The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate

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ABSTRACT

Land use change is a major threat to biodiversity. One mechanism by which land use change influences biodiversity and ecological processes is through changes in the local climate. Here, the relationships between leaf area index and five climate variables – air temperature, relative humidity, vapour pressure deficit, specific humidity and soil temperature – are investigated across a range of land use types in Borneo, including primary tropical forest, logged forest and oil palm plantation. Strong correlations with the leaf area index are found for the mean daily maximum air and soil temperatures, the mean daily maximum vapour pressure deficit and the mean daily minimum relative humidity. Air beneath canopies with high leaf area index is cooler and has higher relative humidity during the day. Forest microclimate is also found to be less variable for sites with higher leaf area indices. Primary forest is found to be up to 2.5 °C cooler than logged forest and up to 6.5 °C cooler than oil palm plantations. Our results indicate that leaf area index is a useful parameter for predicting the effects of vegetation upon microclimate, which could be used to make small scale climate predictions based on remotely sensed data.

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1. Introduction

Microclimate influences a wide range of important ecological processes, such as plant growth and soil nutrient cycling (Bonan, 2008). Species can exploit fine-scale variations in climate (Suggitt et al., 2012) and models that incorporate these microclimatic variations are better at predicting population dynamics (Bennie et al., 2013). However, outputs from global and regional climate models generally have horizontal resolutions of 10–100 km, although higher resolution climate projections are becoming available (Platts et al., 2014). This mismatch between what influences organisms and what can be measured could potentially lead to inaccuracies when considering the ecological impacts of a changing climate. This is especially important in the habitat-heterogeneous tropical zone, where climate change effects may be felt earlier and

where the impacts on biodiversity are likely to be large (Deutsch et al., 2008; Tewksbury et al., 2008). Fine-scale heterogeneity in the future climate may provide microrefugia of tolerable climate that will help species to persist (Noss, 2001). Conversely, heterogeneity in present-day microclimate that is unaccounted for in models may mean that species have greater climatic tolerances than is currently thought (Logan et al., 2013).

Variability in climate on the micro-scale is driven by topography and vegetation cover. Topographical climate variations include effects due to elevation, cold air drainage, wind exposure, slope and aspect (Dobrowski, 2010). These physical processes are relatively well understood; however, running regional climate models at high enough resolutions to accurately simulate these effects is computationally expensive. Vegetation has long been known to modify the climate near the ground (Geiger, 1950). Recent work has shown that climate differences between different habitats can be on the same scale or larger than those projected to occur under climate change (Suggitt et al., 2011) and that canopy cover has a strong influence upon extreme climate conditions (Ashcroft and Gollan, 2012). In Southeast Asia, oil palm plantations have been measured to be

2.8 °C hotter and significantly less humid than nearby forest during the day (Luskin and Potts, 2011). However, a full understanding of the relationship between vegetation and microclimate is currently lacking, but is crucial for the development of microclimate models across heterogeneous landscapes.

There are three mechanistic reasons to expect strong relationships between vegetation structure and microclimate. First, plant canopies absorb, scatter and reflect incoming solar radiation, thus reducing the amount of energy that penetrates through to the soil and below-canopy air. The amount of solar radiation absorbed by a plant canopy depends on its leaf area index (LAI), here defined as one half of the total leaf surface area projected on the local horizontal datum (Chen and Black, 1992). Dense canopies, with high LAIs, can block over 95% of visible light from reaching the Earth's surface (Bonan, 2008), and this should keep the air and soil beneath the canopy cool during the day. In temperate forests, this effect plays a major role in protecting temperature sensitive species from the impacts of climate change (De Frenne et al., 2013). Second, plant canopies absorb momentum from the air and thus wind speed decreases with depth within the canopy (Garratt, 1992). Turbulent mixing of air is therefore suppressed by vegetation and denser canopies allow less mixing than sparse canopies. As the air at the top of the canopy heats up during the day, turbulent mixing acts to force some of this hot air down towards the ground, increasing the air temperature near the ground. Therefore, this effect acts in the same direction as the absorption of sunlight: a denser canopy should result in cooler air beneath the canopy. Finally, the amount of water vapour that air can hold is strongly dependent upon the air temperature. Therefore, in two environments with the same specific humidity (mass of water vapour per unit mass of air) but with different air temperatures, the hotter environment will have a lower relative humidity than the cooler environment. Additionally, transpiration within the forest will help to keep the air moist. In line with these expectations, previous studies have shown that air within a forest canopy has a higher relative humidity than air in nearby open areas (Chen et al., 1993; Williams-Linera et al., 1998).

LAI is a physical metric of vegetation structure that is relevant to the microclimatic processes described above. LAI is commonly measured in the field, using either destructive sampling or optical techniques such as hemispherical photography (Chen et al., 1997). In recent years, biophysical products providing continuous surfaces of LAI estimates derived from remotely sensed observations such as airborne lidar (Zhao and Popescu, 2009) or the MODIS Aqua and Terra satellites have been developed (Myneni et al., 2002). If strong patterns linking LAI to microclimate can be established then there is scope for downscaling of coarse resolution climate predictions based upon remotely measured LAI data, without microclimate data needing to be physically measured at a site. This could be extremely useful in developing high resolution climate models over a large domain.

Land use is an important modifier of LAI in forests and woody biomes (Aragão et al., 2005; Pfeifer et al., 2014). Here, we investigate the relationship between vegetation cover as described by LAI and microclimate across a range of habitats in Borneo, SE Asia. We take advantage of a pre-existing mosaic of LAI caused by a history of logging, deforestation and conversion to oil palm plantation (Ewers et al., 2011).

2. Methods

Data were collected at Kalabakan Forest Reserve (4°33′N, 117°16′E) and Maliau Basin Conservation Area (4°49′N, 116°54′E) as part of the Stability of Altered Forest Ecosystems (SAFE) Project (Ewers et al., 2011). The Kalabakan Forest Reserve has undergone multiple rounds of selective logging since 1978 and has a highly heterogeneous landscape. The habitats in the area range from open grasslands and scrub vegetation through to closed canopy forest. Some parts of the reserve have been converted to oil palm plantation, while other sections are currently in the process of being converted. By contrast, the Maliau Basin Conservation Area receives a high level of protection and as such contains large areas of primary forest that have never been logged.

We used a fractal sampling design to examine spatial variation in microclimate (Ewers et al., 2011; Marsh and Ewers, 2013) with up to 579 sampling points distributed between 17 sampling blocks (Fig. 1). Microclimate sensors were located at the vertices of an equilateral triangle with edges of 56 m (1st order sample sites), with that pattern repeated at distances of $10^{2.25}$ m (2nd order) and again at $10^{2.75}$ m (3rd order). All 3rd order sites were nested within 17 sampling blocks separated by >1 km. The sampling points were located across a gradient of land use that can be broadly split into three categories; old growth forest that has never been logged (OG), old growth forest that has been logged (LF), and oil palm plantations growing on previously forested land (OP). Sites were placed to minimise variation in altitude, with the mean altitude of all sample sites being 450 m (median = 460 m; interquartile range 72 m) (Ewers et al., 2011).

Above-ground climate variables were monitored using Hygrochron iButtons (Maxim Integrated Systems, temperature accuracy <±0.5 °C, RH accuracy <±5%) suspended at a height of 1.5 m at each of the first-order sampling points (N = 247). The sensors were shaded from direct solar radiation due to the presence of tall vegetation at all sites. Soil temperature data were collected using Thermochron iButtons (Maxim Integrated Systems, temperature accuracy <±0.5 °C) buried at a depth of 10 cm at each of the second-order sampling points (N = 140). All sensors were set to record instantaneous values of climate variables every 3 h, starting at midnight each day. Above ground climate data were collected over 242 consecutive days from 15/09/2011 to 13/05/2012, while soil temperature data were collected over 189 days from 26/10/11 to 01/05/2012.

Vertical climate profile data was collected using Hygrochron iButtons, with sensors placed at heights of 0.5, 1, 2, 5, 10, 15 and 20 m above the ground. As some sensors in this study were located at the top of the canopy, all sensors were suspended beneath shallow polystyrene lids, covered on their skyward side with aluminium foil, to shield them from direct solar radiation. Vertical profiles were collected at 10 locations along a 200 m transect in logged forest. Sensors were set to record the instantaneous air temperature and relative humidity every 3 h starting at midnight each day over a period of 128 consecutive days from 30/06/2013 to 04/11/2013.

LAI data was collected between August 2012 and January 2013. Seasonal variation in LAI was not accounted for, as its effect is expected to be small. Malhado et al. (2009) report no significant seasonal variation in LAI in an Amazonian tropical forest. Myneni et al. (2007) found significant seasonal variation in LAI in evergreen forests in the Amazon; however, this variation was closely associated with the annual cycle of rainfall. Meteorological records from nearby Danum Valley Field Centre, show that the climate in this part of Sabah is aseasonal, with occasional dry spells that are usually associated with El Niño events (Walsh and Newbery, 1999). Recent data from Danum Valley (SEARRP: http://www.searrp.org/danum-valley/the-conservation-area/climate) show that no dry months, defined as months in which total rainfall was less than 100 mm (Walsh and Newbery, 1999), occurred between September 2011 and January 2013, the period during which our data was collected. Therefore, significant changes in LAI are unlikely to have occurred during this time.

Values for LAI across 16 sampling blocks were derived from canopy photographs taken using digital cameras equipped with