# Carbon Sink in Peninsular Malaysia Affected by Extreme Drought Events

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## Abstract

Tropical forests serve as an important biome in the regulation of climate globally by exchanging atmospheric water and carbon. It is estimated that tropical forests contained 141–159 bil. tonnes C and sequester 0.47–1.3 bil. tonnes Pg C $yr^{-1}$ which is 8–13 % of anthropogenic $CO_2$ emitted globally. We found that the unlogged forests in Peninsular Malaysia gained 0.7 tonnes C $ha^{-1}$ yr-1 (CI: 0.4 – 1.1), which decreased with the occurrence of the extreme drought event. However, there were no differences in total above-ground carbon density before and during/after extreme drought events. Our study showed that unlogged forests are vulnerable to extreme drought events by temporarily halting tree growth and increasing tree mortality.

Keywords: unlogged forest, drought effect, aboveground carbon density

## 1.0 Introduction

### The Tropical Forest

Tropical forests serve as an important biome in the regulation of climate globally by exchanging atmospheric water and carbon, including supplying renewable raw materials (Lewis et al., 2015). Forests that are managed for sustained yield of timber, fibre, or energy and at the same time maintaining or increasing forest carbon stock are the largest mitigation benefit in addressing climate change (IPCC 2007). Tropical forests are estimated to contain 141–159 bil. tonnes C and sequester 0.47–1.3 bil. tonnes C year $^{-1}$, which is 8–13 % of anthropogenic $CO_2$ emitted globally (Mackey et al. 2020). Any changes in tree mortality or growth will have an impact on global $CO_2$ sequestration (Hubau et al., 2020).

The tropical rainforest is estimated to be 1.83 billion ha or 45% of the total forest in the world (FAO, 2020). These forests can be divided into three main blocks, which are the American rainforest centred around the Amazon basin; the Indo-Malayan rainforest; and the African rainforest centred in the Congo basin (Whittaker, 1975). There are differences in species richness and structures between these forests (Lewis et al., 2015). African forests have a lower number of trees per ha and species, while the Dipterocarpaceae family dominates Amazon and Indo-Malayan forests. Amazon forests have a shorter diameter to height ratio, making aboveground biomass one-third less than African and Indo-Malayan forests.

### Changing Climate Condition

Climate change increased air temperature and changing regimes, including the timing, amount, and interannual variability of rainfall, and these changing conditions have a significant impact on global forestry (Keenan, 2015). The concern of these impacts is not only ecosystems but also ecological services such as timber supply, carbon storage, or biodiversity conservation (Bouchard et al., 2019). As for forest management, the potential effects are forest health, regeneration success, growth and productivity, distribution and composition of species, forest structure, and age-class distribution (Halofsky et al., 2018). Tree growth is observed to increase in some temperate forests under longer growing seasons and warmer temperatures. However, changes in vegetation distribution, including increased tree mortality due to drought or heat, were also recorded ((Bouchard et al., 2019; Brecka et al. 2018; Keenan, 2015).

Hijioka et al. (2014) reported that South East Asia has been experiencing an increase in the temperature rate from 0.14 ° C to 0.20 ° C per decade, including the increase in hot days and warm nights and a decrease in cooler weather. The report also stated that annual total wet-day rainfall increased by 22 mm per decade and the increase in the ratio of rainfall in the wet to dry seasons was recorded from 1955 to 2005. For the past four decades, Malaysia has experienced an increase in mean temperature of 0.13 ° C to 0.24 ° C and rainfall has been increasing since 1990 (Fung et al., 2020; GOM, 2018). These changing climate conditions may affect the growth performance of forests and carbon sequestration.

There were studies carried out on the impact of changing climate conditions on the tropical forest in Peninsular Malaysia. However, these studies were limited to forest growth responding to temperature; small trees responding to solar radiation; $CO_2$ effect on seedling growth; precipitation, temperature, relative humidity and vapour pressure deficit effect on cell layer growth; the flowering condition for Dipterocarpacea; and forest structure and function sensitivity to air temperature, soil temperature, precipitation, total cloud cover, specific humidity and wind velocity (Chen et al., 2018; Dong et al., 2012; Feeley et al., 2007; Sato, 2009; Tomimatsu et al., 2014; Wang & Hamzah, 2018; Yeoh et al., 2017).

## The Effect of Changing Climate Conditions on Tropical Forests

The interaction between changing climate conditions and ecological traits will affect the growth performance of tropical forest trees (Adams et al., 2017; Aleixo et al., 2019; Clark, 2007; de Luis et al., 2009; Fontes et al., 2018; Margrove et al., 2015; Nepstad et al., 2002; Putz et al., 1983; Sevanto et al., 2014; Wang & Hamzah, 2018). Changes in climate conditions such as intense precipitation, extreme drought event, higher temperature, wind storm and extreme El Niño–Southern Oscillation (ENSO) years will affect the growth of the forest.

The mortality rate is higher during the wet months, as intense precipitation usually occurs with strong wind (Aleixo et al., 2019; Margrove et al., 2015). A year-long study in the Amazon recorded that 45% of total tree mortality was caused by storms and only 30% was due to abiotic factors such as senescence, insect, lightning strike, fungi, and liana infestation (Fontes et al., 2018). Intense precipitation will increase the weight and static loading of the crown; whereas strong wind will increase the dynamic loading of the crown. When these forces are stronger than the stem strength, tree snapping will occur (Putz et al., 1983). Intense precipitation will also develop waterlogged soil and weakened root-soil connections that will lead to tree uproots (Margrove et al., 2015). The diameter class also determines the mode of mortality during extreme precipitation and strong wind. Trees with a diameter class below 50 cm are more prone to snap or become uprooted, while trees above 50 cm will only be uprooted due to stronger stem structures (Fontes et al., 2018).

Drought affects the structure and functioning of tropical rainforest trees. If the impact of drought exceeds a tree's tolerance limits, mortality will occur (Nepstad et al., 2002). Extreme long drought events will create hydraulic failure that will lead to tree mortality (Adams et al., 2017). Hydraulic failure occurs when the water intake from roots is smaller than the loss of water through transpiration that leads to tissue desiccation (Sevanto et al., 2014). Mortality caused by drought may occur immediately or up to two years later (Aleixo et al., 2019; Granzow-de et al., 2012).

The high temperature is usually associated with a water deficit, which will have a negative effect on tree physiology functioning. The photosynthesis processes of the canopy leaf showed a sharp decline above 32 ° C for tropical forests, while exposure to a temperature higher than 40 ° C for 30 minutes will damage the leaf photosynthesis apparatus (Clark, 2004). Damage to the apparatus is irreversible and inhibits tree growth. Aleixo et al. (2019) and Clark (2007) also stated that the optimal physiological functioning of the central Amazon forest was between 26.0 and 29.5 ° C.

High temperature, especially during the daytime, affects the growth and biomass gain of tropical forests (Sullivan et al., 2020). A study in La Selva, Costa Rica, showed that temperature influences the growth of wet tropical forests. Trees growth in La Selva was the greatest during the coldest year; depressed during the hot 1997-1998 El-Nino event; and intermediated during the intermediate temperature years (Clark, 2004). In Panama and Pasoh, Malaysia, tree growth rates were also decelerating due to low annual precipitation, higher rain-free days and higher temperature (Feeley et al., 2007). It was concluded that the decrease in growth occurred because trees responded to higher temperatures by increasing respiration processes and slowing photosynthesis processes. These responses will also affect carbon sequestration. During the 1997 - 1998 ENSO event, Borneo saw a halt in carbon sink due to an increased tree mortality rate, which eventually decreased carbon sequestration (Qie et al., 2017).

Tree growth also differs between stem sizes and tree species due to the climate-growth relationship (de Luis et al., 2009). Dong et al. (2012) findings showed that trees with a diameter of less than 20 cm showed positive tree growth to solar radiation or light and negative to increase daily minimum temperature. Light is an important driver for photosynthesis processes. However, in the absence of light, seedlings that grow understorey will benefit from a high concentration of $CO_2$ to substitute light limitation for photosynthesis and eventually increase carbon gain (Tomimatsu et al. 2014). The increased concentration of $CO_2$ in the atmosphere may bring a positive trend to the regeneration of forests. Unlike Dong et al. (2012), a study carried out in Ayer Itam Forest Reserve concluded that cambial activities and cell layers were affected by precipitation, temperature, relative humidity, and vapour pressure deficit. Wang & Hamzah (2018) studied the cambial activities of three species of Dipterocarpaceae in Ayer Hitam Forest Reserve, Malaysia, and found that trees with a diameter below 35cm are more sensitive to changing climate conditions than trees of 40cm above in diameter. Malaysia's forest structure and function were simulated to test its sensitivity to a combination of climatic conditions such as air temperature, soil temperature, precipitation, total cloud cover, specific humidity, and wind velocity over 100 years. The simulation result showed that changing climate conditions do not affect dominant canopy species and eventually the whole forest structures but not the species composition, especially for pioneer species (Sato 2009). The pioneer species decreased due to the accelerated mortality rate due to intensive composition among dominant and subdominant trees.

A combination of low temperatures during day and night time, including drought, contributes to general flowering in tropical forest trees, especially for the Dipterocarpaceae family (Yeoh et al., 2017). Flowering among *Shorea* species also varies with the threshold of a low temperature period of 54 - 90 days between 25.5 – 27.8 ° C and precipitation of 93 - 186 mm per month (Chen et al., 2018; Yeoh et al., 2017). Increased temperature will disrupt dipterocarpaceae flowering, which in turn decreases seedling production. It was also highlighted that the first signal of response by trees to climate change is through changes in phenology (Deb et al., 2018).

## Forest Management in Peninsular Malaysia

Tropical forests in Peninsular Malaysia are classified into State Land Forest, Wildlife Reserved, and Permanent Reserved Forest. The Permanent Reserved Forest is managed under the principle of Sustainable Forest Management, while the other two categories are meant for development and wildlife conservation, respectively. The Permanent Reserve Forest is approximately 4.81 million ha and only 1.84 million ha are classified as a sustained-yielding production forest (FDPM 2020). The concept of sustained yield is that timber taken from the forest must correspond with the volume increment of the forest (Mohd. et al., 1988). The remaining 2.97 million ha are managed as protection forests without logging activities carried out.

Sustainably managed Permanent Reserved Forests are important to Malaysia as these forests contribute to achieving Nationally Determined Contribution under the United Nations Framework Convention on Climate Change (GOM, 2018). Sustainably managed forests removed 61.57 mill tonne C $yr^{-1}$ with an annual sequestration rate of 4.0 tonne C $ha^{-1}$ for inland forests (MNRE 2018). A lower sequestration rate of carbon will affect Malaysia in achieving its Nationally Determined Contribution. This paper aims to understand how extreme drought events affect the carbon sequestration of unlogged forests. The questions to be answered by this paper are (i) What is the carbon sequestration rate before and after an extreme drought event?; (ii) Is there any difference in total carbon before and after an extreme drought event? (iii) what is the implication of sustainable forest management in Peninsular Malaysia?

## 2.0 Methodology

### Study Site

The study was conducted in Lesong Forest Reserve, Rompin, Pahang; Sungai Lalang Forest Reserve, Semenyih, Selangor; and Ulu Muda Forest Reserve, Baling, Kedah (Figure 1). These sites were established by Forestry Department Peninsular Malaysia (FDPM) as permanent sample plots to understand the growth of Dipterocarp forest. The mean annual rainfall for these sites is 2,416 mm with an annual temperature of 26.9 $^0$C. Two monsoon seasons characterised Peninsular Malaysia i.e, North-eastern winds that bring rains from November to March during the boreal winter monsoon and southwestern winds bring dry season from May to September during the boreal summer monsoon (GOM, 2020). The particulars of each site are shown in Table 1.

### Plot Design and Enumeration

Nine permanent plots of one (1) ha each were established at the study sites. Trees were census at 1.3 m height or 0.3 cm above buttress or deformity, tagged, and numbered. All the plots chosen for this study did not experience anthropogenic or natural disturbances such as burning, encroachment and landslides.

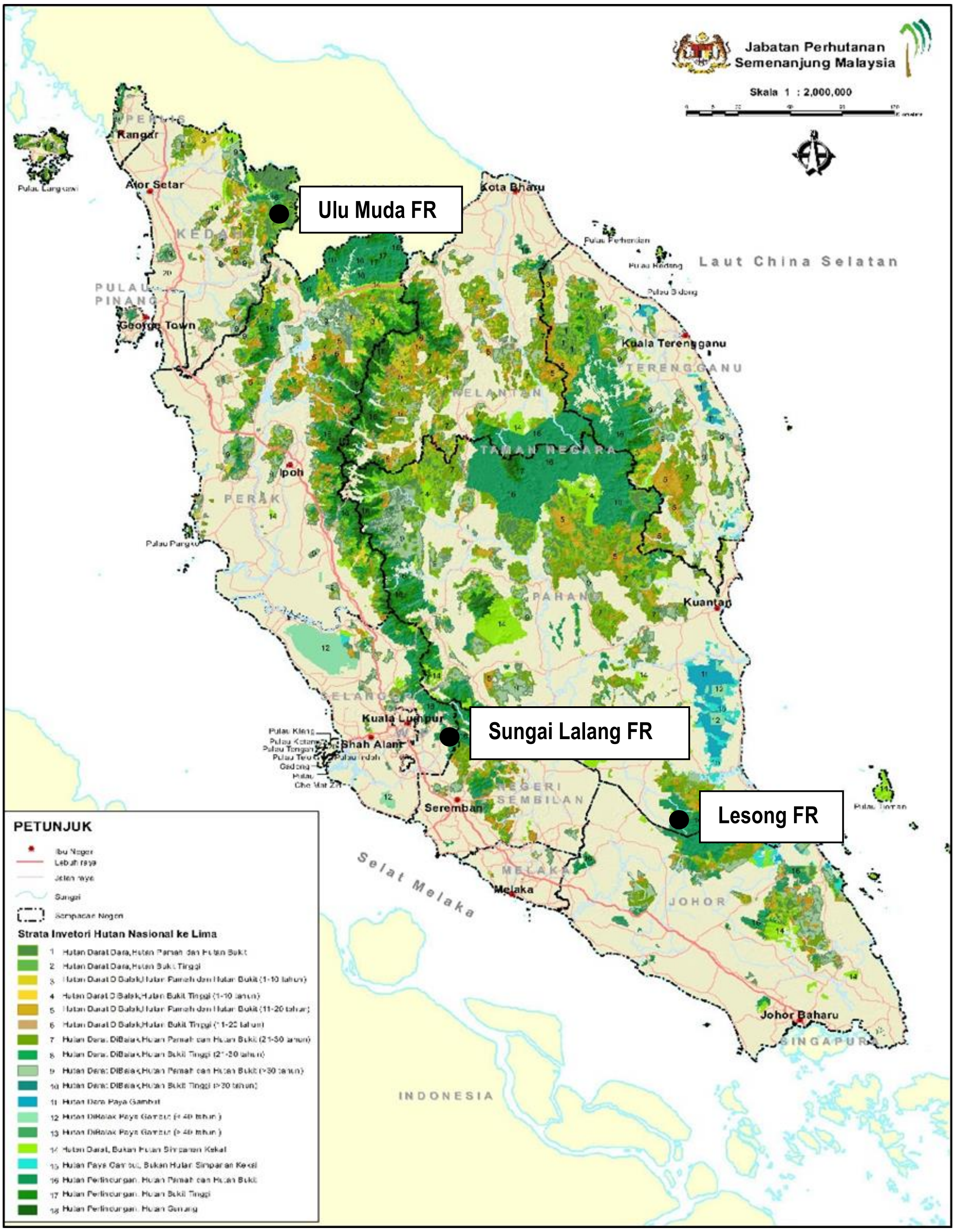


Figure 1 shows the study site of Ulu Muda Forest Reserve, Sungai Lalang Forest Reserve, Selangor and Lesong Forest Reserve (black circle).

Table 1: The details of each study site.

| Site | **Ulu Muda FR** | **Sungai Lalang FR** | **Lesong FR** |
|---|---|---|---|
| Compartment No. | 10 | 50 | 351, 371 & 372 |
| Size of area | 302.176 ha | 420 ha | 445.99 |
| Forest Type | Hill Dipterocarp Forest | Hill Dipterocarp Forest | Lowland Dipterocarp Forest |
| Altitude | 300 – 400m a.s.l | 400 – 800m a.s.l | 100m a.s.l |
| Forest Status | Virgin forest | Virgin forest | Virgin forest |
| Year of study plot established | 1994 | 1992 | 1990 |
| Year enumerated | 1994, 1995, 1996, 1997, 1998, 2000, 2002, 2004, 2006, | 1992, 1993, 1994, 1995, 1996, 1998, 2000, 2002, 2006, | 1990, 1991, 1992, 1993,1994, 1996, 1998, 2000, 2002, 2009 |
| Plot Size | 1.0 ha | 1.0 ha | 1.0 ha |
| No. of plots | 3 | 3 | 4 |
| Total plot size | 3.0 ha | 3.0 ha | 4.0ha |

## Aboveground Carbon Density

The aboveground carbon density was estimated by assuming 47% of the total AGB is carbon (Martin & Thomas, 2011). The AGB was calculated using (Kato et al., 1978). The calculation of ACD as below:

$$H = \frac{(122\ DBH)}{(60 + 2DBH)}$$

$$W_s = 0.313\ (0.1DBH^2\ H)$$

$$W_b = 0.136\ (W_s^{1.070})$$

$$W_l = \frac{(125 \times 0.124W_s^{0.794})}{(0.124W_s^{0.794} + 125)}$$

$$TAGB = \frac{W_s + W_b + W_l}{1,000}$$

$$ACD = TAGB \times (47/100)$$

Where DBH is the diameter at breast height in cm; H is height in m; Ws is the stem weight in Kg; Wb is branch weight in Kg; Wl is the the leaf weight in Kg; TAGB is the total AGB in tonne; and ACD is the above-ground carbon density in tonnes C.

## Drought Calculation

A forest is in an event of drought when there is a negative difference in monthly precipitation and potential evapotranspiration (Aragoa et al. 2007; Mahli et al. 2009). Standardized Precipitation-Evapotranspiration Index (SPEI) is a multi-scalar drought index that combined precipitation and temperature to detect, monitor and analyse droughts intensity (Vicente-Serrano et al., 2010). The intensity of the drought can be defined as follows:

Table 2: Standardized precipitation evapotranspiration index for drought intensity

| SPEI Index | Drought intensity |
|---|---|
| 0 to - 0.99 | Mild |
| -1.00 to – 1.49 | Moderate |
| -1.50 to – 1.99 | Extreme |
| Below -2.00 | Severe |

The SPEI was calculated for a time scale of 3 (three) months or SPEI-3, as midterm droughts are more severe than short term droughts of 1 (one) month (Fung et al., 2020). Before SPEI-3 was calculated using *SPEI* package in R, the monthly difference between precipitation and potential evapotranspiration is determined (Beguería et al., 2014). The formula used is as follows:

$$D_i = P_i - PET_i$$

where $D_i$ is the difference between precipitation and potential evapotranspiration; *P* is the total monthly precipitation; and PET is the potential evapotranspiration over the same period.

PET is estimated using the Thornthwaite method (Thornthwaite 1948; Vicente-Serrano et al. 2010; F.K. Fung et al. 2020) as follows:

$$PET = 16\ (N/12)\ (NDM/30)\ [\ 10\ (T / I)^m\ ]$$

where PET is the monthly potential evapotranspiration in mm; N is the monthly average sunshine hours (hr/day) estimated using FAO 56 guideline; NDM is the number of days in a month; T is the monthly-mean temperature in $^oC$, I is the sum of $(T/5)^{1.514}$ for 12 months of one year; and m is a coefficient $(6.75E\text{-}7)(I^3) - (7.71E\text{-}5)(I^2) + (1.79E\text{-}2)(I) + 0.49$.

The method of estimating PET only requires monthly mean temperature and precipitation, which were obtained from the Climate Research Unit. The Climatic Research Unit gridded Time Series or CRU TS v.4.04 was downloaded at $0.5^o$ spatial resolution for monthly temperature and precipitation data from 1990 to 2009 without any missing value (Aragoa et al. 2007; Chave et al. 2014; Esquivel-Muelbert et al. 2018; Harris et al. 2020).

## Drought Window

The extreme drought threshold was defined at -1.70 using SPEI (Ovenden et. al 2021) as shown in Table 3. The census carried out before an extreme drought event is indicated as 'No' while 'Yes' was indicated for the census carried out during or after an extreme drought event as shown in Table 4.

Table 3: List of extreme and severe drought events based on SPEI-3

| Lesong FR, Pahang | | Sg. Lalang, Selangor | | Ulu Muda, Kedah | |
|---|---|---|---|---|---|
| Jan-97 | -2.11 | Oct-92 | -2.03 | Aug-01 | -1.70 |
| Jul-97 | -1.96 | Apr-98 | -1.71 | Jun-04 | -1.73 |
| Sep-97 | -1.86 | Nov-98 | -2.24 | Jan-05 | -1.77 |
| Oct-97 | -2.06 | Dec-98 | -2.00 | | |
| Nov-97 | -1.93 | Feb-02 | -1.75 | | |
| Apr-98 | -1.91 | Jan-05 | -1.90 | | |
| May-98 | -1.72 | Feb-05 | -1.86 | | |
| Nov-98 | -1.78 | | | | |

Table 4: Indication of Drought Window based on the census year

| Lesong FR, Pahang | | Sg. Lalang, Selangor | | Ulu Muda, Kedah | |
|---|---|---|---|---|---|
| **Census Date** | **Window** | **Census Date** | **Window** | **Census Date** | **Window** |
| Sept-Oct-90 | No | Jan-Feb-92 | No | Jan-94 | No |
| July-91 | No | Jan-Feb-93 | Yes | Jan-95 | No |
| March-92 | No | Feb-April-94 | No | June-96 | No |
| Dec-93 | No | Apr-June-95 | No | March-97 | No |
| Dec-94 | No | Nov-96 | No | April-98 | No |
| Aug-Sept-96 | No | May-98 | Yes | Mar-Apr-00 | No |
| Aug-Sept-98 | Yes | May-00 | Yes | Sept-02 | Yes |
| Oct-00 | Yes | May-July-02 | Yes | June-04 | Yes |
| March-02 | No | Aug-06 | Yes | Jan-Feb-06 | Yes |
| Nov - 09 | No | | | | |

**Statistical Analysis**

Forest growth data are the diameter growth of trees that are repeatedly measured over time at different intervals and times, making these time-series data unbalanced longitudinal data and also not independent as the present tree measured influences the measurement in the future (Shek & Ma, 2011; Zuur et al., 2007). Analysing forest growth data with Linear Mixed Effect Model addressed the issue of longitudinal data by using all available data and testing the hypothesis in a model (Qie et al. 2017). The Linear Mixed Effect Model was used to analyse the changes in the response variable (above-ground carbon density) over time since the first census and the variation of changes from the effect of drought using *lmer* function in the R package *lme4* (Bates et al., 2015). The fitted *R* syntax is shown in Eq.1 below:

response_variable ~ Year * drought + (1|Plot) + (1|Site) (Eq. 1)

The site and plots were added as random effects as the response variable is nested in it. The Linear Mixed Effect Model assumed variance is homogenous and residuals are normally distributed. The validation of the model is carried out by examining the residual variance value fitted against plots and sites. The 95% confidence intervals (CI) were estimated using a restricted maximum likelihood estimator and bootstrapped with 1,000 iterations. The *LmerTest* packages were used to obtain the p-value (Kuznetsova et al., 2017).

## Results and Discussion

### Aboveground Carbon Density Growth

The ACD growth of unlogged forests was 0.7 tonnes C $ha^{-1}$ $yr^{-1}$ (CI: 0.4 to 1.1) when there is no extreme drought events. However, the growth of ACD during or after an extreme drought event was - 0.4 tonne C $ha^{-1}$ $yr^{-1}$ (CI: -1.1 to 0.3). This showed that extreme drought events affected the ACD growth rate as shown in Fig 2. Extreme drought events depressed tree growth and may lead to mortality if they exceed the tolerance level of a tree, which eventually halted ACD growth.

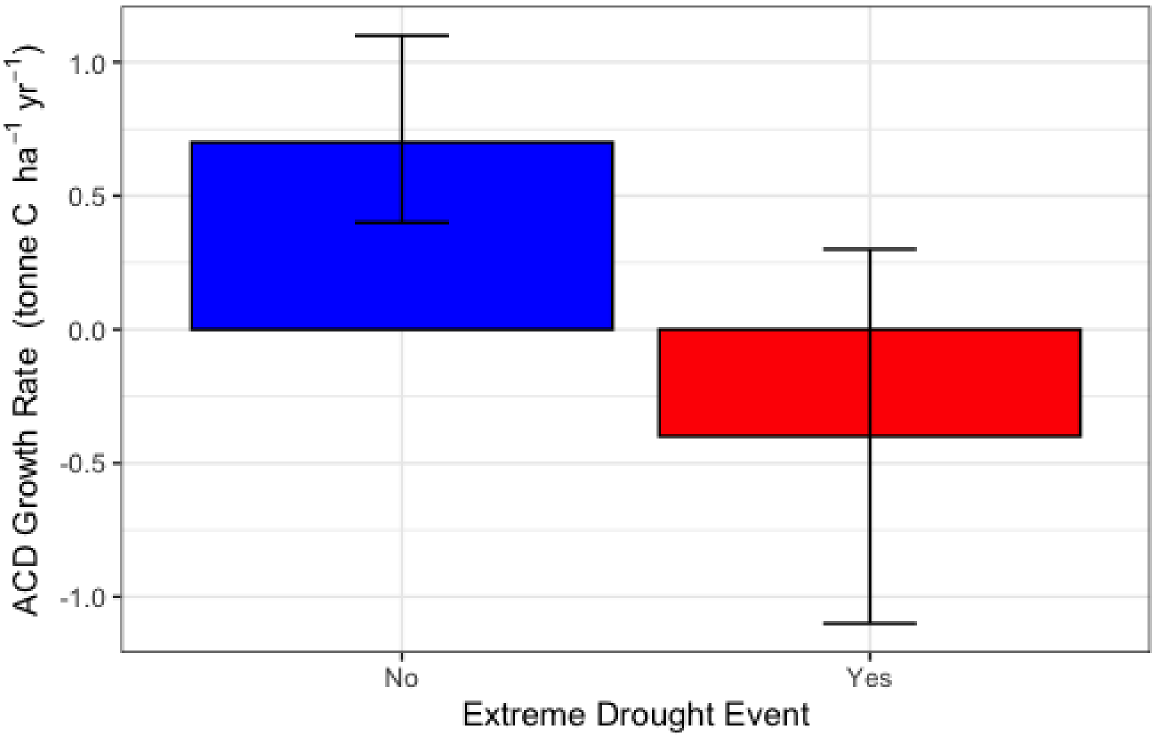


Figure 2 shows the growth rate of ACD. The interval bars that did not overlap each other showed there is a significant difference in ACD growth before and during/after extreme drought events.

### Total Aboveground Carbon Density.

The total ACD during extreme drought events is higher at 239.2 tonnes C $ha^{-1}$ (CI:171.1 to 314.1) compared to 230.6 tonnes C $ha^{-1}$ (CI: 162.1 to 296.2) of a non-event as shown in Figure 3. The total ACD is higher during the occurrence of extreme drought events because all plots were censused in the early 1990s when only one event was recorded in Sungai Lalang. The extreme drought event only occurs frequently after 1997/98. This allowed the plots to accumulate ACD during the early 1990s before the extreme drought events occur in the later census years.

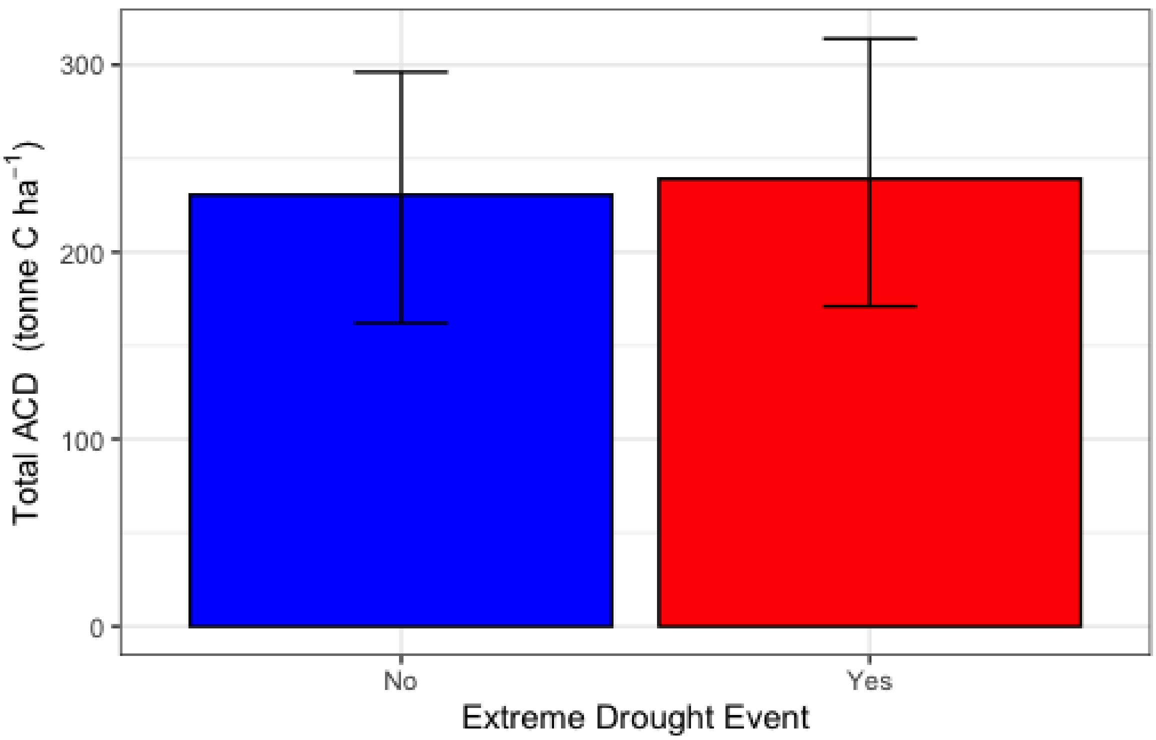


Figure 3 shows the total ACD of the forest. The interval bars that overlap each other showed that there are no significant differences in total ACD between before and during/after extreme drought events.

## Implications to Sustainable Forest Management

Extreme drought events have halted the growth of ACD. Tropical forests that do not experience extreme drought events will have an estimated growth of 251.6 tonnes C $ha^{-1}$ in 30 years. Extreme drought events affected the growth of ACD, so that the estimated ACD after 30 years is 227.4 tonnes C $ha^{-1}$ with a loss of 24.4 tonnes C $ha^{-1}$, as shown in Fig. 4. The loss will ~~may~~ be higher if the occurrence of extreme drought events occurs more frequently or more severe in the future. The growth of ACD is correlated with the growth of the volume of timber. Extreme drought events may affect the growth of the timber volume, which will lead to lower future yield as forest growth is halted.

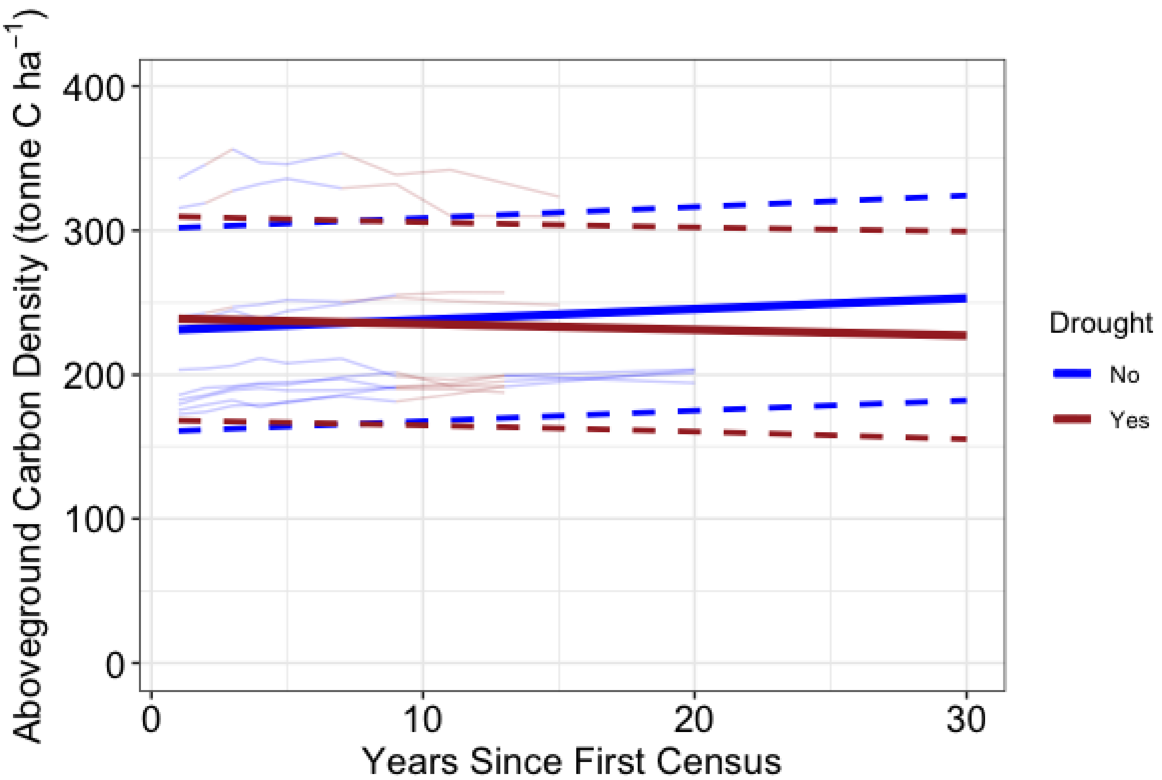


Figure 4 shows the projected total ACD in 30 years. The solid line showed changes over time in total ACD.

The Selective Management System (SMS) is designed to allow the regeneration of logged-over forests in 30 years' time with a projected yield. Residual stand of 30-45 cm in diameter are expected to grow as the next crop trees of 45-50 cm in diameter with the capability of producing 40 – 45 $m^3$ $ha^{-1}$ in the next cutting cycle. However, the effect of extreme drought events to the regeneration of logged-over forests remained unknown. It can hypothetically assume that the volume growth will be lower than estimated in the SMS which may lead to the adaptation of the management system. Another scenario is that frequent future extreme drought events will disrupt the regeneration process of logged-over forests. These frequent disruptions will halt the regeneration processes and resulting a permanently degraded logged-over forests.

## Conclusion

Our study showed that unlogged forests are vulnerable to extreme drought events. Although studies have shown that unlogged forests were able to recover after an El Nino-Southern Oscillation episode. However, future predictions of frequent extreme or even severe drought events will halt forest growth. More studies are needed to understand the effect of climate change on tropical forests. Forest managers must incorporate these findings into management practices to ensure sustainable forest management.

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