson and Khalid is approximately 80, 43 and 140 tonnes per hectare at 25 years, respectively.
- Carbon stock estimated by TURC increases linearly with age and at 25 years, the carbon stock estimated is 170 tonnes per hectare.
- Carbon stock estimated by TURC was found closest to carbon stock estimated by Khalid et al, 1999.
- No other method estimated carbon stock significantly close to each other.
- TURC is most sensitive to four parameters: incoming solar radiation, fAPAR, photosynthetic efficiency and ratio of incident PAR to incident radiation
- TURC overestimated the carbon stock for mature oil palm.
- The estimation of maintenance respiration in TURC is not realistic.
- The allometric equation by Syahrinudin is the most reliable to be used for oil palm in conditions such as Riau province.
- Carbon stocks in the mineral soil are more than the carbon stocks of oil palm growing in peat soil.
- Carbon stocks in oil palm estimated from allometric equation by Syahrinudin is four times less than the total carbon stock in tropical forests.
- Lastly, this study recognizes the limitation of using models to estimate the real carbon stock and agrees with what is said by John D. Sterman, Director of System Dynamics Group, MIT Sloan School of Management: '*All models are wrong but some are useful.'*

The conclusions of the study are made after recognizing the limitations in the study, which are as follows:

- Frond and leaflet along the frond sampled is not consistent for all samples. For mature oil palm, young fronds were not accessible. The sampled fronds were very old and thus, the estimated photosynthetic capacity in the field may be underestimated.
- Quality of fAPAR and incoming solar radiation are not very reliable. Cloud cover and estimation of fAPAR by back up algorithm reduces the

quality of fAPAR data. Incoming solar radiation is at a spatial resolution of 2.5 degrees and fAPAR at 1 km^2 and thus taking this data to model carbon stock in oil palm plantation of 0.5 to 15 hectares can have huge errors.

- Lack of reliable allometric equation to estimate carbon stock in oil palm for the Riau province.
- There is a gap of crucial information for the allometric equations and thus, reliability of the carbon stock estimated in oil palm for the Riau province by these equations cannot be stated with certainty.

The recommendations of the study are as follows:

- Sampling of parameters characterizing photosynthetic capacity should be taken from more than one frond. The fronds sampled should be representative for both old and young fronds to avoid bias in the estimation of photosynthetic capacity.
- Leaflet along the frond that is sampled should be consistent for all the samples to avoid bias. Further research should be conducted to find the leaflet that represents the average photosynthetic characteristics in oil palm.
- There is a need to establish a reliable allometric equation for oil palm based on height that can capture the age-related variation in carbon stocks throughout the lifecycle of oil palm.
- The allometric equation should be published with all the details of plantation and environmental conditions for which it is established.
- The management conditions and other characteristics that may influence the productivity of oil palm should be as similar as possible for all the samples. The age related changes can only be established if such biases are avoided.
- fAPAR is a very crucial input parameter in productivity models such as TURC. However fAPAR derived from remote sensing data always have the possibility to be affected by cloud. Lidar sensors can also be used to estimate fAPAR. Lidar based estimates of fAPAR can improve the accuracy of output of productivity models.
- MOD15 product should be used with prior check on its quality. If fAPAR is derived from back-up algorithm, the quality of data can be quite unreliable.
- Other productivity models should be tested for further studies to explore their potential for estimating carbon stock in oil palm.

- If only one method is used to estimate carbon stocks, one should be fully aware of the limitations of the method. As it can be seen in this study, different methods can give completely different estimates.
- Accuracy of carbon stock estimates should be established before any further use. This avoids using poor estimates for important assessments.

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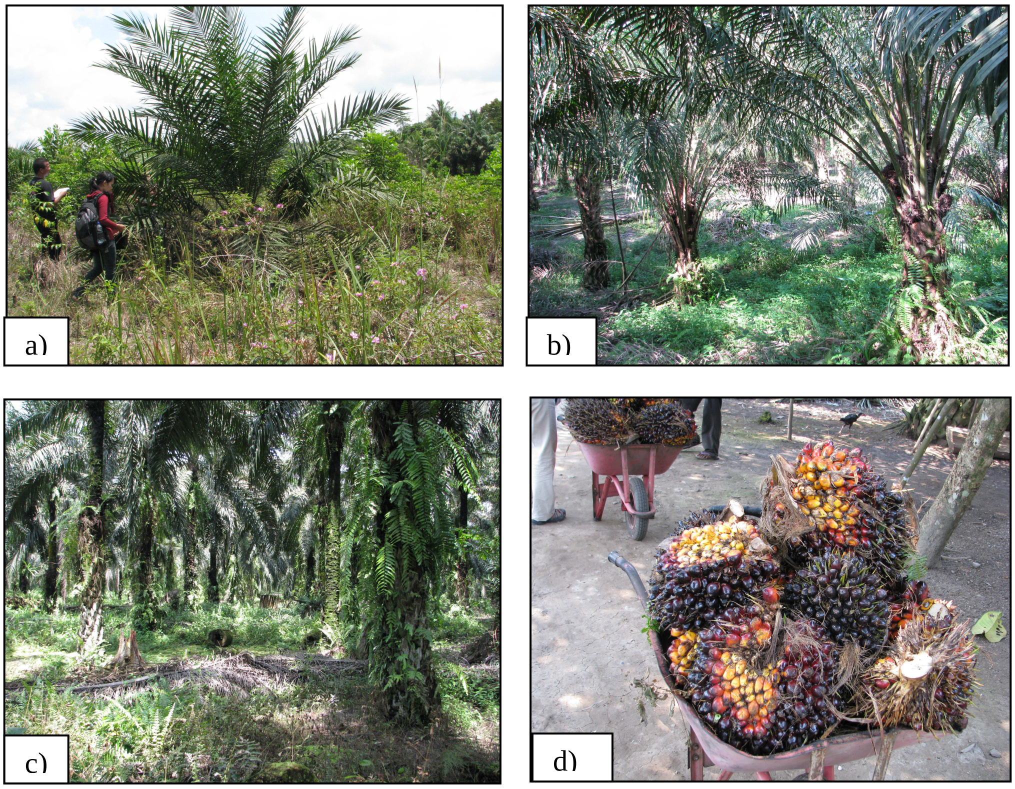
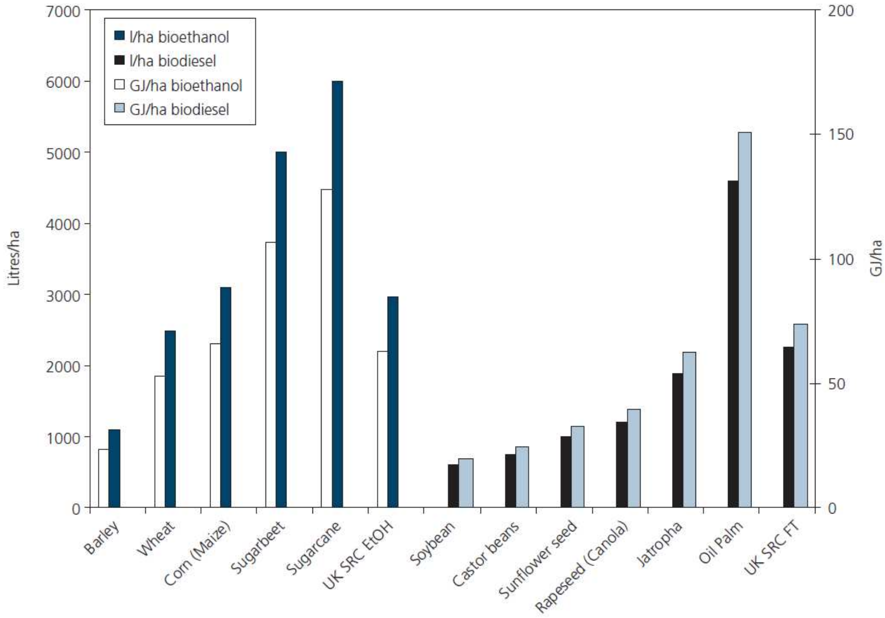
Appendices

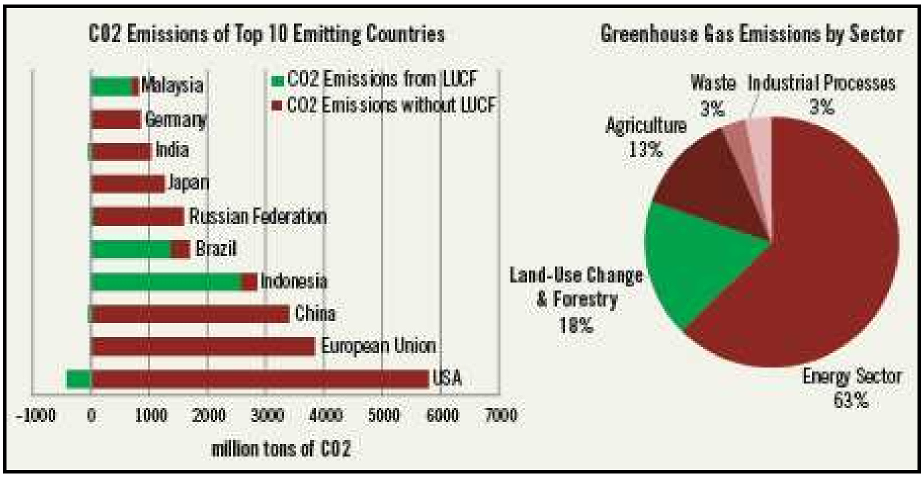
Appendix 1 Oil palm of a) 2 years, b) 6 years, c) 22 years old growing on mineral soil and d) fruit bunches of oil palm ready to go to the palm oil mill



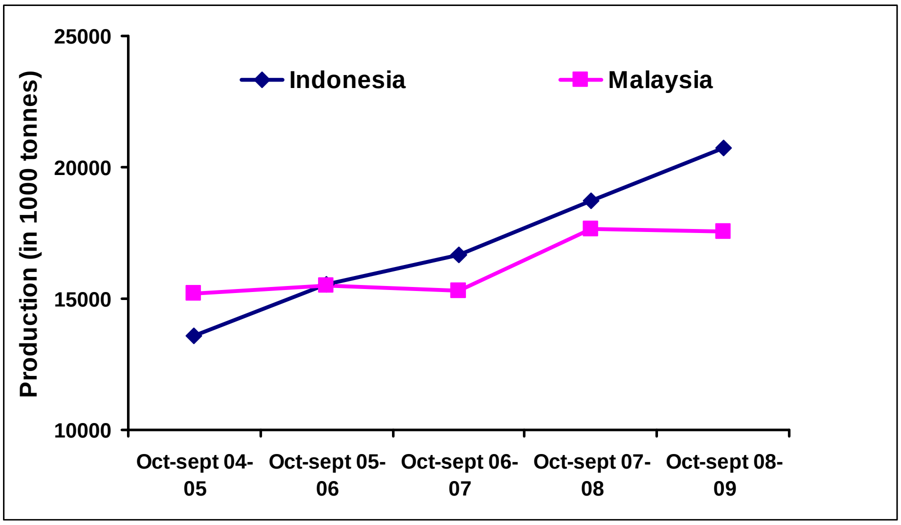
Appendix 2: Quantitative yield (Litres/ha) and energy content (GJ/ha) of various bio fuels producing oil crops. Source: [RS, 2008]



Appendix 3: CO2 emissions due to LUCF and without LUCF by top 10 emitting countries.Source:http://earthtrends.wri.org/images/LUCF_emissions.jpg

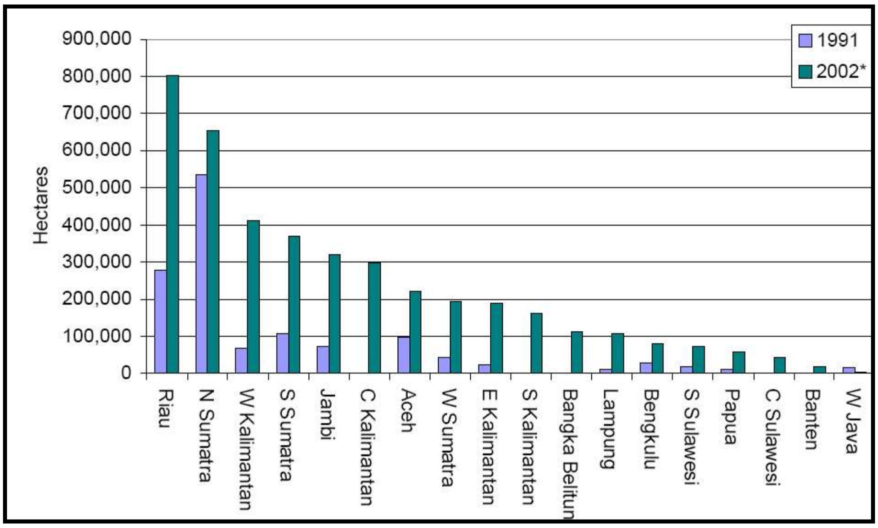


Appendix 4: Production of Crude Palm Oil in thousand tonnes by Indonesia and Malaysia for 2004 to 2009. Source: [Falk, 2008]

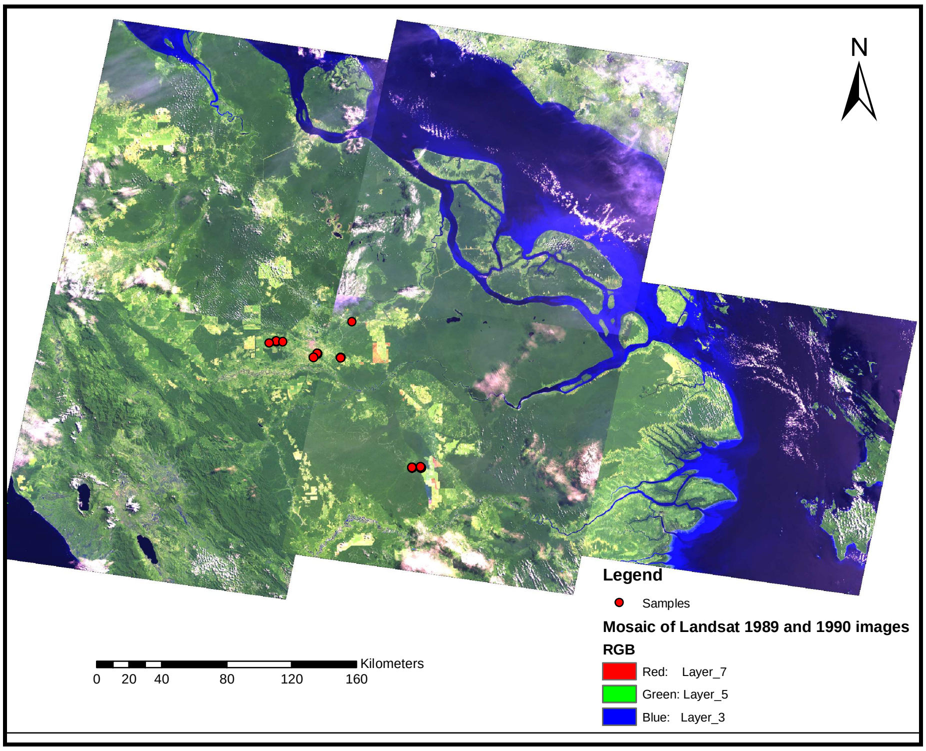


* Values for Oct-Sept 2008-09 are predicted

Appendix 5: Expansion of oil palm plantations from 1991 to 2002 in various provinces of Indonesia. Source: [Casson, 2003]



Appendix 6: Sampling sites for this study in Riau province of Sumatra, Indonesia



Appendix 7: Field data collected in mineral soil for height, photosynthetic rate (Pn), stomatal conductance (C), transpiration rate (E), PAR, air temperature(Tair) and leaf temperature(Tleaf) from 21/09/2008 to 22/10/2008

Age	*Height*	*PAR*	T_{air}	*Pn*	T_{leaf}	*C*	*E*	*Description*
2	0.9	1666.8	35.6	-33.68	43	57.28	2.59	Near to road; leaf unhealthy; 'hama' disease; cloudy
2	1.02	220	34.1	-	34.9	-	-	
2	1	312.9	33.5	8.16	36	216.06	3.14	leaf falling into the ground; unhealthy near to house
2	1.02	1199.6	37.41	16.1	41.7	319	7.54	on the boundary; sampled leaf healthy; sunny
2	1	1780	40.5	-	41.9	-	-	on the slope; leaves on ground; healthy
2	0.55	500	37.1	-	40.3	-	-	on a steep slope; leaves unhealthy
2	0.8	1950	36.8	-	45.5	-	-	slope; severely affected by disease; leaves above are completely destroyed
2	1.03	1800	39.9	-	45.5	-	-	
2	1.15	1750	41	-	45.2	-	-	
2	1.02	508	37.6	-	36.8	-	-	near to road
4	3.3	25.1	28.1	2.4	30.2	94	0.88	
4	2.77	19	27.4	-0.86	29	83.79	0.58	
4	2.83	11.7	27.3	-4.75	28.6	166.53	0.77	
4	2.8	40	27.1	2.46	28.7	170.5	0.78	
4	3.15	16.8	27.7	-6.54	30.1	87.47	0.7	
4	2.53	9.1	27.8	-3.34	29.2	99.77	0.59	
4	3.58	32.9	27.4	-3.1	28.6	858.75	1.45	near to pond
4	3.79	35.1	27.4	-3.02	29	129.29	0.71	
4	4.15	8.6	27.5	-3.52	29.1	84.45	0.63	

4	4.37	31.7	27.6	-29.13	29.8	65.95	0.57	
6	1.6	77	33.2	-	33.2	-	-	started fruiting
6	1.45	18	32.3	-	34	-	-	on slope; lower leaves damaged; shaded
6	1.7	10	32.3	-	33.8	-	-	on slope, weeds, hama disease, shaded
6	1.3	35	33	-	34.8	-	-	near to drainage; like peat swamp; dense under canopy
6	1.7	65	33	-	34.9	-	-	on slope
6	2.45	21	32.4	-	33.8	-	-	on flat surface; very tall
6	1.774	1	32.1	-	34	-	-	leaf wider
6	1.78	18	32	-	34	-	-	
6	1.1	30	31.9	-	33.7	-	-	near to boundary; lot of ants
6	1.25	100	32.4	-	33.7	-	-	near to road
10	3.22	91	32.5	-	33.2	-	-	near to road
10	2.9	111	30.4	-	31.9	-	-	on slope
10	2.77	68	29.6	-	31.2	-	-	
10	3.05	53	30.3	-	32	-	-	on flat surface
10	3.3	69	30.1	-	32	-	-	near drainage; wet soil
10	3.3	17	29.5	-	30.8	-	-	
10	2.85	5	28.6	-	29.7	-	-	
10	3	40	28.4	-	29.8	-	-	
10	3.33	28	27.4	-	29.1	-	-	
10	2.62	18	28.3	7.2	30.7	59	0.6	
11	4.75	68	29.2	-	30.3	-	-	near to road

11	7.25	63	29.2	-	31	-	-	too tall from others
11	6.15	31.2	29.1	1.52	30.6	81.28	0.69	leaf falling down
11	5.05	84.3	29.8	2.63	31.6	132.4	1.12	leaf falling down
11	4.35	105.8	30.8	5.5	32.4	248.07	1.87	leaf falling down
11	5.74	271.2	31.2	6.35	32.4	229.23	2.14	leaf falling down
11	5.5	157.5	31.1	17.88	32.8	221.76	2.19	
11	5.45	98.4	30.2	5.33	31.5	215.32	1.59	
11	4.52	106.7	31.1	3.42	33	109.49	1.37	leaf falling down
11	4.6	81.3	30.8	5.68	32	221.86	1.66	
15	5.3	21.7	29.9	-4.16	31.3	117	1.1	
15	5	74.8	30.2	-2.4	33.1	44	0.72	
15	6.2	72	30.1	-	31.5	-	-	
15	6	67.4	32.5	-2.51	34.4	69.36	1.17	
15	4.9	111	30.5	-	33.3	-	-	
15	4.8	33.1	31	2.47	32.3	214.43	2.6	
15	6.4	11	33.9	-	35.3	-	-	
15	5.8	18	31.3	-	33.3	-	-	
15	5.5	399.7	30.9	3.33	34.4	102.28	1.72	
15	5.2	295	31.6	-	35	-	-	
17	7.5	41	28.4	-1.5	29.4	71	0.5	
17	7.8	75	27.9		29			
17	6.5	80	29		30.6			

17	8	110	28.5		30.9			
17	6	40	29.3		30.6			
17	8.5	120	30		32.2			
17	7	78	30.6		32.6			
17	5.8	210	30.9		32.7			
17	8	203	30.8		32.8			
17	7	82	30.6		32.9			
22	7.1	12	27.4	-	29	-	-	
22	7.5	24	28.2	-	30.9	-	-	
22	7.35	8	29.5	-	31.1	-	-	
22	7.1	70	29.2	-	31	-	-	
22	7.6	20	29.6	-	31	-	-	
22	7	44	29.8	-	31.8	-	-	
22	6.8	53	30.6	-	32.6	-	-	
22	7.32	61	31.6	-	33	-	-	
22	7.6	80	30.6	-	32.6	-	-	
22	7.1	50	30.5	-	32.1	-	-	
24	8.6	55	30.8	-	32.1	-	-	
24	8.1	51	30.6	-	31.9	67	0.7	leaf slipped from leaf chamber that's why Pn 0
24	7	38	30.6	-	32.1	-	-	
24	6.9	37	30.1	-14	31.8	70	0.7	
24	8.3	38	30.1	0.9	31.5	141	1	

24	9.1	22	29.9	1.4	31.1	55	0.4	
24	8.35	17	29.4	-14	30.8	34	0.3	
24	8.32	25	28.9	1.7	31	0	0	
24	8.5	16	28.7	-3.4	30.6	0	0	
24	7.7	6	29.2	-1.5	31.3	40	0.3	

- Height in meters
- PAR and Pn in µmol m^{-2} s^{-1}
- C and E in millimol m^{-2} s^{-1}
- T_{air} and T_{leaf} in °C

Appendix 8: Field data collected in peat soil for height, photosynthetic rate (Pn), stomatal conductance (C), transpiration rate (E), PAR, air temperature(Tair) and leaf temperature(Tleaf) from 21/09/2008 to 22/10/2008

Age	*Height*	*DBH*	*PAR*	T_{air}	*Pn*	T_{leaf}	*C*	*E*	*Notes*
2	0.1		1152.2	36.5	-0.38	39.2	33.21	1.18	
2	0.1		1297.5	37.4	-0.4	42.8	14.08	0.74	
2	0.1		1201.4	38.2	-1.48	42.1	13.94	0.69	
2	0.1		1170.7	37	3.01	39.7	52.79	1.91	
2	0.1		249.2	34.1	0.35	35.4	21.4	0.52	
2	0.1		295.2	34	0.55	34.8	109.83	2.01	
2	0.1		1470.8	37	-3.06	43.8	11.98	0.66	
2	0.1		1339.2	39.7	-1.73	46.1	26	1.4	
2	0.1		1228.2	40.6	-1.95	46	8.41	0.56	
2	0.1		950	39.8	0.1	35.8	33	0.8	
3	0.5		250	29.9	-	31	39	0.6	
3	0.5		520	33.9	0.9	37.3	-	-	
3	0.5		680.5	35.6	6.09	35.7	123.35	2.58	
3	0.5		456	37.3	3	39.9	25	0.9	
3	0.5		1194.7	38.1	16.28	41.2	177.49	5.55	
3	0.5		806.2	38.2	2.2	41.3	51.27	2.16	
3	0.5		453.4	37.9	-4.37	38.6	24.33	0.85	
3	0.5		840	39.3	1.48	44.1	25.64	1.43	
3	0.5		65.7	36.6	1.46	36.1	49.42	1.26	
3	0.5		163.7	35	0.31	35.9	39.38	0.99	

7	2.8	2.5	380	30.5	0.1	32.5	-	-	
7	2.34	2.8	430	31.4	-	34.7	-	-	
7	2.85	2.44	940	32.7	3.7	37.2	77	1.7	
7	2.52	2.3	600	30.3	-	37	-	-	
7	2.63	2.32	970	33.9	-	39.2	-	-	
7	2.44	2.35	350	33.4	4.9	35.8	30	0.7	
7	2.05	2.95	1000	33.9	-	38.7	-	-	
7	2.3	2.52	500	32.6	3.3	34.2	78	2.3	
7	2.5	2.9	900	35.1	1.4	38.8	75	2.1	
7	2.01	2.45	600	34	2.1	38.4	33	0.9	
9	3.8		651	33.1	-	34.9	-	-	Instrument not stabilizing; PAR changing a lot
9	4		99.8	32.8	-0.2	33.9	76.71	1.24	Near to boundary
9	4.05		311	34.7	-	36	-	-	Bended tree, leaf falling on the ground
9	3.75		555	33.6	-	35.5	-	-	leaf yellow
9	4.4		74	33.3	-	34.2	-	-	very tall
9	4.25		150	33.3	-	35.1	-	-	near to drain
9	4.6		44	33.5	-	34.6	-	-	more leaves than surrounding trees. Near to house; trees near it has dried leaves
9	4.4		200	33.6	-	34.8	-	-	better leaves
9	3.3		44	33	-	34.4	-	-	near to boundary
9	3.9		27	32.8	-	34.1	-	-	leaf falling down
12	4.13	2.07	169	33.1	5.1	34.9	58	1.2	
12	3.53	2.24	45	34.1	3.5	34	31	0.5	

12	4.66	2.17	100	33.5	-	35.3	-	-	
12	3.5	2.5	200	33.7	0.9	35.9	42	1	
12	3.57	2.16	280	35	-	-	-	-	
12	4.64	3.1	140	35.5	-	36.2	-	-	
12	3.53	2.31	200	35	-	36.6	-	-	
12	4.45	2.43	100	34.5	-	34.8	-	-	
12	4.53	2.25	250	33.9	-	34.2	-	-	
12	3.53	2.1	85	33.6	-	33.6	-	-	
18	6.8		155	30.5	3.9	31.7	130	1.2	
18	5.1		171	30.1		31.5			
18	3.77		19	29.9		31.7			
18	3.5		188	30.2		32.8			
18	4		125	30.6		32.1			
18	2.9		127	30.5		31.7			
18	3.2		55	30.2		31.6			
18	4.55		122	29.8		31.4			
18	3.05		40	30.1		30.9			
18	2.85		67	30.2		32.2			

- Height and DBH in meters
- PAR and Pn in μmol m^{-2} s^{-1}
- C and E in millimol m^{-2} s^{-1}
- T_{air} and T_{leaf} in °C