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PROJECTION OF SOIL CARBON CHANGES AND FOREST PRODUCTIVITY FOR 100 YEARS IN MALAYSIA USING DYNAMIC VEGETATION MODEL LUND-POTSDAM-JENA

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The gaseous exchange of carbon dioxide in the atmosphere will affect the rate of carbon uptake in the soils. When carbon dioxide increases, the productivity of soil organic carbon also increases. The study aimed to determine the soil carbon changes and forest productivity in Malaysia using climate data from five Global Climate Models on 0.5 × 0.5 grid resolution by implementing three scenarios from year 1990 to 2099. The Lund-Potsdam-Jena model calculated changes in net primary production and forest areas. The results showed that soil carbon increased by 15% in Representative Concentration Pathway 8.5 (RCP8.5) but decreased by 17% in RCP8.5 C90. The simulated soil carbon change projection increased by an average of 2.5% by the year 2099 due to the increased carbon dioxide concentration. The soil carbon fell under the RCP8.5 C90 scenario by an average of -27.5%, which was caused by the increasing heterotrophic respiration due to an increase in temperature. Carbon dioxide concentration and temperature had a tendency to speed up decomposition. Climate change will be a key driver of change in soil carbon over the 21st century as the forest ecosystems would respond to any future increase of carbon dioxide concentration by increasing forest productivity.

Keyword: terrestrial carbon, climate change, land ecosystem, sustainable forest management

INTRODUCTION

Soil carbon is the largest carbon pool in the terrestrial forest habitats and the soil parameters are to assess the soil carbon flux (Jobbagy & Jackson 2000). Global carbon cycle regulation and carbon management is crucial (Walker et al. 2015). However, future variations and changes in the size of soil carbon especially for forest areas are unpredictable due to the increase in carbon dioxide in the atmosphere and the leading cause of climate change (Smith et al. 2005, Sun & Mu 2017a). Due to the increase in atmospheric carbon dioxide and the changes in climate, soil carbon balance was also altered and subsequently affecting the terrestrial carbon stock (Lal 2004, Smith 2004). The possible effected under climate warming on soil carbon was raised by several researchers (Baveye et al. 2020, Cox et al. 2000, Jenkinson et al. 1991, Melillo et al. 2002). Soil carbon loss was observed in Coupled Climate-Carbon Cycle projections as a potentially strong positive response to climate change (Cox et al. 2000, Friedlingstein et al. 2001). Across the globe, the value of soil carbon stocks is declining even though there is increase in organic carbon from plants (Jones et al. 2003a). The decrease of soil carbon stocks depends critically on soil carbon response to changes in climatic conditions with several reports indicating that soil carbon decreases was due to an increase in soil temperature (Cox et al. 2001, Jones et al. 2003a, Wu et al. 2021).

A recent study by Sun & Mu (2017b) projected soil carbon stock using methods of Conditional Nonlinear Optimal Perturbation related to Parameter error (CNOP-P) and General Circulation Model (GCM) from Coupled Model Inter-comparison Project 5 (CMIP5) under the Representative Concentration Pathway (RCP) 4.5 scenario, which was explored by the Dynamic Global Vegetation Model (DGVM) and Lund-

Potsdam-Jena (LPJ). These studies compared approaches between 10 GCMs and CNOP-P. The results of 10 GCMs indicated that the mean soil carbon from 2011 to 2100 was 75.6 GT carbon to 86.7 GT carbon, while the CNOP-P approach showed higher mean soil carbon of 93.1 GT carbon to 84.1 GT carbon.

Previously, Jones et al. (2004) used the Hadley Centre's Coupled Climate-Carbon Cycle GCM (HadCM3LC) to model global climate change and soil carbon stocks by involving a single-pool soil carbon model to simulate the response. Other studies which also used the HadCM3LC (Cox et al. 2000, Jones et al. 2003b) had included the response of terrestrial biosphere carbon changes against atmospheric carbon dioxide. Previous studies by Jenkinson et al. (1991) and Smith et al. (2005) used the Rothamsted Carbon Model (RothC-26.3) to stimulate the impact of global warming on soil carbon; nevertheless, the study did not observe the impact of changing organic carbon inputs to the soil. Smith et al. (2005), Jones et al. (2004) and Jenkinson et al. (1991) recorded soil carbon stocks changed slightly during the half of the 21st century. Both models of HadCM3LC and RothC-26.3 simulated global soil carbon stock to decrease from 140 GT carbon and 86 GT carbon to 80 GT carbon and 54 GT carbon, respectively (Jenkinson et al. 1991, Jones et al. 2004).

The impacts of projected land-use changes were also simulated but had relatively minor implications on the global scale. The balance between carbon inputs and decomposition depended either from soils gain or lose soil carbon (Gottschalk et al. 2012). Based on the study by Azian et al. (2018), the understanding of the parametric changes such as atmospheric carbon dioxide level, temperature and precipitation pattern through projection could enhance a better understanding of the factors that could positively and negatively impact climate change.

The present study investigated the projected impacts of climate change on Malaysian forest soils using the Lund-Potsdam-Jena model in three scenarios. It specifically evaluated the boundary shifts in soil carbon stock and the vulnerability of existing forests to future climate change. It was anticipated that the information of this study would assist Malaysia's strategic directions in relation to forest adaptation to climate change.

METHODOLOGY

Study area

Malaysia which is located in the Southeast Asia. Together with its territorial waters, it lies between 0°51'N – 7°33'N and 98°01'E – 119°30'E covering the Peninsular Malaysia, Sabah and Sarawak. The nation consists of 13 states and three Federal Territories with an approximately 330,803 km of land cover including about 5,267 km of coastline and over 879 islands. The temperature is relatively uniform at 26 °C–28 °C throughout the year. Although the annual variation of daily mean temperature may be small (about 2 °C–3 °C), the diurnal variation may be significant at about 12 °C. The north-eastern monsoon is dominant from November to March, bringing a high amount of rainfall; while the south-western monsoon occurs between June and September. More than 3,550 mm of annual rainfall is recorded in the lowlands.

Model and data requirements

The Lund-Potsdam-Jena model was used to analyse all the data. The model was previously used to combine process-based, large-scale representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework (Sitch et al. 2003). It was a well-established and active model that represented forest types well across different parts of the world. Several publications were produced from various applications of this model (Sitch et al. 2003, Sun & Mu 2017a, Yurova et al. 2010, Wania et al. 2010). The Lund-Potsdam-Jena model features included feedback through canopy conductance between photosynthesis and transpiration as well as the interactive coupling between these "fast" processes and other ecosystem processes, including resource competition, tissue turnover, population dynamics, soil organic matter and litter dynamics and fire disturbance. All related processes were shown in the diagram for the Lund-Potsdam-Jena model in Figure 1.

In this study, the impact of climate change on soil carbon was analysed under Malaysia's forest pixel for three different scenarios. The three scenarios involved are (i) baseline (observed data from 1976 to 2005 with carbon dioxide in

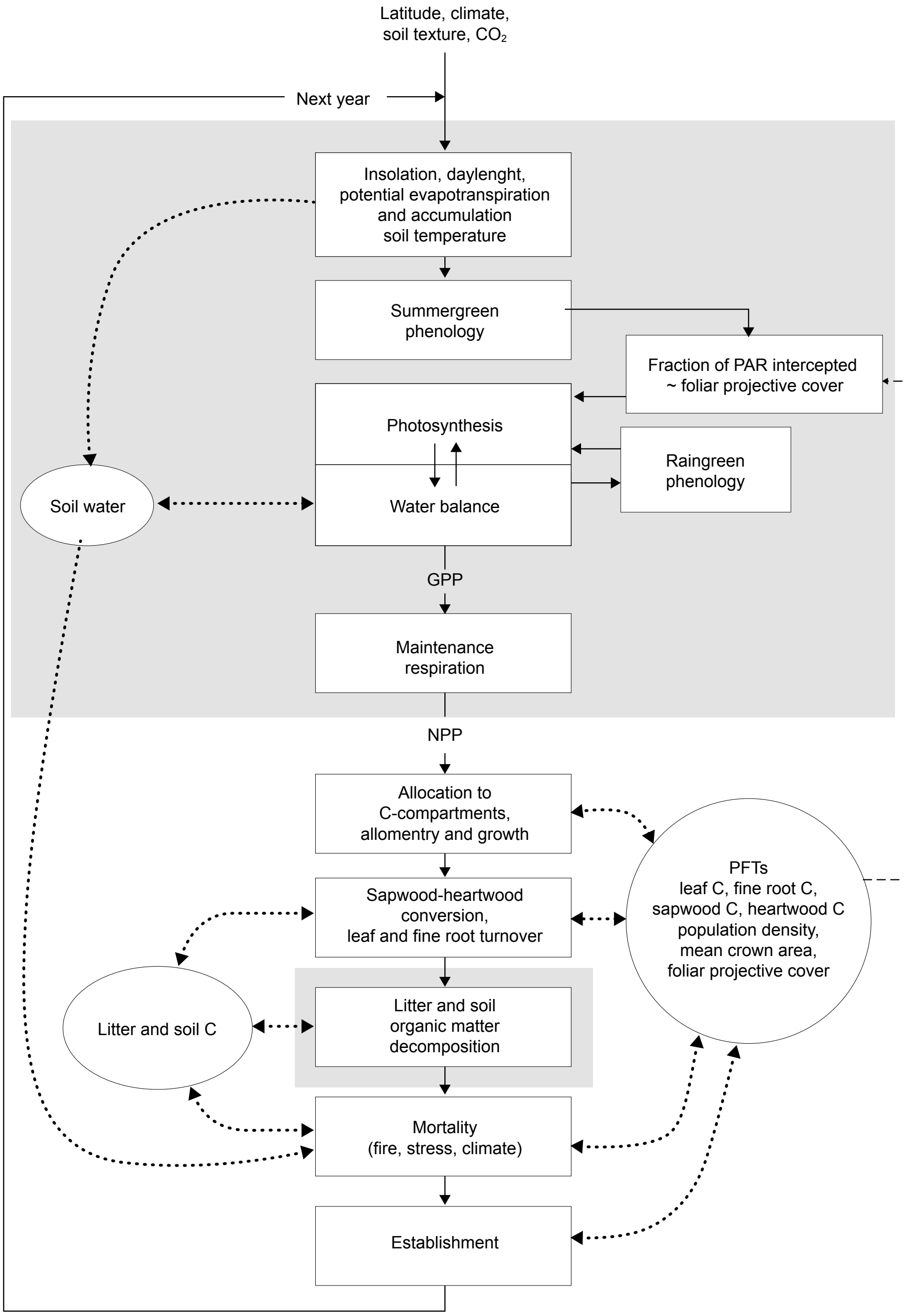

Figure 1 Schematics diagram of the Lund-Potsdam-Jena model

1990 at 345 ppm and temperature at 30.5 °C), (ii) Representative Concentration Pathways (RCP), namely RCP8.5 which was developed with five model ensemble of CMIP5 data from 2070 to 2099 with carbon dioxide increases from 345 ppm to 801 ppm in 2084 and a temperature increase from 30.5 °C to 32.8 °C and (iii) RCP8.5 with control carbon dioxide (RCP8.5 C90) which was developed the same way as RCP8.5 but using 1990 carbon dioxide data with a temperature increase from 30.5 °C to 32.8 °C. The RCP8.5 was the highest carbon dioxide concentration projection compared to the other three RCPs: RCP2.6, RCP4.5 and RCP6.0, where RCP8.5 was always used as the worst-case scenario in the future. Other key input data requirements for Lund-Potsdam-Jena model were cloudiness, precipitation and temperature as climatic parameters, soil, carbon dioxide and grid as non-climatic parameters (Table 1). Additionally, the source of input data required for Lund-Potsdam-Jena model is shown in Table 2. Meanwhile, Table 3 shows the five General Circulation Model used for this training program and their attributes.

RESULTS

The present study compared the simulated soil carbon for the RCP8.5 scenario with the baseline soil carbon (Figures 2, 3 and 4) using the Lund-Potsdam-Jena model. Figure 2 displays the soil carbon spatial maps for baseline scenario based on the historic data from 1976–2005 with carbon dioxide in 1990. Figure 3 shows the RCP8.5 scenario with carbon dioxide from 2070–2099 using carbon dioxide projection data in 2084. Figure 4 exhibits the RCP8.5 C90 scenario with the projected carbon dioxide from 2070–2099 using the 1990 carbon dioxide data.

From the observations on the three scenarios, there was a positive change in soil carbon for the RCP8.5 scenario compared to RCP8.5 C90. The soil carbon was observed to exceed 5,160 g m^{-2} from the west to the central of Peninsular Malaysia. For East Malaysia, areas in the northeast of Sarawak and most of the areas towards the coast of Sabah had soil carbon value exceeding 6,020 g m^{-2}, especially in the southeast and northwest. The results showed that the soil carbon changed from the baseline (min-max $_{Baseline}$)of 5,590 g m^{-2}–8,170 g m^{-2} to the RCP8.5 scenario (min-max $_{RCP8.5}$) of 6,450 g m^{-2}–8,170 g m^{-2}. However, the comparison of soil carbon between RCP8.5 C90 and baseline scenario revealed declining values of the soil carbon for the RCP8.5 C90 (min-max $_{RCP8.5C90}$) of 3,870 g m^{-2} – 5,590 g m^{-2} as compared to the baseline of 5,590 g m^{-2}– 8,170 g m^{-2} (Figure 4). The simulation showed that the soil carbon level fell in the range between more than 4,300 g m^{-2}–5,160 g m^{-2} in the north of Peninsular Malaysia. In Sabah and in the east of Sarawak, the range was between more than 5,160 g m^{-2}–6,020 g m^{-2}.

Table 1 Key input data

Climate parameters	Non-climatic parameters
Monthly mean cloudiness (%)	Soil
Monthly mean precipitation (mm/month)	CO_2
Monthly mean temperature (°C)	Grid or domain

Table 2 Source of input data required for Lund-Potsdam-Jena

Climate parameters-grid in 0.5 0.5 resolution	Observe data source: https://crudata.uea.ac.uk/cru/data/hrg/	GCM (projected) data source: http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html
Monthly mean cloudiness (%)	CRU	CMPI5
Monthly mean precipitation (mm/month)	CRU	CMPI5
Monthly mean temperature (°C)	CRU	CMPI5

Table 3 Five models used for this program and their attributes

Modelling centre	Model	Regridded resolution	Historical period	RCP (4.5 & 8.5) period
MRI	MRI-CGCM3	0.5 × 0.5	1850–2005	2006–2099
MIROC	MIROC5	0.5 × 0.5	1850–2005	2006–2099
MIROC	MIROC-ESM	0.5 × 0.5	1850–2005	2006–2099
MIROC	MIROC-ESM-CHEM	0.5 × 0.5	1850–2005	2006–2099
IPSL	IPSL-CM5A-LR	0.5 × 0.5	1850–2005	2006–2099

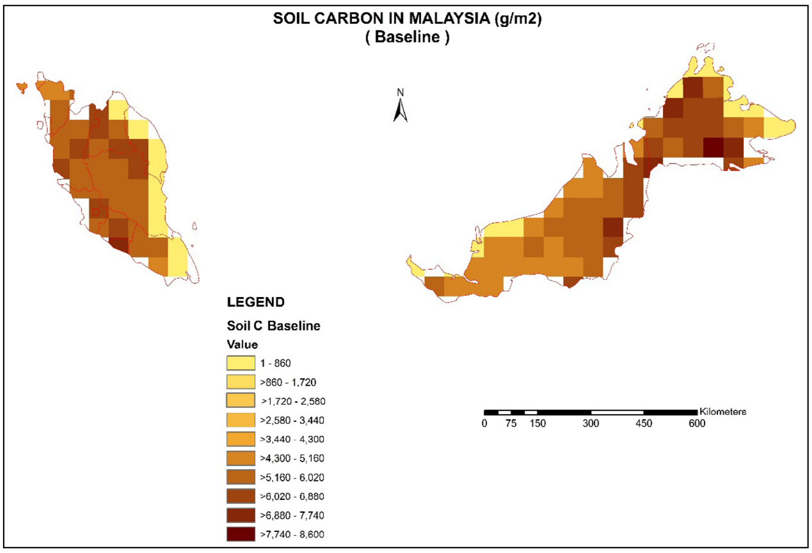

Figure 2 Lund-Potsdam-Jena simulated distribution of soil carbon in Malaysia using baseline scenario

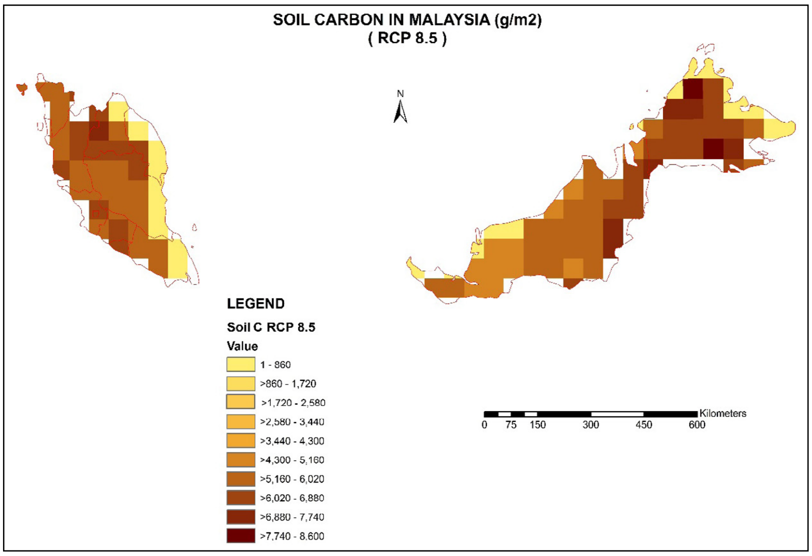

Figure 3 Lund-Potsdam-Jena simulated distribution of soil carbon in Malaysia using RCP8.5 scenario

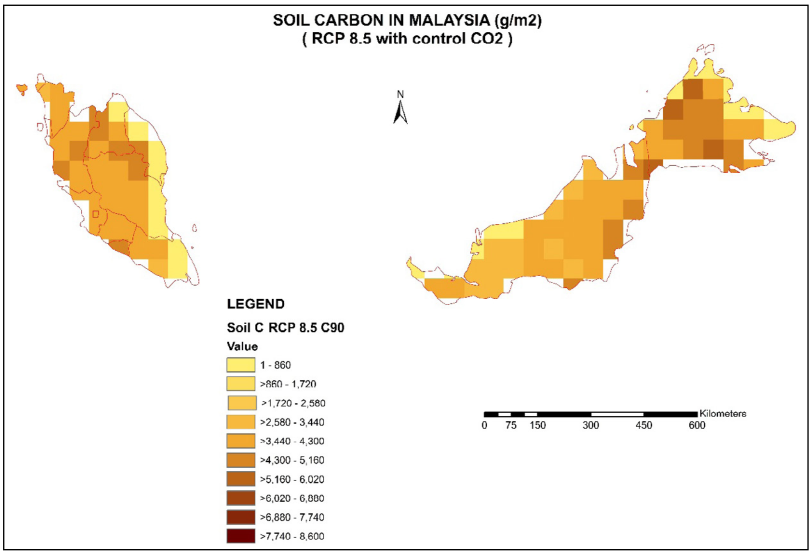

Figure 4 Lund-Potsdam-Jena simulated distribution on soil carbon in Malaysia for RCP8.5 C90 (with 1990 CO_2) scenario

Table 4 shows the value of soil carbon in g m^{-2} and the changes in percentage for all scenarios. The soil carbon value for both baseline and RCP8.5 was not much different, which was at 1–8,190 g m^{-2} and 1–8,507 g m^{-2} for baseline and RCP8.5 soil carbon value, respectively. In comparison, the soil carbon value was slightly different for RCP8.5 C90 at 1–5,881 g m^{-2}. The increase in soil carbon was not affected by the rise in carbon dioxide but was greatly influenced by the temperature changes. The percentage of soil carbon increased by 14% and 17%. It showed that the RCP8.5 percentage of soil carbon changed from negative to positive from -5.32% to 20% and similarly the soil carbon of RCP8.5 C90 changed from -37.45% to -20%.

In terms of the simulation of the percentage of soil carbon changes without carbon dioxide in Malaysia, the rate was higher when approaching the northern part of Peninsular Malaysia, with the value ranging between 5%–20%. While in East Malaysia, the percentage of soil carbon changes was observed to increase, especially in the east of Sabah with more than 10%–15% (Figure 5).

On the contrary, the percentage of soil carbon in the eastern part of Peninsular Malaysia was more than -30% to -25% (Figure 6). While in East Malaysia, especially in Sabah's area had a range between more than -30% to -20%. The soil carbon value was less than 4,500 g m^{-2} in Peninsular Malaysia, while the northeast part of East Malaysia exceeded 6,020 g m^{-2}.

DISCUSSIONS

Impacts of climate change on soil carbon

Soil carbon contained a mixture of both inorganic and organic matters. The availability of soil carbon effects is importang for photosynthesis and growth,especially with increasing carbon dioxide (Stitt & Krapp 1999, Thompson et al. 2017). The results indicated that with the increase in carbon dioxide and followed by the increase in temperature, will cause the soil carbon value to increase. It was observed that southern Peninsular Malaysia and most of Sarawak had lower soil

Table 4 Soil carbon value in g m^{-2} for all three scenarios and changes in percentage for both RCP8.5 scenarios in Malaysia

Scenario	Soil carbon (g m^{-2})	Soil carbon % increase
Base line	1–8,189.72	-
RCP8.5	1–8,506.80	-5.32% to 20%
RCP8.5 C90	1–5,880.85	-37.45% to -20%

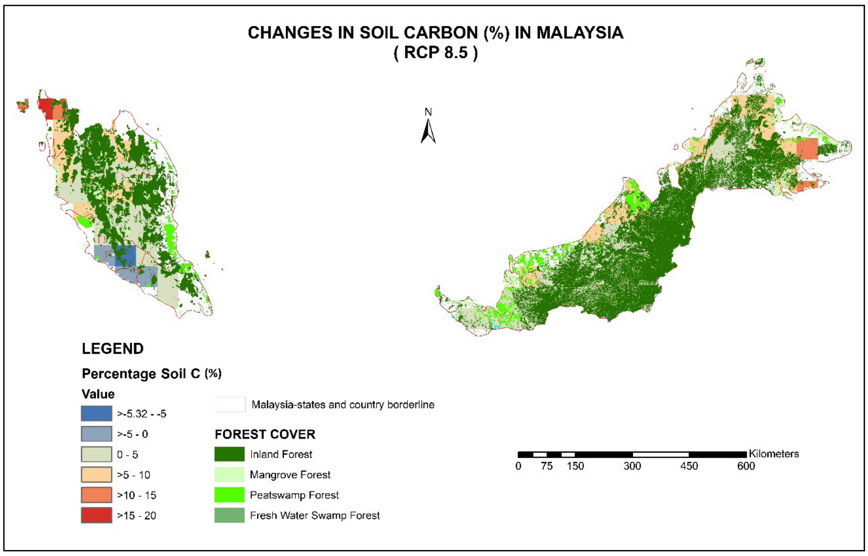

Figure 5 Lund-Potsdam-Jena simulated percentage of soil carbon change projections for the whole of Malaysia under the RCP8.5 without CO_2

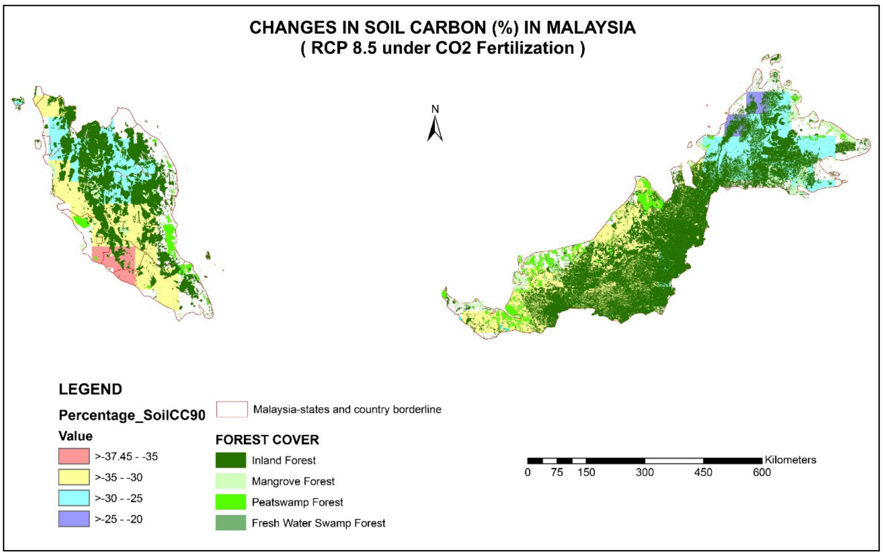

Figure 6 Lund-Potsdam-Jena simulated percentage of soil carbon change projections for the whole of Malaysia under the RCP8.5 with CO_2

carbon. The vulnerability of soil carbon was highly influenced by seasonal or drought-related drying. The impacted area would experience higher temperatures that could contribute to higher carbon loss due to the higher microbial decomposition activities (Frey et al. 2013).

However, the soil carbon simulation represented only a percentage of the soil and the changes in g m^{-2} without indicating the soil type. Soil carbon changes should involve soil types and land-use change, such as forest areas, urban areas, watersheds, croplands, shrubs, and grasslands. The higher estimates of soil carbon in these areas might be related to the high soil acidity of tropical forests, reducing the decomposition rate of soil organic matter and carbon losses from the soil into the atmosphere (McIntosh & Allen 1993, Shi et al. 2012). In addition, Nie et al. (2015) claimed that the soil acidity contributed to the carbon stock and tree productivity. Furthermore, tropical regions were dominated by precipitation effects causing the climate models to show a large variability as well as Lund-Potsdam-Jena projected differing responses in vegetation patterns and carbon balance (Schaphoff et al. 2006).

Simulated soil carbon projection based on RCP8.5 and RCP8.5 C90 scenarios

Soil carbon was expected to increase based on the RCP8.5 scenario compared to the baseline scenario. An increase in soil carbon could be due to the use of carbon dioxide. When carbon dioxide was present, it brought several effects on the terrestrial biosphere, such as the increase in carbon dioxide could enhance the efficiency of photosynthesis. Furthermore, the increase in carbon dioxide could reduce the heterotrophic respiration by increasing the carbon/nitrogen ratios of the litter and soil carbon pools (Herrington 2013). Moreover, it might lead to a temporary increase in carbon dioxide uptake by the land. However, global warming will increase soil respiration and cause the terrestrial biosphere to become a net source of carbon dioxide in the long term. Hence, the increased atmospheric carbon dioxide concentration can promote carbon dioxide fertilisation effects which allowed rapid uptake of carbon dioxide by the land.

Simulated soil carbon change projection based on RCP8.5 C90

Soil carbon decreased for the RCP8.5 C90 scenario compared with the baseline scenario. The RCP8.5 C90 scenario had a constant carbon dioxide concentration with the baseline scenario but at an increased temperature of 32.8 °C. Increased temperature was caused by the increasing greenhouse gases in the atmosphere. Greenhouse gases trapped more heat in the Earth's atmosphere, causing the average temperature to rise worldwide, leading to global climate change. Thus, the increasing temperature could cause changes in the terrestrial ecosystem. Climate change was measured as changes in temperature and precipitation which led to the variation in soil carbon (Heyder et al. 2011, Tian et al. 2015). Weather was vital in determining the growth rate and species accumulations. The changes in temperature and precipitation had adverse effects on the soil carbon stock due to the enhancement of heterotrophic respiration and decreasing litter input resulting from the reduced net primary production.

During the first 30 years of climate change, it significantly increased soil carbon as the carbon dioxide concentration was maintained at a constant level Sun & Mu (2017b). However, for the last 50 years, the soil carbon has increased steadily due to the increasing carbon dioxide concentration. The carbon dioxide concentration might influence the long-term variation in soil carbon, while temperature and rainfall patterns might determine the temporary variation in soil carbon. Cox et al. (2000) estimated that global land carbon began to decline by 2050 despite continued emissions and elevated carbon dioxide concentrations in the atmosphere. The decline in global soil carbon was due to the increasing soil respiration and decreasing precipitation and warmer temperature.

Biodiversity response to soil carbon projection

A previous study by Sun & Mu (2017b) indicated that variations of soil carbon components and plants were due to climate change can be explained by exploring the relationships between soil carbon and plants. Within the Lund-Potsdam-Jena model, the soil carbon variations were dependent on the decomposition of aboveground and belowground litters. Soil carbon received inputs from litterfall which were divided into contributions from leaf, stem and root carbon from each plant functional type present. The rate of soil carbon pools came from the decompositions of aboveground and belowground components of litter into the soil, depending on the root growth. An increase in atmospheric carbon dioxide mostly increased the rate of photosynthesis and decomposition in the soil. Hence, future climate change and carbon dioxide concentration would increase the amount of vegetation and its litter. Fast soil carbon pool was the main contribution to the variation of soil carbon. However, soil carbon started to decline because of increased soil respiration and changed in vegetation cover.

Furthermore, microbial respiration could reduce soil carbon. The soil respiration rate depended on the soil temperature, soil moisture content and the soil carbon content (Cox et al. 2001; Onwuka & Mang 2018). Soil temperature might influence the activities of soil microorganisms. In normal ecosystems under a specific temperature range, microbial respiration rate increased by the increasing soil temperature. Thus in the long term, soils could lose more carbon and in order to mitigate the soil carbon losses, the respiration of temperature sensitive microbial activities must be reduced.

Carbon emission response to soil carbon projection

The rising global temperature might alter the soil ability to store carbon (Wieder et al. 2013). Global warming would contribute to a loss of about 55 trillion kilograms of carbon from the mid-century soil (Dennehy 2016). This indicated that soil carbon decreased with increasing temperature. Increasing temperature will also cause a net release of carbon dioxide from soils by triggering microbes to speed up their plant debris consumption and organic matter. Herrington (2013) showed that the soil carbon pool took up about 1–12 % of the total cumulative carbon emissions by the year 3000. The carbon emission from the soil was due to microbial activities and human-related activities. According to Dennehy (2016), about 30 Pg carbon soil carbon was lost to the atmosphere due to human activities. Thus, one of the reasons for soil carbon losses was due to global warming.

CONCLUSION

Soil is the largest organic carbon pool in the terrestrial biosphere. Soil carbon displays high variation between ecosystems and the variations could be partly due to climate change effects and increasing carbon dioxide concentration in the atmosphere. However, in the long term global warming will increase soil respiration and negatively impact soil carbon. Climate change is no longer a distant possibility and Malaysia is already experiencing adverse impacts of climate change such as flooding and drought and such effects will become even more intense in the future. Therefore, it is timely for Malaysia to integrate appropriate climate research with the development strategies to reduce impacts of the climate change in the future. It is crucial that any adaptation efforts to manage the unavoidable impacts of climate change must be set in motion in the near futurs, preferably based on the efficient utilisation of forest resources.

The findings of the current study showed positive impact of the projected climate change under the RCP8.5 scenario but the increasing soil carbon which might restrict the possible positive response of plant productivity to the increasing carbon dioxide concentration. Thus a significant upward trend is a good condition from a climate change mitigation point of view, while a declining trend is considered an inferior condition. As carbon dioxide level might increase, it might not guarantee the predicted positive impact on the forest sector. In the real world, carbon dioxide level might not be efficient to give the impact on climate change. Changes in precipitation and temperature patterns might additionally affect the impact of climate change. However, there are still many unknown factors affecting climate change and further studies are much required. The results from the current study can be one of the useful future predictions for forest management in the forestry sector.

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