Title: Mapping mangrove biomass in different climatic scenarios in the Sunda Banda Seascape:

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Abstract: Mangrove forests have a significant role in the ecological, economic and social development of coastal urban communities. However, they are under threat by climate change and anthropogenic activities. The Sunda Banda Seascape (SBS), Indonesia, is among the world's richest regions of mangrove biomass and biodiversity. In order to help inform current and future management strategies, it is critical to estimate the baselines how mangroves will response to climate change in this region. Therefore, this paper utilized climatic models derived from temperature and precipitation metrics in conjunction with mangrove distribution maps to estimate a benchmark of mangrove biomass of the SBS in six scenarios, namely Last Inter-glacial Period (LIP), current scenario (1950-2000) and all four projected Representative Concentration Pathways (RCPs) in 2070 due to climate change. Our results revealed with climate change and increasing CO_2 concentration, mangroves gain more biomass. It also highlighted the great proportion of below-ground biomass in mangrove forests. Finally, it showed the climate change would impose a higher degree of spatial variability in mangrove biomass across all six scenarios. As mangroves have been proposed as an essential component of climate change strategies such as REDD+ and blue carbon, this study can serve as a baseline for future studies and resource management strategies.

Keywords: mangrove forests; biomass; climate change; IPCC; carbon sequestration; GIS

1. Introduction

Mangrove forests have a significant role in the ecosystem function, as well as economic and social development of coastal urban communities (Tomascik et al. 1997, Alongi 2007). The financial return of mangrove ecosystem services are considered to be as much as 100,000 USD per hectare per year, and 170 billion USD globally per year (Costanza et al. 1997). They sequestrate carbon (Donato et al. 2011, Beaumont et al. 2014), support biodiversity through their complex habitat (Hendy et al. 2013) and reduce coastal impacts from hurricanes (Alongi 2002, Das and Crépin 2013). Litters of mangrove forests provide nutrients and food for many species (Nagelkerken et al. 2000, Cragg and Hendy 2010), which have been linked to increased fish populations (Mumby et al. 2004). Other ecosystem services include, food production (Tomascik et al. 1997), disease and water purification; provisions of wood, fiber and fuel and habitat regeneration – such as nutrient cycling, soil formation and primary production (MA 2005).

Like in other ecosystems, biomass of mangroves is the key to provide those abovementioned ecosystem services. Inherently, the biomass of mangrove forests distributed with great spatial variation (Komiyama, Ong, and Poungparn 2008, Donato et al. 2011). This spatial variation can be magnified because of climate change. Climate change may intensify the spatial variability of mangrove biomass because it facilitates changes in precipitation and temperature, creating an environment (un)suitable for the organisms that live in the affected areas (Walther et al. 2002). It may increase the loss of mangrove forests, which will alter the environment and cause ecological shifts that may impede the function and productivity of adjacent coastal habitats (Gilman et al. 2006, Duke et al. 2007). Importantly, coastal development and human settlements may accelerate this process, because mangrove are harvested for aquaculture and agriculture (Alongi 2007). Therefore, the synergistic effects of climate change and anthropogenic activities will exacerbate this spatial variation of mangrove biomass.

The Sunda Banda Seascape (SBS), is located in the Coral Triangle (Figure 1A) in Indonesian waster and surrounded by major cities (Figure 1B) in the region. This area has 48 different recorded mangrove species (Duke, Ball, and Ellison 1998), the highest species diversity of mangroves worldwide. Indonesia itself contains almost one quarter of the world's mangrove forest land area (Giri et al. 2011) and the world's top country with the highest mangrove above-ground biomass (AGB)[1] (730 million tons) (Hutchison et al. 2014). Moreover, the SBS has a high level of vulnerable ecosystems, marine biodiversity and endemism (Roberts et al. 2002, Allen 2008, Wang et al. 2015). Due to its high biodiversity and predicted threats to large losses of essential ecosystem services, the SBS has tremendous conservation opportunities (Tomascik et al. 1997). Therefore, understanding how mangrove biomass spatial patterns vary under different climatic scenarios provides critical information needed for managers to integrate future projections into mangrove conservation strategies.

[Insert Figure 1 about here]

In order to understand the spatial patterns of mangrove forests in different climate scenarios, methods were proposed based on (1) remote sensing and (2) spatial models. Satellite remote sensing has been successfully applied to mapping the extent of mangrove

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[1] According to FAO (http://www.fao.org/home/en), above-ground biomass (AGB) refers to all living biomass above the soil including stem, stump, branches, bark, seeds and foliage; below-ground biomass (BGB) refers to all living biomass of live roots.

forests at different scales (Jensen et al. 1991, Hirano, Madden, and Welch 2003, Giri et al. 2011). However, this can be problematic in tropic regions (like SBS), where dense clouds limit the performance of optical remote sensing. Although estimating mangrove forest biomass with data fusion from Synthetic-aperture Radar (SAR), very high resolution (VHR) imagery and Light Detection and Ranging (LiDAR) (Heumann 2011) can overcome the obstacles of optical remote sensing, those data are costly to acquire and the financial burden restricts their access to developing countries, such as Indonesia. Alternatively, estimating mangrove biomass can be modeled based on known existing mangrove distributions and output from climate change models. First, climatic model projections are based on inputs of temperature and precipitation data which are universally recognized, historically recorded and globally accessible. Historical evidence has shown that such data are the most self-evident factors representing the changing climate. Second, estimating mangrove biomass through climatic model is consistent with mangrove ecology because mangroves are ultimately limited by temperature, and at regional scales, variations in precipitation greatly determine their expanse and biomass (Alongi 2012). Third, climatic models based on temperature and precipitation are more cost-effective compared to remote sensing based models, thus such methods may be especially applicable to developing countries. Thus, it is easy to implement and customize across regions and scales.

Therefore, in this study, we expanded the climatic models in Hutchison et al. (2014) to estimate mangrove biomass in the SBS from the Last Inter-glacial Period (LIP; ~120,000 - 140,000 years BP) to current (1950 —2000), and future (2070) according to the Fifth Assessment of IPCC Report (Pachauri et al. 2014). The primary goal of this study is to setup a benchmark and broad estimates of mangrove biomass from the last inter-glacial period, current status and future scenarios using climatic data. We also aim to use these data to support understanding regional-scale effects from climate change on mangrove forests. Effective and efficient mangrove management requires regional monitoring of the extent, health and ecological functions of mangrove ecosystems. The implications of this study will help with informed mangrove conservation strategies by integrating future climate projections.

2. Materials and Methods

2.1 Climatic model and metrics

Current climatic information was acquired from the WorldClim Bioclim database at 30 arc-second (~1km) spatial resolution (www.worldclim.org). The database includes 19 climatic variables using monthly temperature and rainfall data sets from 1950 to 2000 through global geospatial sensor networks (Hijmans et al. 2005). Past climatic information was downscaled to the LIP (Otto-Bliesner et al. 2006) because widespread evidence of a 4 – 6 meter increment of sea-level rise during the LIP has led to warnings that present ice sheets will deteriorate owing to global warming – this may initiate a rise of similar magnitude by 2100 (Blanchon et al. 2009). Future climatic variables are derived from the GISS-E2-R model, provided by the Goddard Space Flight Center, National Aeronautics and Space Administration (NASA), U.S.A. This is one of the most recent global climate projections used in the Fifth Assessment IPCC report (Schmidt et al. 2012, Nazarenko 2013). The IPCC report contains global climate models for four representative concentration pathways (RCPs). RCPs are four greenhouse gas concentration trajectories. RCPs depend on the emission of greenhouse gases in future years, simulating four possible climate future scenarios. The four RCPs scenarios, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values, + 2.6, + 4.5, + 6.0, and + 8.5 W/m^2 respectively.

Mangrove above-ground biomass (AGB) and below-ground biomass (BGB) predication models (Equations 1 and 2) were adopted using the published model by Hutchison et al. (2014). Models were validated from peer-reviewed journal articles with meta-analyses:

1. $\text{AGB (t/ha)} = 0.295*X_1+0.658*X_2+0.234*X_3+0.195*X_4-120.3$
2. $\text{BGB (t/ha)} = 0.073*\text{AGB}^{1.32}$

For Equation 1, X_1 denotes mean temperature of warmest quarter, X_2 denotes mean temperature of coldest quarter (°C), X_3 denotes precipitation of wettest quarter (mm) and X_4 denotes precipitation of driest quarter (mm). In the current scenario, X_1 to X_4 are applied with values reflecting the current situation, in the LIP scenario, X_1 to X_4 are applied with those values in the LIP, as processed by Otto-Bliesner et al. (2006). In RCP 2.6, RCP 4.5, RCP 6.0 and the RCP 8.5 scenarios, X_1 to X_4 are applied with those values simulated according to (Schmidt et al. 2012) and Nazarenko (2013), respectively.

Biomass metrics were developed to improve the climatic modeling results. *Total Biomass* (TB, t/ha) was defined as AGB + BGB. The proportion between below-ground biomass and above-ground biomass (*Ratio*) was defined as BGB/AGB. To compare the biomass changes in the changing climate, δTB was defined as the TB in LIP or four RCPs in 2070, divided by the TB in the current stage.

In conjunction with using climatic information, groundtruthing measurements in six mangrove forests within East Sulawesi (05° 12’ - 06° 10’ S, 123° 20’ - 124° 39’ E), SBS were taken, and environmental variables were recorded, to estimate biomass. One of the surveyed mangrove forests, Sombano is land-locked and has limited tidal inundation, freshwater input and reaches only to the high-intertidal. The remaining five mangrove forests (Langira, Kaluku, One Onitu, Loho, and Gili) are fully emerged twice per day. Tree species basal areas within each forest were used to calculate mangrove tree biomass, using allometric equations (*see* Komiyama, Ong, and Poungparn (2008), Komiyama, Poungparn, and Kato (2005). This method is less intrusive and less destructive than regression methods (Kairo et al. 2009). We then measured environmental variables as proxies to determine tree-species dominance, within different mangrove forests within the SBS.

To determine the basal areas of each tree species, twenty-five 20 x 20 meter plots from each site were used. Diameter at breast height (DBH), or the circumference at breast height (CBH) of each tree was recorded using the equation πr^2 (where π = 3.142 x radius^2). The radius was calculated by dividing the circumference by π x 2, or by dividing the diameter by 2.

2.2 Mangrove distribution and data processing

Mangrove species distribution data were acquired from The International Union for Conservation of Nature (IUCN 2013). Mangrove species data are in ESRI shapefile format as polygons. ESRI ArcMap 10.1 was used to crop the global dataset into study area coordinates (0 ~ 13°S, 113°E ~135°E, See Figure 1), and polygons of 46 different mangrove species were dissolved to obtain the mangrove distribution map.

Six scenarios (LIP, Current and 4 RCPs of 2070) of climatic data were downloaded globally in raster (geotiff) format and cropped by the study area coordinates

(0 ~ 13°S, 113°E ~135°E). The extracted mangrove distribution map covers the ocean area. All climatic data are only available to land area, thus spatial extrapolation is required to match all the climatic models and metrics to develop the mangrove distribution map. A spatial extrapolation method, the spring metaphor, was used for the balance of accuracy and computational efficiency (D'Errico 2012). Along with spatial extrapolation, all climatic data, models and metrics were preprocessed using MATLAB® 2012a. Polynomial curve fitting was utilized to study the relationships between patterns of mangrove biomass-change and longitude.

The univariate and non-parametric multivariate techniques, PERMANOVA and distance-based linear modelling (DistLM) contained in the PRIMER 6 (Plymouth Routines in Multivariate Ecological Research) package were used to explore forest biomass. To investigate spatial patterns of biomass, each mangrove forest was grouped by overlaying data from Bray-Curtis matrices. DistLM was employed to verify relationships between emersion time, salinity and substratum type with mangrove forest biomass across each of the forests. *Note: reduced salinity was used as a proxy for rainfall, as freshwater flows in to the land-locked Sombano mangrove forest in the form of several streams. The most parsimonious model was identified using the Akaike information criterion (AIC). AIC ranks models from all possible combinations of the environmental variables. The DISTLM was based on abundance data with 4999 permutations.

3. Results

Generally, from LIP to the year of 2070, there is an estimated increase of mangrove biomass in the SBS. On average, *TB* in current stage is 9.4 t/ha greater than that in the LIP; TB in RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 7.3 t/ha, 12.1 t/ha, 11.7 t/ha and 17.8 t/ha greater than that in current stage, respectively. Shifts in distribution patterns associated with latitude in the LIP, current and future environmental conditions were found with all four RCPs (Figure 2). For example, in the four RCPs, the total biomass from 0° to 5°S decreases as much as 13%, while the total biomass at 5°S to 13°S increases as much as 38%.

Using mangrove tree basal area measurements in East Sulawesi to calculate biomass, the Sombano mangrove forest had the greatest estimates of biomass compared with all other mangrove forests within this study. Estimates ranged from 66.4 ± 0.3 t ha to 605.8 ± 0.1 t ha within the plots (PERMANOVA, $F_{5,78} = 24.4$, $p = < 0.001$). The remaining mangrove forests exposed to direct oceanic tidal inundation had comparatively low estimates of biomass, ranging from 7.8 ± 01 t ha to 111.2 ± 26.7 t ha (PERMANOVA pairwise tests, $P = < 0.001$).

Sombano mangrove biomass was strongly correlated with low salinity (DistLM test, $P = < 0.001$), 15.3 ± 0.7 psu. Several freshwater streams, from rainfall enters the Sombano mangrove, which greatly reduces the salinity concentration. The remaining forests are fully marine, open to the ocean, and those forests were correlated with reduced emersion (DistLM test, $P = < 0.001$ and PERMANOVA, $F_{1, 83} = 85.9$, $p = < 0.001$). Those forest were each exposed to direct tidal flow.

[Insert Figure 2 about here]

The global mangrove mean *Ratio* of 0.39 (Hutchison et al. 2014) was compared with those calculated from all six scenarios. The lowest *Ratio* in the current scenario of the SBS is 0.35, which is 25% greater than that for global tropical forests (Saatchi et al.

2011). On average, the *Ratio* is increased from LIP to RCP 8.5 (ANOVA, $P<0.001$, Figure 3). *Ratio* patterns were grouped according to latitude (Figure 4). Similar to the patterns with those found of the *TB*, the *Ratio* increases to the equator from the southern hemisphere for all of the six scenarios. In general, the current ratio is higher than those calculated for the LIP at all locations, except at 3°S and 6°S; but the ratios of RCPs are greater than those in the current, in all locations (paired t-test, $P = < 0.01$).

[Insert Figure 3 about here]

[Insert Figure 4 about here]

Overall, there is a slight increase of estimated mangrove biomass in the SBS in current scenario compared to the LIP scenario (Figure 5), with the average δTBLIP is 0.96. Unlike the patterns of total biomass which is associated with latitude, the pattern of δTBLIP has a strong positive correlation with longitude (Adjusted $R^2 = 0.98$, RMSE =0.01). Total biomass increases as longitude increases from 113°E to 130°E, but then decreases from 130°E to 135°E.

[Insert Figure 5 about here]

Moreover, there is a great increase of predicted mangrove biomass in the SBS in all four RCPs compared to current scenario (Figure 6). However, the predicted spatial variability of mangrove biomass becomes greater with increment of CO_2 availability (from RCP 2.6 to RCP 8.5). From RCP 2.6 to RCP 8.5, a more dispersed δTB was found: from 0.94- 1.08 in RCP 2.6 to 0.95-1.12 in RCP 4.5; then from 0.91- 1.12 in RCP 6.0 to 0.87-1.20 in RCP 8.5. When we aggregate the δTB by latitude, it decreases 2% - 6% from the equator to 4°S and increases 4% - 14% from 4°S to 13°S (Figure 7A). When we further aggregate the δTB by longitude (Figure 7B), the δTB of the four RCPs are highly fluctuated, ranging from 1.01 to 1.12.

[Insert Figure 6 about here]

[Insert Figure 7 about here]

4. Discussion

This paper used climatic models in conjunction with mangrove distribution maps to estimate a benchmark of mangrove biomass spatial patterns in the SBS from LIP to all four RCPs in the year of 2070. Our predicted mangrove biomass range in current scenario is consistent with Donato et al. (2011), where a range of carbon storage of 112–392 t/ha of mangrove forests was reported. Moreover, Figure 2 shows estimated mangrove biomass spatial patterns are associated with changes in latitude— as it approaches higher latitude from the equator, mangrove biomass gradually decreases, which is consistent with earlier studies (Twilley, Chen, and Hargis 1992, Giri et al. 2011). Our findings contribute to literatures and inform mangrove conservation strategies in the following three ways.

Our results firstly indicate total biomass of mangrove forests increased using a five models from LIP to current and then to all four RCPs in 2070 (Figure 2). Importantly, from RCP 2.6 to RCP 8.5 (with an increment of level of CO_2 concentration), there is an increasing trend of mangrove biomass accumulation. In Figure 6, especially in the RCP 8.5 scenario, projected mangrove biomass in some area of the SBS is as much as 1.38 times of that in current scenario. Vegetation sequestrates carbon and then gains its biomass, and mangroves are among the most carbon-rich tropical ecosystems (Alongi 2012). Given the increasing trend of mangrove biomass in the SBS in the future, these findings imply a huge potential that mangroves can serve as a critical role in future carbon sequestration and climate change mitigation. In practice, mangroves have been applied as major ecosystems for reforestation and restoration. In this case, we give conservation managers some more confidence to keep up with such strategies in the future.

However, an alarming fact is that estimate of global mangrove forest area is less than half since 1980, with the remaining forests under severe degradation (Spalding, Blasco, and Field 1997). As mangroves are carbon-rich tropical ecosystems, when disturbed, they will release equivalent to 2–10% of global deforestation emissions (Van der Werf et al. 2009). Noting that there is an increasing trend of projected mangrove biomass in the SBS, degradation of mangroves in the future will release more carbon emissions than they do today. The SBS is surrounded by highly populated land areas (Figure 1B), which increases its chance to be disturbed by human activities. Therefore, mangrove forests management should be well-organized. Otherwise, the increment of mangrove biomass—as a ‘gift’ from climate change—will be diminished, or even worse, totally destroyed by ill-regulated anthropogenic activities.

This study has also highlighted the importance of below-ground biomass (BGB) in mangrove forests in the SBS, as climate change can also potentially impose more below-ground biomass proportion (Figure 3). The lowest estimated BGB ratio in all six scenarios (Figure 3) an all locations (Figure 4) is greater than the average below-ground biomass proportion of global tropical forests (which is 0.26) (Saatchi et al. 2011). Mangroves have higher BGB to AGB biomass ratios than terrestrial trees, and allocate proportionally more carbon belowground. The fact that most mangrove carbon is stored as large pools in soil and dead roots is critical to understand the mitigation role of mangroves in carbon sequestration and climate change. However, it is often undervalued and neglected by mangrove resource management strategies, partly due to difficulties in measurement. As Alongi (2012) points out, standardization of methods used to measure biomass and soil carbon stock is required to facilitate mangrove resource studies and conservation practices. Our findings reemphasize the great proportion of BGB in mangrove forests and that proportion potentially increases as climate changes in the SBS, shedding light on future research and practices.

Thirdly, this study has revealed that changes of mangrove biomass exhibit great spatial variability. Change detection analysis showed that in the SBS, compared to current scenario, the greater the CO_2 concentration (from RCP 2.6 to RCP 8.5) is; the more dispersed the changes of total biomass will be (Figure 6 and Figure 7), which means areas with increasing trend of biomass may gain more while areas with decreasing trend of biomass may lose more. Moreover, there is also an increasing magnitude of biomass change from RCP 2.6 to RCP 8.5. An intuitive take-away here is that given the spatial variability of mangrove biomass patterns of the SBS in the context of climate change, there is not a single conservation strategy that can fit all situations. A coordinated systems for mangrove management and conservation priorities are needed, such as assigning mangrove forests within a reserve category (Alongi 2002) and managing mangrove forests under different biophysical regions (Wang et al. 2015). Moreover, finer scale data and measurements are required to better understand the spatial and temporal variations of mangrove biomass in this area.

5. Limitations and conclusion

Undoubtedly, this study has at least the following four limitations, which provides opportunities for future research. First, we applied a single mangrove distribution map to estimate mangrove biomass in all scenarios. While this approach set a benchmark for fair comparison, the actual distribution of mangrove forest won't remain the same from LIP to all four RCPs in the year of 2070. Therefore, remote sensing will facilitate measuring more accurate extent of mangrove forests. Second, in order to provide baselines, we simplified that climate change would pose the same effect to different mangrove species. Thirdly, we utilized temperature and precipitation to derive our climatic model; however, there are more factors contributing to the extent of mangrove biomass, such as sea level rise (He et al. 2007), natural hazards related to cyclones, lightening, tsunamis and floods (Smith et al. 1994). Fourthly, this research did not account for specific anthropogenic degradation of mangroves, as most mangrove forests have a history of both natural and human disturbances, and these two factors are often intertwined and indistinguishable.

To summarize, this paper utilized climatic models derived from temperature and precipitation metrics in conjunction with mangrove distribution maps to estimate a benchmark of mangrove biomass of the SBS in six scenarios, namely LIP, current and all four RCPs due to climate change. Our results revealed with climate change and increasing CO_2 concentration, mangroves gain more biomass in the SBS. It also highlighted the great proportion of below-ground biomass compared to above-ground-biomass in mangrove forests. Finally, it illustrated that climate change would impose a higher degree of spatial variability in mangrove biomass. As mangroves have been proposed as an essential component of climate change strategies such as REDD+ and blue carbon, this study can serve as a baseline for future studies and resource management strategies.

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Figures

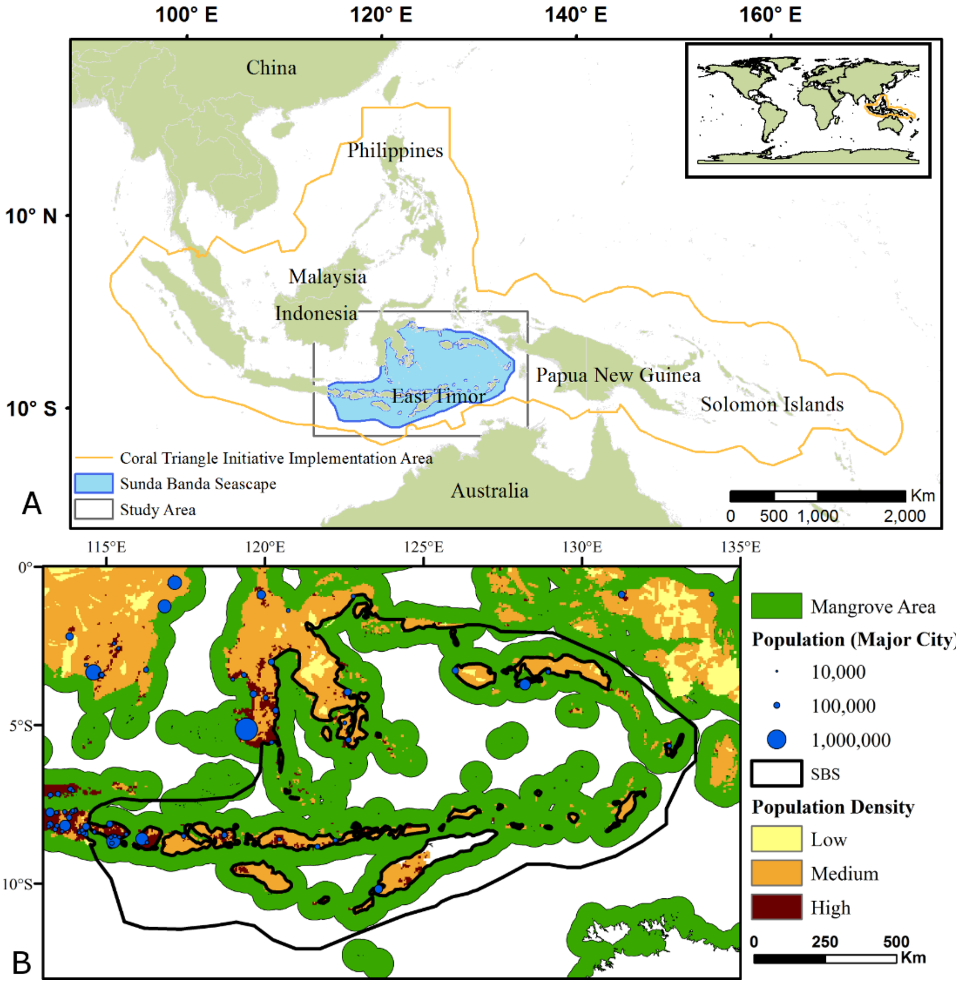

Figure 1. A) Geography of the Sunda Banda Seascape; B) Mangrove distribution overlaid with major city and population density of the Sunda Banda Seascape. Population information was obtained from Gridded Population of the World Version 3 (GPWv3) (CIESIN 2005) and Global Rural-Urban Mapping Project Version 1 (GRUMPv1) (CIESIN 2011).

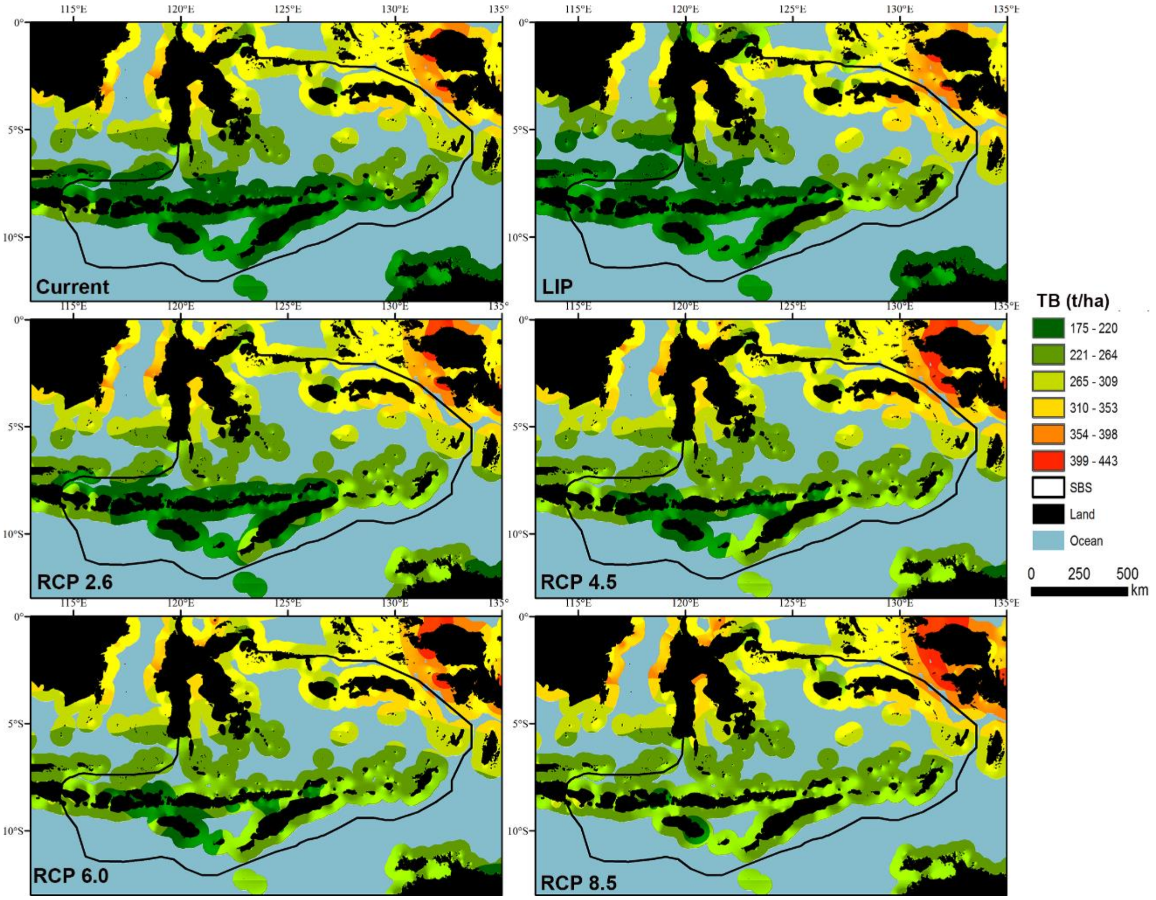

Figure 2. Climatic-modeled patterns of total biomass per unit area in the Last Inter-glacial Period (LIP), current stage (1950-2000) and in 2070. Categories of biomass volume, tons per hectare are designated using different colors.

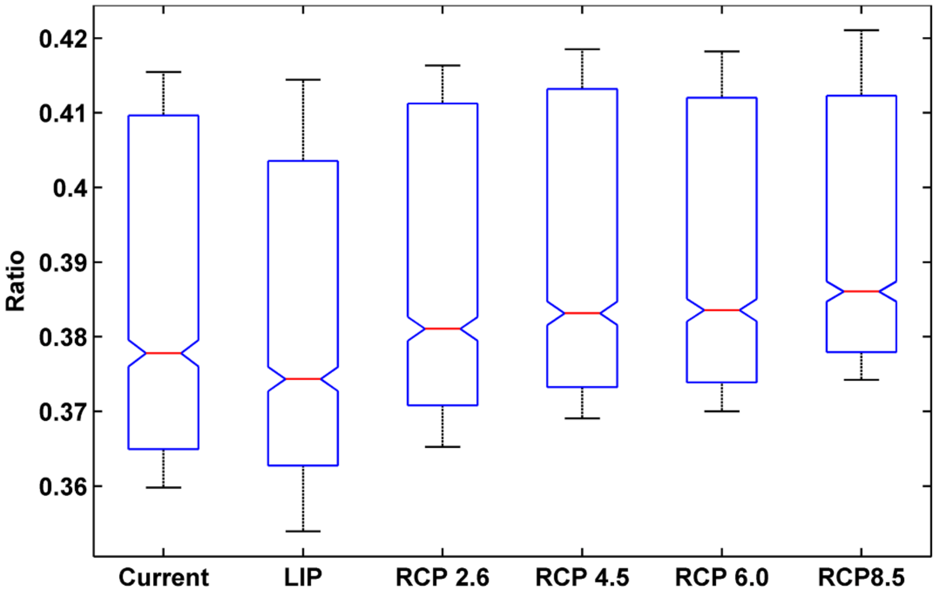

Figure 3. *Ratio* of below-ground biomass divided by above-ground biomass, for all six scenarios (P<0.001, the central mark is the median, the distal edges of the box are the 25th and 75th percentiles, the whiskers extend to the most maximum and minimum points).

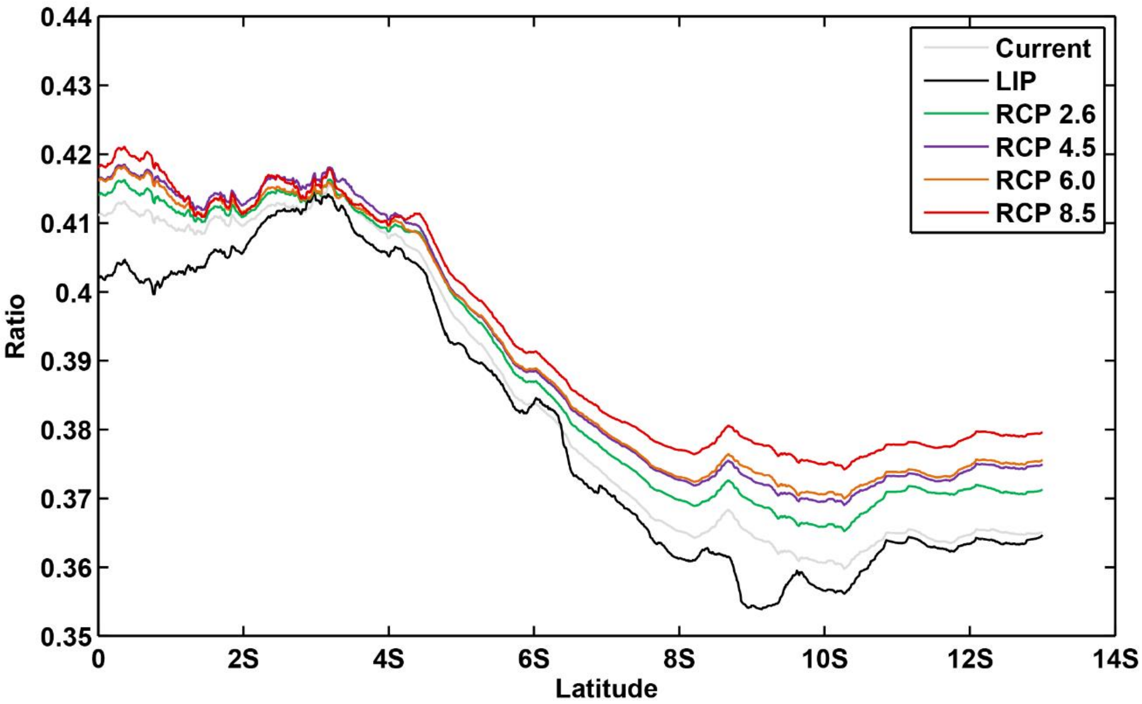

Figure 4. The *Ratio* (below-ground biomass divided by above-ground biomass) for all six scenarios (current stage, LIP, and all four RCPs in 2070).

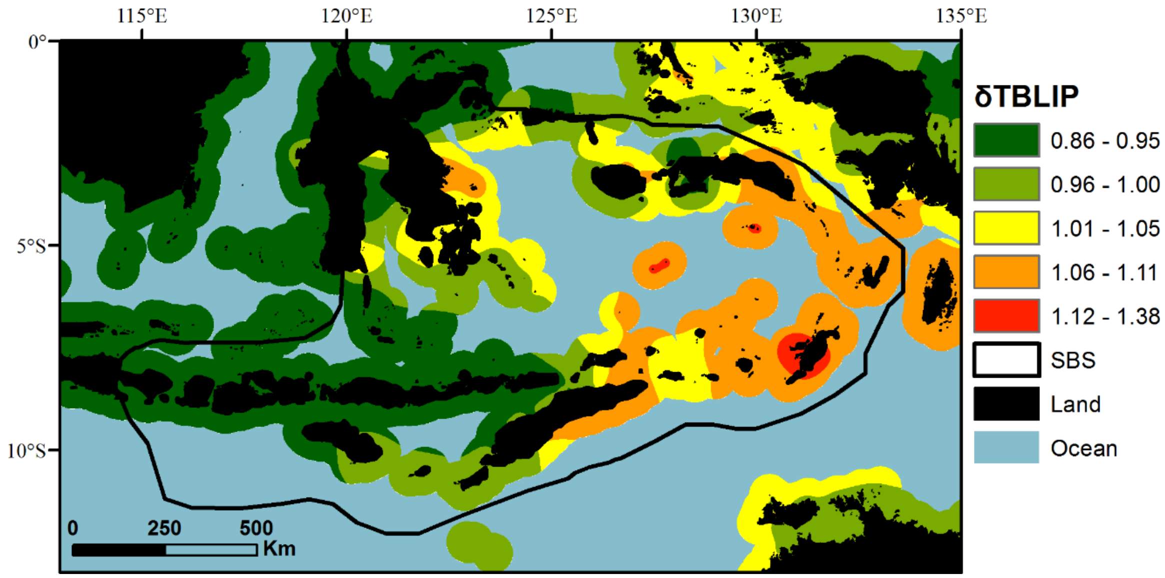

Figure 5. Total biomass change of Last Inter-glacial Period (LIP) compared to current condition (1950-2000). Categories of biomass volume, tons per hectare are designated using different colors.

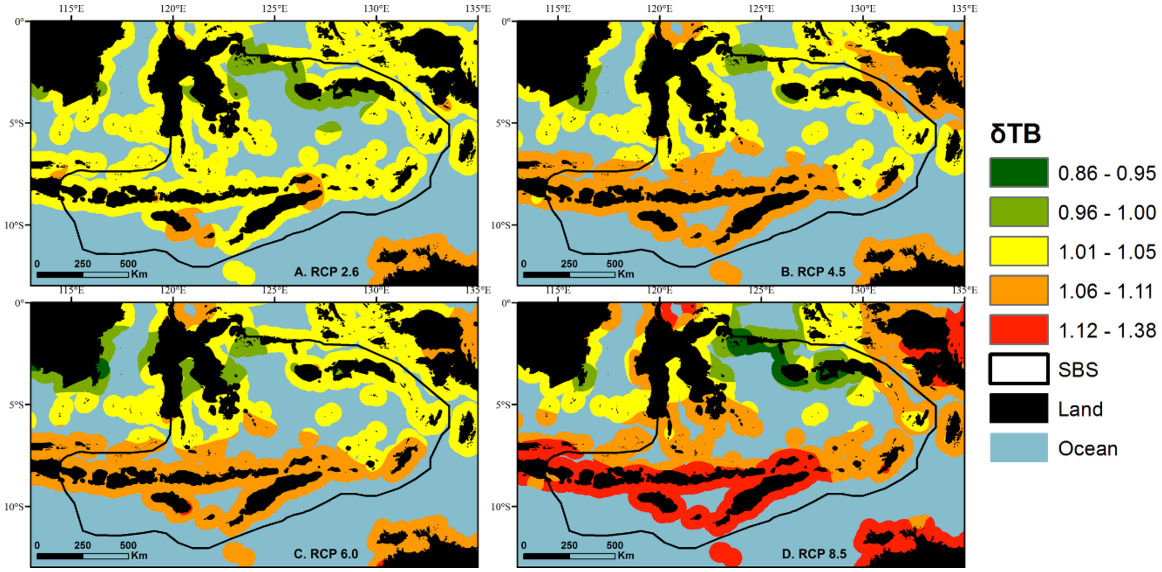

Figure 6. Total biomass change from simulated 2070 compared to current (1950-2000). (A): scenario of representative concentration pathway (RCP) 2.6; (B): RCP 4.5; (C): RCP 6.0 and (D): RCP 8.5. Categories of biomass volume, tons per hectare are designated using different colors.

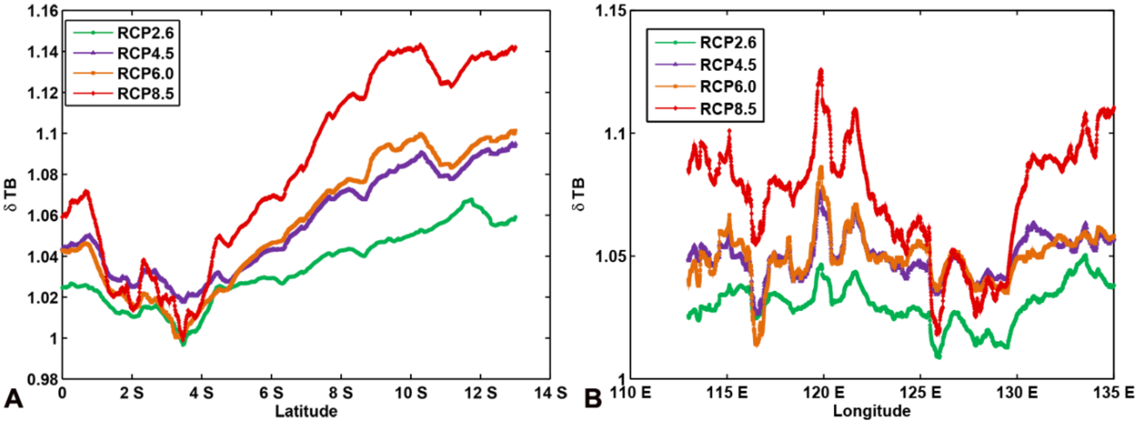

Figure 7. Latitude and longitude future trends of mangrove changes in biomass. (A): Latitudinal trends of total biomass change of all representative concentration pathways (RCPs) compared to current (1950-2000); (B): Longitudinal trends of total biomass change of all representative concentration pathways (RCPs) compared to current (1950-2000).

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