LAND-USE TRAJECTORIES IN LOWLAND SUMATRA: IMPACTS ON LEAF AREA INDEX AND BELOW-CANOPY TEMPERATURES

Dissertation
zur Erlangung des akademischen Grades Doctor of Philosophy (PhD)
der Fakultät für Forstwissenschaften und Waldökologie
der Georg-August-Universität Göttingen

vorgelegt von
Pallavi
geboren in Yedthare - Karnataka, India

Göttingen, 2025

1. Gutachter: Prof. Dr. Dirk Hölscher
2. Gutachter: Prof. Dr. Bernhard Schuldt
3. Gutachter: Prof. Dr. Dominik Seidel

Tag der mündlichen Prüfung: 28.03.2025

TABLE OF CONTENTS

Abstract

Land-use change is widespread across the globe, leading to significant biodiversity loss and impairing ecosystem functions. The land-use trajectories from forest to agriculture contributes to increased surface and air temperatures, both in the upper layers of vegetated land and the areas below the canopy. Below the canopy environment is critical, where significant biodiversity thrives, essential ecosystem functions are regulated, and humans live and work. However, little is known about below-canopy temperature dynamics in the context of land-use change and ecosystem restoration. In our study we assessed the canopy leaf area index (LAI) and below-canopy surface temperatures in a rural lowland landscape in Sumatra, Indonesia – a region, known for its land-use changes over the past decades, has transitioned from forests to monoculture plantations. In the first study, we examined the impact of conventional land-use trajectories (forest to rubber and oil palm monocultures) on canopy leaf area index (LAI) and below-canopy surface temperatures. In the second study, we explored the potential to partially reverse these trajectories by integrating trees into oil palm monoculture. Further, we explore the potential role of rubber agroforestry, and discuss options for a healthier thermal rural environment.

Our first study tested the hypothesis that forest conversion to monocultures reduces LAI, leading to increased below-canopy surface temperatures. In the landscape assessment (EFForTS-LA), we measured LAI and below-canopy surface temperature across four land-use types: forest, shrubland, rubber, and oil palm - spanning 132 spatially well-distributed plots. We found that LAI varied more than tenfold, with the highest values observed in forests and the lowest in rubber and oil palm plantations. Below-canopy surface temperatures increased significantly as LAI decreased. A decrease in LAI by one unit (m^2 leaf area per m^2 ground area) increased ground surface temperature by 0.95 °C (confidence interval: 1.07 - 0.83 °C) around noon. Likewise, the temperatures measured on peoples' cap or hijab surfaces under the canopy was strongly affected. For a light-brown hijab, the average noon surface temperature increased by 4.0 °C from forest to oil palm. This study concluded that the land-use trajectories from forest to rubber and oil palm negatively impact on LAI and increased below-canopy temperatures.

Our second study tested the hypotheses a) Tree integration into oil palm plantations enhances LAI and thereby reduces below-canopy temperatures, b) Below-canopy temperatures decrease with increasing canopy LAI, stand structural complexity and observed woody diversity, and 3) Planted tree diversity and island area increase LAI and reduce below-canopy temperatures. In

oil palm monoculture, trees are integrated with varied planting diversity (0 - 6) and tree island area (25 m^2, 100 m^2, 400 m^2, 1600 m^2). This study was conducted nine years after tree planting in an experiment on biodiversity enrichment in lowland Sumatra (EFForTS-BEE). Data from forests and monoculture oil palm plantations from a larger-scale EFForTS-LA were used as a reference for the experiment. Compared to monoculture oil palm plantations in the landscape, tree integration (tree planting plus natural recruitment) in the experiment increased the canopy leaf area index by 0.8 $m^2 m^{-2}$ (27%) and reduced below-canopy surface temperature of the ground around noon by 1.5 °C. Similarly, the surface temperatures of workers' hijabs and black and white reference boards were notably reduced. In old-growth forests LAI was much higher and below-canopy temperatures were lower than in the tree integration experiment. On the experimental plots, tree planting plus natural recruitment was more effective in increasing LAI than natural recruitment alone. Mixed-effects models identified leaf area index as a key predictor of below-canopy surface temperatures, together with solar irradiance and time of the day. Other factors such as tree island area, observed tree diversity, and stand structural complexity, were less important. Our findings indicated that tree integration by planting and natural recruitment offers opportunities to curb high below-canopy temperatures in oil palm cultivation, and that leaf area index is a crucial factor therein.

In the synthesis of our study, we also examined LAI and below-canopy temperature dynamics within two types of rubber cultivation in the same landscape: rubber agroforests, often referred as jungle rubber, and conventional rubber monocultures. Our findings revealed that the average LAI in jungle rubber (4.5 $m^2 m^{-2}$) was nearly double that of rubber monocultures (2.3 $m^2 m^{-2}$). The average below-canopy ground surface temperature in rubber monoculture is significantly higher (1.99 °C) compared to jungle rubber. Surface temperature measurements of workers' caps and hijabs followed a similar trend, further underscoring the influence of canopy cover on local temperature conditions. Our study also showed that shrublands, jungle rubber, and tree-integrated oil palm plantations exhibited similar below-canopy ground surface temperatures. These temperatures were lower than those observed in oil palm and rubber monocultures but higher than in forests. This finding clearly demonstrates that the integration of trees effectively reduces below-canopy temperatures.

Considering rural thermal environment, the reduction of 1.5 °C around noon may seem modest in view of the increasing heat stress imposed on nature and humans, given the steep increase in global temperatures and the additional direct effects of land-use change on below-canopy surfaces. However, for nature and people exposed to heat and its adverse effects on health, tree integration appears as a potential way to mitigate such effects.

Overall, in addition to climate warming, land transformation and associated declines in canopy leaf area index significantly increase below-canopy surface temperatures. Mitigation strategies to address these adverse temperature effects include integrating a higher density of trees and incorporating species with dense foliage into landscapes. We conclude that planting native tree species within monoculture plantations offers an opportunity to partially reverse the rising temperature and support ecosystem restoration in dynamic mosaic landscapes.

Zusammenfassung

Landnutzungsänderungen von Wald zu landwirtschaftlichen Flächen sind weltweit weit verbreitet und führen zu einem erheblichen Verlust an Biodiversität und beeinträchtigen Ökosystemfunktionen. Die Landnutzungsänderungen vom Wald zur Landwirtschaft tragen zu erhöhten Oberflächen- und Lufttemperaturen bei, sowohl in den oberen Schichten der Vegetation als auch in den Bereichen unterhalb des Kronendachs. Die Temperaturen unterhalb des Kronendachs sind von großer Bedeutung, da hier eine bedeutende Artenvielfalt vorkommt, wesentliche Ökosystemfunktionen reguliert werden, und Menschen leben und arbeiten. Über die Temperaturdynamik unterhalb des Kronendachs im Zusammenhang mit Landnutzungsänderungen und der Wiederherstellung von Ökosystemen ist jedoch wenig bekannt. In unserer Studie haben wir den Kronendach-Blattflächenindex (LAI) und die Oberflächentemperaturen unterhalb des Kronendachs in einer ländlichen Region im Tiefland von Sumatra, Indonesien, untersucht – eine Region, die für ihre Landnutzungsänderungen in den letzten Jahrzehnten bekannt ist und von Wäldern zu Monokulturplantagen führte. In der ersten Studie untersuchten wir die Auswirkungen konventioneller Landnutzungsverläufe (Wald zu Kautschuk- und Ölpalmenmonokulturen) auf den Kronendach-Blattflächenindex (LAI) und die Oberflächentemperaturen unterhalb des Kronendachs. In der zweiten Studie untersuchten wir das Potenzial diese Entwicklungen teilweise umzukehren; Bäume wurden in den Ölpalmanbau integriert. Darüber hinaus untersuchten wir die mögliche Rolle der Kautschuk-Agroforstwirtschaft und diskutieren Optionen für eine gesündere thermische ländliche Umgebung.

Unsere erste Studie prüfte die Hypothese, dass die Umwandlung von Wäldern in Monokulturen den LAI verringert, was zu höheren Temperaturen unter der Baumkronenoberfläche führt. Bei diese Studie auf Landschaftsebene im EFForTS-Projekt (EFForTS-LA) haben wir den LAI und die Temperaturen unter der Baumkrone in vier Landnutzungstypen gemessen: Wald, Buschland, Kautschuk und Ölpalme – und das auf 132 räumlich gut verteilten Plots. Wir fanden heraus, dass der LAI mehr als den Faktor 10 variierte, wobei die höchsten Werte in Wäldern und die niedrigsten in Kautschuk- und Ölpalmenplantagen beobachtet wurden. Die Temperaturen unter der Baumkronenoberfläche stiegen mit abnehmendem LAI deutlich an. Ein Rückgang des LAI um eine Einheit (m^2 Blattfläche pro m^2 Bodenfläche) erhöhte die Bodenoberflächentemperatur um die Mittagszeit um 0,95 °C (Vertrauensintervall: 1,07 - 0,83 °C). Ebenso wurden die Temperaturen, die auf den Oberflächen von Kopfbedeckungen oder

Hijabs unter dem Blätterdach gemessen wurden, stark beeinflusst. Bei einer hellbraunen Hijab stieg die durchschnittliche Oberflächentemperatur mittags von Wald zu Ölpalme um 4,0 °C. Diese Studie kam zu dem Schluss, dass die Landnutzungsverläufe vom Wald zum Kautschuk- und Ölpalmenanbau einen negativen Einfluss auf den LAI und die Erhöhung der Temperaturen unter den Baumkronen haben.

Unsere zweite Studie prüfte die Hypothesen: a) Die Integration von Bäumen in Ölpalmenplantagen erhöht den LAI und reduziert dadurch die Temperaturen unter dem Kronendach, b) Die Temperaturen unter dem Kronendach sinken mit zunehmendem LAI im Kronendach, struktureller Komplexität des Bestandes und beobachteter Gehölzvielfalt, und c) Die Vielfalt gepflanzter Bäume und die Inselfläche erhöhen den LAI und reduzieren die Temperaturen unter dem Kronendach. In Ölpalmenmonokulturen wurden Bäume mit unterschiedlicher Artenvielfalt (0 - 6) und Bauminselfläche (25 m^2, 100 m^2, 400 m^2, 1600 m^2) integriert. Diese Studie wurde neun Jahre nach der Baumpflanzung in einem Experiment zur Bereicherung der Artenvielfalt (EFForTS-BEE) im Tiefland von Sumatra durchgeführt. Daten aus Wäldern und Monokultur-Ölpalmenplantagen aus einem groß angelegten EFForTS-LA wurden als Referenz für das Experiment verwendet. Im Vergleich zu Monokultur-Ölpalmenplantagen in der Landschaft erhöhte die Baumintegration (Baumpflanzung plus natürliche Verjüngung) im Experiment den Kronendach-Blattflächenindex um 0,8 m^2 m^{-2} (27 %) und reduzierte die Oberflächentemperatur des Bodens unter dem Kronendach um 1,5 °C um die Mittagszeit. Ebenso wurden die Oberflächentemperaturen der Hijabs der Arbeiterinnen und der schwarz-weißen Referenztafeln deutlich reduziert. In Naturwäldern war der LAI allerdings viel höher und die Temperaturen unter der Baumkrone niedriger als im Baumintegrationsexperiment. Auf den Versuchsflächen waren das Pflanzen von Bäumen und die natürliche Verjüngung in Kombination wirksamer bei der Steigerung des LAI als die natürliche Verjüngung alleine. Gemischte Effektmodelle identifizierten den Blattflächenindex als Schlüsselfaktor für die Temperatur unter der Baumkrone, zusammen mit der Sonneneinstrahlung und der Tageszeit. Andere Faktoren wie die Bauminselfläche, die beobachtete Baumartenvielfalt und die strukturelle Komplexität des Bestandes waren weniger wichtig. Unsere Ergebnisse zeigten, dass die Baumintegration durch Pflanzen und natürliche Verjüngung Möglichkeiten bietet, die hohen Temperaturen unter der Baumkrone beim Ölpalmenanbau einzudämmen, und dass der Blattflächenindex dabei ein entscheidender Faktor ist.

Im Weiteren untersuchten wir auch den LAI und die Temperaturdynamik unter der Baumkrone in zwei Arten des Kautschukanbaus: Kautschuk-Agroforste (Jungle Rubber) und konventionelle Kautschuk-Monokulturen. Unsere Ergebnisse zeigten, dass die durchschnittliche LAI im Jungle Rubber (4,5 m^2 m^{-2}) fast doppelt so hoch war wie in Kautschuk-Monokulturen (2,3 m^2 m^{-2}). Die durchschnittliche Bodenoberflächentemperatur unter der Baumkrone waren in Kautschuk-Monokulturen deutlich höher (1,99 °C) als im Jungle Rubber. Oberflächentemperaturmessungen von Arbeitermützen und Hijabs folgten einem ähnlichen Trend, was den Einfluss der Baumkronenbedeckung auf die lokalen Temperaturbedingungen weiter unterstreicht. Unsere Studie zeigte auch, dass Buschland, Jungle Rubber und baumintegrierte Ölpalmenplantagen ähnliche Bodenoberflächentemperaturen unter der Baumkrone aufwiesen. Diese Temperaturen waren niedriger als die in Ölpalmen- und Kautschuk-Monokulturen beobachteten, aber höher als in Wäldern. Dieses Ergebnis zeigt deutlich, dass die Integration von Bäumen die Temperaturen unter der Baumkrone effektiv senkt.

In Anbetracht der zunehmenden Hitzebelastung von Natur und Mensch, die durch den starken Anstieg der globalen Temperaturen und die zusätzlichen direkten Auswirkungen der Landnutzungsänderungen auf die Oberflächen unterhalb der Baumkronen entsteht, mag die Verringerung der Mittagstemperatur um 1,5 °C bescheiden erscheinen. Für Natur und Menschen, die der Hitze und ihren negativen Auswirkungen auf die Gesundheit ausgesetzt sind, erweist sich die Integration von Bäumen jedoch als eine mögliche Möglichkeit, diese Auswirkungen abzumildern.

Insgesamt führten Landnutzungsänderungen von Wald zu Kautschuk- und Ölpalmplantagen und die damit verbundene Abnahme des LAI im Kronendach zu einem deutlichen Anstieg der Oberflächentemperaturen unterhalb des Kronendachs. Die Integration von dicht belaubten Bäumen hat sich als eine Strategie zur Abschwächung dieser nachteiligen Temperatureffekte erwiesen. Die Integration von Bäumen in diese Monokulturen bietet eine vielversprechende Möglichkeit, den Temperaturanstieg abzumildern.

Chapter 1
Introduction

Introduction

1.1 Background

Tropical forests harbor enormous biodiversity, regulate biogeochemical cycles and environmental processes, maintain ecosystem balance, and contribute significantly to various ecological functions (Malhi et al., 2022; Pillay et al., 2022; Chen and Xu, 2010). Human activities are increasingly dismantling the Earth's ecosystems. As society's needs grow over time, they exert tremendous pressure on forests and other natural resources. This pressure leads to deforestation, land-use changes, emissions, and pollution. The conversion of intact forests into other land uses, such as agriculture, plantations, or infrastructure development, results in habitat loss, biodiversity decline, and increased carbon emissions (Sharma et al., 2018; Jantz et al., 2015). Agricultural expansion and monoculture plantation results in soil nutrient depletion, soil erosion, water pollution through herbicide and pesticide applications (Liu et al., 2018; Wang et al., 2020; Shete et al., 2016). Additionally, it has socio-economic impacts by creating economic disparities among communities, local landholders, and companies; which are often unevenly distributed. In 2020, forest land covered 31.2% and agricultural land covered 36.5% of the world's total land area. Both forest (32.0%) and agricultural land (37.5%) showed slight reductions compared to 2000. Despite contributing a large share of global forest area, many tropical countries continue to experience significant forest loss. For example, Brazil lost 54 million hectares of forest between 2000 and 2020, the highest loss among all countries (FAO, 2022). This forest degradation, coupled with agricultural expansion, significantly contributes to greenhouse gas emissions and climate change (Kirschbaum et al., 2013; Pendrill et al., 2019).

Global warming and climate change pose significant challenges to ecosystem, biodiversity as well as human societies. Intergovernmental parties have committed to limiting the rise in global average temperature to 1.5 °C, as outlined by the IPCC (2023). However, the world continues to warm, already exceeded the 1.5 °C above the pre-industrial level. The year 2024 was the warmest on record, with 1.60 °C increase in global temperature since records began in 1850 (Climate.copernicus.eu). In addition to climate change, land-use changes also contribute to rising temperatures. Mean warming caused by land cover changes may account for up to 18% of the current global warming trend (Alkama and Cescatti, 2016). Particularly in tropical regions, forest loss increases local and non-local daily temperatures and temperature extremes (McAlpine et al., 2018; Cohn et al., 2019). Tropical forest tree canopies are approaching critical temperature thresholds (Doughty et al., 2023). Converting forests into plantations or agricultural land reduces canopy cover and increases local ambient temperatures, impair water recycling, adverse impact on soil and microorganism (Hardwick et al., 2015; Keys et al., 2024; Wang et al., 2021). Extensive land-cover and land-use changes further threaten remaining ecosystems and amplify climate-induced temperature rises on local and regional scales, often leading to unfavourable habitat conditions and adverse health impacts for many organisms, including humans (Chandrashekhar 2023; Määttänen et al. 2023; Scherer et al., 2023; Sun et al., 2023; IPCC 2023).

Land surface temperatures and air temperatures have been the primary focus of studies investigating the effects of climate change and land-use change on both global and regional scales (Bento et al., 2020; Merga et al., 2022). A pantropical study showed that the average microclimatic air temperature in forest is 1.6 °C cooler than open air temperature and the diurnal temperature range inside the forest is 1.7 °C lower compared to open air (Ismaeel et al., 2024). This variability is regulated by large-scale climate condition, vegetation structure and topography. However, very little is known about microclimatic temperatures, particularly below-canopy surface temperatures.

Efforts are being made worldwide to restore degraded forests and fallow lands by planting trees (Mangueira et al., 2019; Aerts and Honnay, 2011). Global greening has received unparalleled focus in recent decades. Numerous researches are focused on afforestation, reforestation, and community-based conservation across the globe (Aerts and Honnay, 2011; Buechel et al., 2024; Haseeb et al., 2024; Kemppinen et al., 2020; Le et al., 2012). Similarly, agroforestry is endorsed as nature based solution to ameliorate the negative effect of climate change (Terasaki Hart et al., 2023; Quandt et al., 2023; Gomes et al., 2020). A remote sensing-based vegetation greenness study by Chen et al. (2024) found that global greening continued during 2001-2020. A positive greening acceleration was observed in 55.15% of the globe, while negative browning acceleration detected in only 7.28%. A study by Zhu et al. (2016) also showed persisted increase in greening is over 25% to 50% of the global vegetated area, whereas < 4% of the globe shows browning. However, in the current UN decade of ecosystem restoration, there remains a critical gap regarding effectively balancing economic needs with maintaining key ecological functions and curbing rising temperatures.

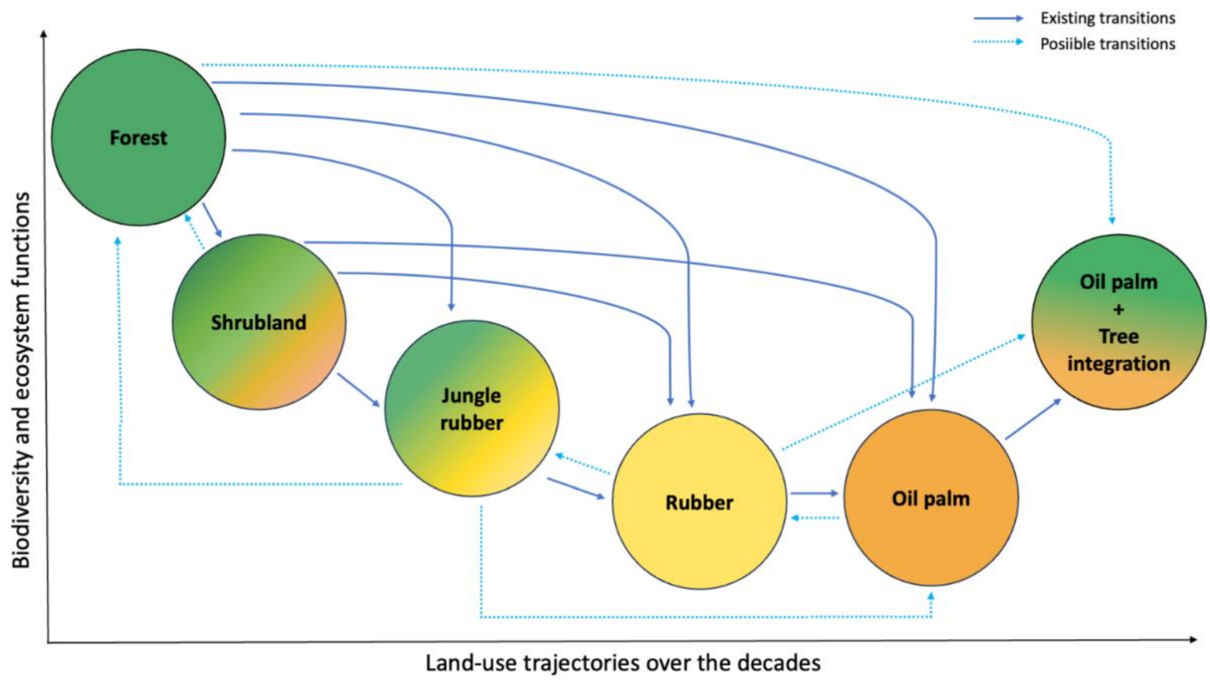


Fig.1.1 Schematic representation of land-use trajectories at landscape level in the lowland Sumatra. Position of the different land-use types on the y-axis indicates the amount of biodiversity and ecosystem functions these land-use types supports. Solid dark-blue arrows show transitions that already been seen and ongoing in the landscape. The light-blue dotted arrows indicate a possible transition. Tree integration into oil palm (upper right circle) are a special landscape element established within oil palm monoculture.

Forest conversion into agriculture and monoculture plantation is pantropical. One classic example is massive conversion of rain forest into plantations in Indonesia (Lee et al., 2014; Prabowo et al., 2017). In Indonesia, over the 50 years government has been releasing commercial logging concessions and supporting transmigration schemes (1098s and 1990s) from densely populated areas into less inhabited islands like Sumatra to improve the economic development, played an instrumental role in spread of oil palm in Jambi (Gatto et al., 2015). Over the time by 2013, only 30% of rainforest of the province remained mainly in mountains and protected areas. Almost 55% of the land accounted for agricultural area, with 10% of degraded or fallow land waiting for monoculture conversion. Rubber *(Hevea brasiliensis)* and oil palm (*Elaeis guineensis*) are two species were largely cultivated in Indonesia by the colonizer and continued to expand. The large-scale expansions are by big companies and small holders have small illegal land acquisition of forest to expand or new plantation (Lee et al., 2014) . Forest conversion to other land uses in lowland Sumatra has resulted in the loss of biodiversity and ecosystem functions (Fig. 1). Such land-use changes may influence, and most likely increase, below-canopy surface temperatures (Pallavi et al., 2024), although the extent of this change remains unknown.

Oil palm and rubber are usually grown in monocultures (Azhar et al., 2017; Niu et al., 2017). such plantations negatively impact on biodiversity, severely impair ecosystem function and degrad local environment (Foster et al., 2011; Drescher et al., 2016; Barnes et al., 2014; Dislich et al., 2017). Conversion of forests into oil palm monoculture has resulted in profitability gains for land owners that led to a significant reduction in biodiversity (Grass et al., 2020), diminished carbon storage (Guillaume et al., 2018), increased soil compaction, degradation and erosion (Guillaume et al., 2015) and the loss of hydrological buffering against floods and droughts (Merten et al. 2017), among other adverse effects (Dislich et al. 2017; Cardinale et al. 2012; Edwards et al. 2014; Foster et al. 2011). It was also reported that forest conversion to oil palm results in elevated land-surface temperatures (Lawrence et al., 2022; Sabajo et al., 2017), increased local and regional temperature. Forests were up to 2.2 °C cooler than oil palm and rubber plantation (Meijide et al., 2018). A study from Borneo showed that primary forest is 6.5 °C cooler than oil palm plantation (Hardwick et al., 2015). Conversion leads to soil degradation, invasion of alien species, microbial diversity loss (Guillaume et al., 2016; Widyati et al., 2022; Rembold et al., 2017; Singh et al., 2019). For an oil palm agroforest, an influence of stand structural complexity on land-surface temperatures and microclimate was reported (Donfack et al., 2021).

Several studies have explored biodiversity, temperature, humidity, soil health, tree growth, and productivity, stand structure and meteorological aspects like microclimatic temperature, land surface temperature, hydrological parameters to better understand the impact of land-use trajectories (Rembold et al., 2017; Donfack et al., 2021; Niu et al., 2017). However, a research gap exists in understanding below-canopy surface temperature and its relationship with leaf area index. Monoculture plantations often have single layered canopy and have fixed spacing between plant to plant and row to row. It creates considerable gaps in canopy and allow large amount of solar radiation to reach below-canopy surface. Also, the transpirational cooling effect of canopy restrict to the canopy layer, but the effect of cooling below the canopy or in vertical column of space is less. Below canopy surface temperature is mainly regulated by canopy structure under the ongoing meteorological conditions at given time and place (Cheung et al., 2021). The amount of light mediated through the canopy to the ground surface largely depends on canopy foliage and canopy structure, which is characterized as leaf area index (LAI)(Unger et al., 2013; Pfeifer et al., 2018).

Leaf area is a key biophysical parameter, act as interface between vegetation and atmosphere (Cohen et al., 2003; Fournier et al., 2003; Turner et al., 1999), controls radiation and thermal conditions within the canopy (Fournier et al., 2003) and closely connected to critical processes such as evapotranspiration, respirations, photosynthesis, biogeochemical cycles, and it is essential to the climate system (Brown et al., 2017; Qiao et al., 2020; Fang et al., 2019; Tian et al., 2017). Plant canopies are dependent on species composition, microclimatic conditions, nutrient dynamics, management activities (Parker, 2020). As a core parameter, LAI connects canopy structure to ecosystem function, making it essential for assessing the impact of global environment changes on forest (Khairiah et al., 2017). Despite its vital role, there is not much is investigated about variation in LAI across different land use types at landscape scale in tropical region, this may be due to the challenges in measurement. There is no study on below canopy surface temperature across the land use types, which is predominantly influenced by LAI under the existing meteorological conditions. Also, the canopy attributes and composition generally moderates temperature below the canopy and thus creates microclimate (Von Arx et al., 2012, Zellweger et al., 2019). This energy exchange can impact both surface and air temperature, changes in one affects the other. Below canopy ground surface temperature is strongly influenced by factors such as background air temperature, relative humidity, radiant temperature, and shortwave radiation (Cheung et al., 2021). Despite the fact that many organisms thrive in the subcanopy and on the ground, challenges in estimating below-canopy surface temperatures often being unstudied or undervalued. These temperatures, along with human experiences of heat, can also be influenced by factors such as humidity, wind speed, and evapotranspiration.

1.2 EFForTS project

Lowland Sumatra is a highly dynamic landscape that has experienced forest conversion into rubber and oil palm monocultures over several decades. In this landscape, the EFForTS (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems) project has been investigating various aspects since 2012. EFForTS project aimed to generate science-based knowledge to safeguard and optimize the ecological functions of tropical forests and agriculturally transformed system at a landscape scale, while improving human well-being. Further, the initiative focuses on developing and implementing nature-based solution to address conservation challenges through integrated approaches to agricultural land use. The research is conducted within Jambi Province, Sumatra, encompassing two landscapes and 32 core sites which include transformation system and forests serving as reference sites. The project operated in three different phases, Phase 1 focused on Differences in ecological and socioeconomic functions of land-use changes due to rainforest transformation into rubber and oil palm plantations in Indonesia. Phase 2 focused on Heterogeneity as a new umbrella theme and, phase 3 extends the investigation of heterogeneity in space and time by focusing on the theme from heterogeneity towards sustainable landscapes, this investigated heterogeneity at the i) landscape level (EFForTS-LA) with the establishment of spatially well distributed 100 new plots, ii) in biodiversity enrichment experiment (EFForTS-BEE) and iii) in management of oil palm management (EFForTS-OPMX).

The EFForTS project systematically analyses and compares a wide array of factors associated with rainforest transformation, encompassing above- and below-ground biodiversity, soil fertility, water dynamics, nutrient cycling, greenhouse gas fluxes, and the economic, social, cultural, and political dimensions. Particular emphasis is placed on identifying synergies and trade-offs among and between ecological and socioeconomic functions, which are critical prerequisites for the development and implementation of more sustainable land-use systems (For more details of the project and findings please refer to https://www.uni-goettingen.de/en/science/412128.html). However, there is a knowledge gap regarding below-canopy surface temperatures and the factors that influence them. Understanding below-canopy surface temperatures is crucial, as many organisms, including humans, live beneath the canopy, and several geochemical cycles are regulated there.

1.3 Research objectives and hypotheses

In our study, we conducted a landscape-level assessment (EFForTS-LA) comprising 132 spatially well-distributed plots across the lowland landscapes of Sumatra. These plots represented various land-use types, including forests, shrublands, oil palm plantations, and rubber plantations (see study location in Chapter 2). Additionally, we investigated the Biodiversity Enrichment Experiment (EFForTS-BEE), a novel approach within the project. This experiment involved planting tree species with varying diversity (0 -6) and tree islands with different sizes (25 m^2, 100 m^2, 400 m^2, 1600 m^2) within oil palm plantations, using a randomized partition design (see Chapter 3).

In both studies, we examined below-canopy surface temperature and leaf area index under existing meteorological conditions. The overarching objectives were to understand the impact of land-use trajectories on leaf area index and below-canopy temperatures, as well as to evaluate the potential of tree integration in mitigating the adverse effects of land-use trajectories.

The following hypotheses were tested in Chapters 2 and 3.

Chapter 2

- Land-use trajectory from forest to oil palm and rubber reduces leaf area index (LAI) and increases below-canopy surface temperatures.
- Below-canopy surface temperatures can be predicted by LAI.
- Farm workers experience heat stress under reduced canopy cover.

Chapter 3

- Tree integration into oil palm plantations enhances LAI and thereby reduces below-canopy temperatures.
- Below-canopy temperatures decrease with increasing canopy LAI, stand structural complexity, and observed woody diversity.
- Planted tree diversity and island area increase LAI and reduce below-canopy temperatures.

1.4 Reference

Aerts, R., Honnay, O., 2011. Forest restoration, biodiversity and ecosystem functioning. BMC Ecol 11, 29. https://doi.org/10.1186/1472-6785-11-29

Alkama, R., Cescatti, A., 2016. Biophysical climate impacts of recent changes in global forest cover. Science 351, 600–604. https://doi.org/10.1126/science.aac8083

Azhar, B., Saadun, N., Prideaux, M., Lindenmayer, D.B., 2017. The global palm oil sector must change to save biodiversity and improve food security in the tropics. Journal of Environmental Management 203, 457–466. https://doi.org/10.1016/j.jenvman.2017.08.021

Barnes, A.D., Jochum, M., Mumme, S., Haneda, N.F., Farajallah, A., Widarto, T.H., Brose, U., 2014. Consequences of tropical land use for multitrophic biodiversity and ecosystem functioning. Nat Commun 5, 5351. https://doi.org/10.1038/ncomms6351

Bento, V.A., Gouveia, C.M., DaCamara, C.C., Libonati, R., Trigo, I.F., 2020. The roles of NDVI and Land Surface Temperature when using the Vegetation Health Index over dry regions. Global and Planetary Change 190, 103198. https://doi.org/10.1016/j.gloplacha.2020.103198

Brown, L.A., Dash, J., Ogutu, B.O., Richardson, A.D., 2017. On the relationship between continuous measures of canopy greenness derived using near-surface remote sensing and satellite-derived vegetation products. Agricultural and Forest Meteorology 247, 280–292. https://doi.org/10.1016/j.agrformet.2017.08.012

Buechel, M., Slater, L., Dadson, S., 2024. Broadleaf afforestation impacts on terrestrial hydrology insignificant compared to climate change in Great Britain. Hydrol. Earth Syst. Sci. 28, 2081–2105. https://doi.org/10.5194/hess-28-2081-2024

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. Nature 486, 59–67. https://doi.org/10.1038/nature11148

Chandrashekhar, V., 2023. Heat-proofing India. Science 381, 1393–1397. https://doi.org/10.1126/science.adl0416

Chen, C., Xu, Z., 2010. Forest ecosystem responses to environmental changes: the key regulatory role of biogeochemical cycling. J Soils Sediments 10, 210–214. https://doi.org/10.1007/s11368-009-0164-z

Chen, X., Chen, T., He, B., Liu, S., Zhou, S., Shi, T., 2024. The global greening continues despite increased drought stress since 2000. Global Ecology and Conservation 49, e02791. https://doi.org/10.1016/j.gecco.2023.e02791

Cheung, P.K., Jim, C.Y., Hung, P.L., 2021a. Preliminary study on the temperature relationship at remotely-sensed tree canopy and below-canopy air and ground surface. Building and Environment 204, 108169. https://doi.org/10.1016/j.buildenv.2021.108169

Cheung, P.K., Jim, C.Y., Hung, P.L., 2021b. Preliminary study on the temperature relationship at remotely-sensed tree canopy and below-canopy air and ground surface. Building and Environment 204, 108169. https://doi.org/10.1016/j.buildenv.2021.108169

Cohen, W.B., Maiersperger, T.K., Gower, S.T., Turner, D.P., 2003. An improved strategy for regression of biophysical variables and Landsat ETM+ data. Remote Sensing of Environment 84, 561–571. https://doi.org/10.1016/S0034-4257(02)00173-6

Cohn, A.S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., Thompson, S., 2019. Forest loss in Brazil increases maximum temperatures within 50 km. Environ. Res. Lett. 14, 084047. https://doi.org/10.1088/1748-9326/ab31fb

Dislich, C., Keyel, A.C., Salecker, J., Kisel, Y., Meyer, K.M., Auliya, M., Barnes, A.D., Corre, M.D., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., Tarigan, S., Tölle, M.H., Tscharntke, T., Wiegand, K., 2017. A review of the ecosystem functions in oil palm plantations, using forests as a reference system: Ecosystem functions of oil palm *versus* forest. Biol Rev 92, 1539–1569. https://doi.org/10.1111/brv.12295

Donfack, L.S., Röll, A., Ellsäßer, F., Ehbrecht, M., Irawan, B., Hölscher, D., Knohl, A., Kreft, H., Siahaan, E.J., Sundawati, L., Stiegler, C., Zemp, D.C., 2021. Microclimate and land surface temperature in a biodiversity enriched oil palm plantation. Forest Ecology and Management 497, 119480. https://doi.org/10.1016/j.foreco.2021.119480

Doughty, C.E., Keany, J.M., Wiebe, B.C., Rey-Sanchez, C., Carter, K.R., Middleby, K.B., Cheesman, A.W., Goulden, M.L., da Rocha, H.R., Miller, S.D., Malhi, Y., Fauset, S., Gloor, E., Slot, M., Oliveras Menor, I., Crous, K.Y., Goldsmith, G.R., Fisher, J.B., 2023. Tropical forests are approaching critical temperature thresholds. Nature 621, 105–111. https://doi.org/10.1038/s41586-023-06391-z

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., Fauzi, A.M., Gunawan, D., Hertel, D., Irawan, B., Jaya, I.N.S., Klarner, B., Kleinn, C., Knohl, A., Kotowska, M.M., Krashevska, V., Krishna, V., Leuschner, C., Lorenz, W., Meijide, A., Melati, D., Nomura, M., Pérez-Cruzado, C., Qaim, M., Siregar, I.Z., Steinebach, S., Tjoa, A., Tscharntke, T., Wick, B., Wiegand, K., Kreft, H., Scheu, S., 2016. Ecological and socio-economic functions across tropical land use systems after rainforest conversion. Phil. Trans. R. Soc. B 371, 20150275. https://doi.org/10.1098/rstb.2015.0275

Edwards, F.A., Edwards, D.P., Sloan, S., Hamer, K.C., 2014. Sustainable Management in Crop Monocultures: The Impact of Retaining Forest on Oil Palm Yield. PLoS ONE 9, e91695. https://doi.org/10.1371/journal.pone.0091695

Fang, H., Baret, F., Plummer, S., Schaepman-Strub, G., 2019. An Overview of Global Leaf Area Index (LAI): Methods, Products, Validation, and Applications. Rev. Geophys. 57, 739–799. https://doi.org/10.1029/2018RG000608

FAO – Statistical Yearbook 2022. FAO. https://doi.org/10.4060/cc2211en

Foster, W.A., Snaddon, J.L., Turner, E.C., Fayle, T.M., Cockerill, T.D., Ellwood, M.D.F., Broad, G.R., Chung, A.Y.C., Eggleton, P., Khen, C.V., Yusah, K.M., 2011. Establishing the evidence base for maintaining biodiversity and ecosystem function in the oil palm landscapes of South East Asia. Phil. Trans. R. Soc. B 366, 3277–3291. https://doi.org/10.1098/rstb.2011.0041

Fournier, R.A., Mailly, D., Walter, J.-M.N., Soudani, K., 2003. Indirect Measurement of Forest Canopy Structure from In Situ Optical Sensors, in: Wulder, M.A., Franklin, S.E. (Eds.), Remote Sensing of Forest Environments. Springer US, Boston, MA, pp. 77–113. https://doi.org/10.1007/978-1-4615-0306-4_4

Gatto, M., Wollni, M., Qaim, M., 2015. Oil palm boom and land-use dynamics in Indonesia: The role of policies and socioeconomic factors. Land Use Policy 46, 292–303. https://doi.org/10.1016/j.landusepol.2015.03.001

Global climate highlights. Copernicus Climate Change Service. Available at: https://climate.copernicus.eu/global-climate-highlights [Accessed 8 Jan. 2025].

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Fernandes, R.B.A., Filho, E.I.F., Schulte, R.P.O., 2020. Agroforestry systems can mitigate the impacts of climate change on coffee production: A spatially explicit assessment in Brazil. Agriculture, Ecosystems & Environment 294, 106858. https://doi.org/10.1016/j.agee.2020.106858

Grass, I., Kubitza, C., Krishna, V.V., Corre, M.D., Mußhoff, O., Pütz, P., Drescher, J., Rembold, K., Ariyanti, E.S., Barnes, A.D., Brinkmann, N., Brose, U., Brümmer, B., Buchori, D., Daniel, R., Darras, K.F.A., Faust, H., Fehrmann, L., Hein, J., Hennings, N., Hidayat, P., Hölscher, D., Jochum, M., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Leuschner, C., Lobite, N.J.S., Panjaitan, R., Polle, A., Potapov, A.M., Purnama, E., Qaim, M., Röll, A., Scheu, S., Schneider, D., Tjoa, A., Tscharntke, T., Veldkamp, E., Wollni, M., 2020. Trade-offs between multifunctionality and profit in tropical smallholder landscapes. Nat Commun 11, 1186. https://doi.org/10.1038/s41467-020-15013-5

Guillaume, T., Damris, M., Kuzyakov, Y., 2015. Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by δ^{13} C. Global Change Biology 21, 3548–3560. https://doi.org/10.1111/gcb.12907

Guillaume, T., Holtkamp, A.M., Damris, M., Brümmer, B., Kuzyakov, Y., 2016. Soil degradation in oil palm and rubber plantations under land resource scarcity. Agriculture, Ecosystems & Environment 232, 110–118. https://doi.org/10.1016/j.agee.2016.07.002

Guillaume, T., Kotowska, M.M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., Scheu, S., Kuzyakov, Y., 2018. Carbon costs and benefits of Indonesian rainforest conversion to plantations. Nat Commun 9, 2388. https://doi.org/10.1038/s41467-018-04755-y

Hardwick, S.R., Toumi, R., Pfeifer, M., Turner, E.C., Nilus, R., Ewers, R.M., 2015. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology 201, 187–195. https://doi.org/10.1016/j.agrformet.2014.11.010

Haseeb, M., Tahir, Z., Mehmood, S.A., Gill, S.A., Farooq, N., Butt, H., Iftikhar, A., Maqsood, A., Abdullah-Al-Wadud, M., Tariq, A., 2024. Enhancing Carbon Sequestration through Afforestation: Evaluating the Impact of Land Use and Cover Changes on Carbon Storage Dynamics. Earth Syst Environ. https://doi.org/10.1007/s41748-024-00414-z

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.

Ismaeel, A., Tai, A.P.K., Santos, E.G., Maraia, H., Aalto, I., Altman, J., Doležal, J., Lembrechts, J.J., Camargo, J.L., Aalto, J., Sam, K., Avelino do Nascimento, L.C., Kopecký, M., Svátek, M., Nunes, M.H., Matula, R., Plichta, R., Abera, T., Maeda, E.E., 2024. Patterns of tropical forest understory temperatures. Nat Commun 15, 549. https://doi.org/10.1038/s41467-024-44734-0

Jantz, S.M., Barker, B., Brooks, T.M., Chini, L.P., Huang, Q., Moore, R.M., Noel, J., Hurtt, G.C., 2015. Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. Conservation Biology 29, 1122–1131. https://doi.org/10.1111/cobi.12549

Kemppinen, K.M.S., Collins, P.M., Hole, D.G., Wolf, C., Ripple, W.J., Gerber, L.R., 2020. Global reforestation and biodiversity conservation. Conservation Biology 34, 1221–1228. https://doi.org/10.1111/cobi.13478

Keys, P.W., Collins, P.M., Chaplin-Kramer, R., Wang-Erlandsson, L., 2024. Atmospheric water recycling an essential feature of critical natural asset stewardship. Glob. Sustain. 7, e2. https://doi.org/10.1017/sus.2023.24

Khairiah, R.N., Setiawan, Y., Prasetyo, L.B., Permatasari, P.A., 2017. Leaf Area Index (LAI) in different type of agroforestry systems based on hemispherical photographs in Cidanau Watershed. IOP Conf. Ser.: Earth Environ. Sci. 54, 012050. https://doi.org/10.1088/1755-1315/54/1/012050

Kirschbaum, M.U.F., Saggar, S., Tate, K.R., Thakur, K.P., Giltrap, D.L., 2013. Quantifying the climate-change consequences of shifting land use between forest and agriculture. Science of The Total Environment 465, 314–324. https://doi.org/10.1016/j.scitotenv.2013.01.026

Lawrence, D., Coe, M., Walker, W., Verchot, L., Vandecar, K., 2022. The Unseen Effects of Deforestation: Biophysical Effects on Climate. Front. For. Glob. Change 5, 756115. https://doi.org/10.3389/ffgc.2022.756115

Le, H.D., Smith, C., Herbohn, J., Harrison, S., 2012. More than just trees: Assessing reforestation success in tropical developing countries. Journal of Rural Studies 28, 5–19. https://doi.org/10.1016/j.jrurstud.2011.07.006

Lee, J.S.H., Abood, S., Ghazoul, J., Barus, B., Obidzinski, K., Koh, L.P., 2014. Environmental Impacts of Large-Scale Oil Palm Enterprises Exceed that of Smallholdings in Indonesia. Conservation Letters 7, 25–33. https://doi.org/10.1111/conl.12039

Liu, C.L.C., Kuchma, O., Krutovsky, K.V., 2018. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. Global Ecology and Conservation 15, e00419. https://doi.org/10.1016/j.gecco.2018.e00419

Määttänen, A.-M., Virkkala, R., Leikola, N., Aalto, J., Heikkinen, R.K., 2023. Combined threats of climate change and land use to boreal protected areas with red-listed forest species in Finland. Global Ecology and Conservation 41, e02348. https://doi.org/10.1016/j.gecco.2022.e02348

Malhi, Y., Riutta, T., Wearn, O.R., Deere, N.J., Mitchell, S.L., Bernard, H., Majalap, N., Nilus, R., Davies, Z.G., Ewers, R.M., Struebig, M.J., 2022. Logged tropical forests have amplified and diverse ecosystem energetics. Nature 612, 707–713. https://doi.org/10.1038/s41586-022-05523-1

Mangueira, J.R.S.A., D. Holl, K., Rodrigues, R.R., 2019. Enrichment planting to restore degraded tropical forest fragments in Brazil. Ecosystems and People 15, 3–10. https://doi.org/10.1080/21513732.2018.1529707

McAlpine, C.A., Johnson, A., Salazar, A., Syktus, J., Wilson, K., Meijaard, E., Seabrook, L., Dargusch, P., Nordin, H., Sheil, D., 2018. Forest loss and Borneo's climate. Environ. Res. Lett. 13, 044009. https://doi.org/10.1088/1748-9326/aaa4ff

Meijide, A., Badu, C.S., Moyano, F., Tiralla, N., Gunawan, D., Knohl, A., 2018. Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event. Agricultural and Forest Meteorology 252, 208–219. https://doi.org/10.1016/j.agrformet.2018.01.013

Merga, B.B., Moisa, M.B., Negash, D.A., Ahmed, Z., Gemeda, D.O., 2022. Land Surface Temperature Variation in Response to Land-Use and Land-Cover Dynamics: A Case of Didessa River Sub-basin in Western Ethiopia. Earth Syst Environ. https://doi.org/10.1007/s41748-022-00303-3

Merten, J., Röll, A., Guillaume, T., Meijide, A., Tarigan, S., Agusta, H., Dislich, C., Dittrich, C., Faust, H., Gunawan, D., Hein, J., Hendrayanto, Knohl, A., Kuzyakov, Y., Wiegand, K., Hölscher, D., 2016. Water scarcity and oil palm expansion: social views and environmental processes. E&S 21, art5. https://doi.org/10.5751/ES-08214-210205

Niu, F., Röll, A., Meijide, A., Hendrayanto, Hölscher, D., 2017. Rubber tree transpiration in the lowlands of Sumatra. Ecohydrology 10, e1882. https://doi.org/10.1002/eco.1882

Parker, G.G., 2020. Tamm review: Leaf Area Index (LAI) is both a determinant and a consequence of important processes in vegetation canopies. Forest Ecology and Management 477, 118496. https://doi.org/10.1016/j.foreco.2020.118496

Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S., Wood, R., 2019. Agricultural and forestry trade drives large share of tropical deforestation emissions. Global Environmental Change 56, 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002

Pfeifer, M., Gonsamo, A., Woodgate, W., Cayuela, L., Marshall, A.R., Ledo, A., Paine, T.C.E., Marchant, R., Burt, A., Calders, K., Courtney-Mustaphi, C., Cuni-Sanchez, A., Deere, N.J., Denu, D., de Tanago, J.G., Hayward, R., Lau, A., Macía, M.J., Olivier, P.I., Pellikka, P., Seki, H., Shirima, D., Trevithick, R., Wedeux, B., Wheeler, C., Munishi, P.K.T., Martin, T., Mustari, A., Platts, P.J., 2018. Tropical forest canopies and their relationships with climate and disturbance: results from a global dataset of consistent field-based measurements. For. Ecosyst. 5, 7. https://doi.org/10.1186/s40663-017-0118-7

Pillay, R., Venter, M., Aragon-Osejo, J., González-del-Pliego, P., Hansen, A.J., Watson, J.E., Venter, O., 2022. Tropical forests are home to over half of the world's vertebrate species. Frontiers in Ecol & Environ 20, 10–15. https://doi.org/10.1002/fee.2420

Prabowo, D., Maryudi, A., Senawi, Imron, M.A., 2017. Conversion of forests into oil palm plantations in West Kalimantan, Indonesia: Insights from actors' power and its dynamics. Forest Policy and Economics 78, 32–39. https://doi.org/10.1016/j.forpol.2017.01.004

Qiao, K., Zhu, W., Xie, Z., 2020. Application conditions and impact factors for various vegetation indices in constructing the LAI seasonal trajectory over different vegetation types. Ecological Indicators 112, 106153. https://doi.org/10.1016/j.ecolind.2020.106153

Quandt, A., Neufeldt, H., Gorman, K., 2023. Climate change adaptation through agroforestry: opportunities and gaps. Current Opinion in Environmental Sustainability 60, 101244. https://doi.org/10.1016/j.cosust.2022.101244

Rembold, K., Mangopo, H., Tjitrosoedirdjo, S.S., Kreft, H., 2017. Plant diversity, forest dependency, and alien plant invasions in tropical agricultural landscapes. Biological Conservation 213, 234–242. https://doi.org/10.1016/j.biocon.2017.07.020

Sabajo, C.R., le Maire, G., June, T., Meijide, A., Roupsard, O., Knohl, A., 2017. Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. Biogeosciences 14, 4619–4635. https://doi.org/10.5194/bg-14-4619-2017

Scherer, L., Rosa, F., Sun, Z., Michelsen, O., De Laurentiis, V., Marques, A., Pfister, S., Verones, F., Kuipers, K.J.J., 2023. Biodiversity Impact Assessment Considering Land Use Intensities and Fragmentation. Environ. Sci. Technol. 57, 19612–19623. https://doi.org/10.1021/acs.est.3c04191

Sharma, R., Nehren, U., Rahman, S.A., Meyer, M., Rimal, B., Aria Seta, G., Baral, H., 2018. Modeling Land Use and Land Cover Changes and Their Effects on Biodiversity in Central Kalimantan, Indonesia. Land 7, 57. https://doi.org/10.3390/land7020057

Shete, M., Rutten, M., Schoneveld, G.C., Zewude, E., 2016. Land-use changes by large-scale plantations and their effects on soil organic carbon, micronutrients and bulk density: empirical evidence from Ethiopia. Agric Hum Values 33, 689–704. https://doi.org/10.1007/s10460-015-9664-1

Singh, D., Slik, J.W.F., Jeon, Y.-S., Tomlinson, K.W., Yang, X., Wang, J., Kerfahi, D., Porazinska, D.L., Adams, J.M., 2019. Tropical forest conversion to rubber plantation affects soil micro- & mesofaunal community & diversity. Sci Rep 9, 5893. https://doi.org/10.1038/s41598-019-42333-4

Sun, L., Yu, H., Sun, M., Wang, Y., 2023. Coupled impacts of climate and land use changes on regional ecosystem services. Journal of Environmental Management 326, 116753. https://doi.org/10.1016/j.jenvman.2022.116753

Terasaki Hart, D.E., Yeo, S., Almaraz, M., Beillouin, D., Cardinael, R., Garcia, E., Kay, S., Lovell, S.T., Rosenstock, T.S., Sprenkle-Hyppolite, S., Stolle, F., Suber, M., Thapa, B., Wood, S., Cook-Patton, S.C., 2023. Priority science can accelerate agroforestry as a natural climate solution. Nat. Clim. Chang. 13, 1179–1190. https://doi.org/10.1038/s41558-023-01810-5

Tian, J., Wang, L., Li, X., Gong, H., Shi, C., Zhong, R., Liu, X., 2017. Comparison of UAV and WorldView-2 imagery for mapping leaf area index of mangrove forest. International Journal of Applied Earth Observation and Geoinformation 61, 22–31. https://doi.org/10.1016/j.jag.2017.05.002

Turner, D.P., Cohen, W.B., Kennedy, R.E., Fassnacht, K.S., Briggs, J.M., 1999. Relationships between Leaf Area Index and Landsat TM Spectral Vegetation Indices across Three Temperate Zone Sites. Remote Sensing of Environment 70, 52–68. https://doi.org/10.1016/S0034-4257(99)00057-7

Unger, M., Homeier, J., Leuschner, C., n.d. Relationships among leaf area index, below-canopy light availability and tree diversity along a transect from tropical lowland to montane forests in NE Ecuador 14.

Unger, M., Homeier, J., Leuschner, C., n.d. Relationships among leaf area index, below-canopy light availability and tree diversity along a transect from tropical lowland to montane forests in NE Ecuador.

Von Arx, G., Dobbertin, M., Rebetez, M., 2012. Spatio-temporal effects of forest canopy on understory microclimate in a long-term experiment in Switzerland. Agricultural and Forest Meteorology 166–167, 144–155. https://doi.org/10.1016/j.agrformet.2012.07.018

Wang, J., Zou, Y., Di Gioia, D., Singh, B.K., Li, Q., 2020. Conversion to agroforestry and monoculture plantation is detrimental to the soil carbon and nitrogen cycles and microbial communities of a rainforest. Soil Biology and Biochemistry 147, 107849. https://doi.org/10.1016/j.soilbio.2020.107849

Wang, Y., Chen, L., Xiang, W., Ouyang, S., Zhang, T., Zhang, X., Zeng, Y., Hu, Y., Luo, G., Kuzyakov, Y., 2021. Forest conversion to plantations: A meta-analysis of consequences for soil and microbial properties and functions. Global Change Biology 27, 5643–5656. https://doi.org/10.1111/gcb.15835

Widyati, E., Nuroniah, H.S., Tata, H.L., Mindawati, N., Lisnawati, Y., Darwo, Abdulah, L., Lelana, N.E., Mawazin, Octavia, D., Prameswari, D., Rachmat, H.H., Sutiyono, Darwiati, W., Wardani, M., Kalima, T., Yulianti, van Noordwijk, M., 2022. Soil Degradation Due to Conversion from Natural to Plantation Forests in Indonesia. Forests 13, 1913. https://doi.org/10.3390/f13111913

Zellweger, F., Coomes, D., Lenoir, J., Depauw, L., Maes, S.L., Wulf, M., Kirby, K.J., Brunet, J., Kopecký, M., Máliš, F., Schmidt, W., Heinrichs, S., Den Ouden, J., Jaroszewicz, B., Buyse, G., Spicher, F., Verheyen, K., De Frenne, P., 2019. Seasonal drivers of understorey temperature buffering in temperate deciduous forests across Europe. Global Ecol Biogeogr 28, 1774–1786. https://doi.org/10.1111/geb.12991

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. Nature Clim Change 6, 791–795. https://doi.org/10.1038/nclimate3004

Chapter 2

Changes in leaf area index by tropical forest transformation to plantations increase below-canopy surface temperatures

Changes in leaf area index by tropical forest transformation to plantations increase below-canopy surface temperatures

Pallavi[a*], Alexander Röll[a,b], Isa Marques[c], Delima Nur Ramadhani[a], Alejandra Valdes-Uribe[a] Hendrayanto Hendrayanto[d], Dirk Hölscher[a,e]

[a] *Tropical Silviculture and Forest Ecology, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany*

[b] *Horticultural Sciences, Institute of Crop Science and Resource Conservation, University of Bonn, Germany*

[c] *Chair of Statistics, University of Göttingen, Humboldtallee 3, 37073 Göttingen, Germany*

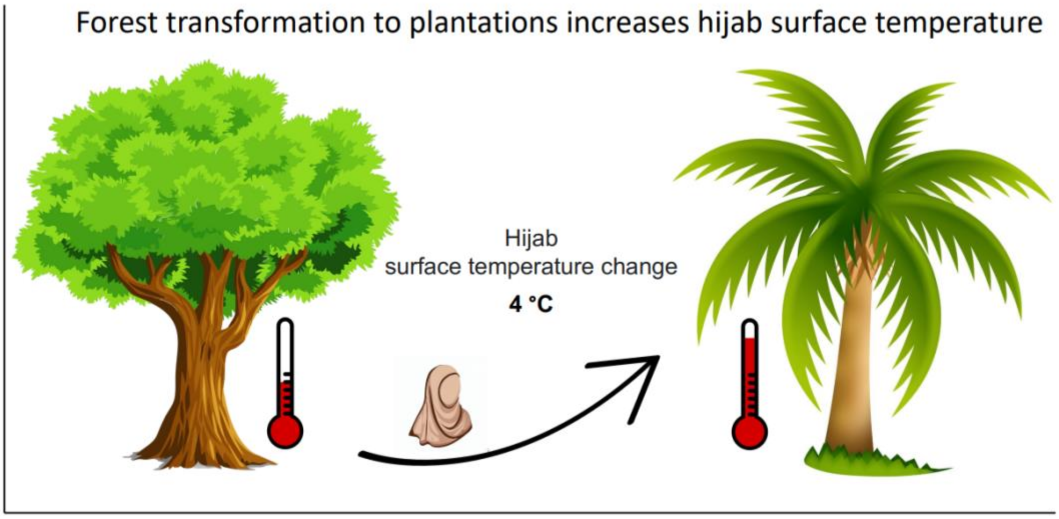
[d]*Department of Forest Management, Bogor Agricultural University, Kampus IPB Darmaga, 16680 Bogor, Indonesia*

[e]*Centre of Biodiversity and Sustainable Land Use, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany*

Published in Global Ecology and Conservation

Available at: https://doi.org/10.1016/j.gecco.2024.e03001

Graphical abstract



Abstract

Climate change affects life in tropical landscapes by increasing temperatures, among other impacts. In addition, land transformation from forest to other land cover types typically increases temperatures of surfaces exposed to direct solar radiation. In rural areas, however, many organisms including humans live sheltered below canopies, but little is known about below-canopy surface temperatures. We assessed canopy leaf area index (LAI) and below-canopy surface temperatures in a landscape of rural lowland Sumatra, Indonesia. In this region, land-use trajectories in the past decades led from forest to monocultural plantations. We found that LAI varied more than 10-fold, with the highest values observed in forest and low values in rubber and oil palm plantations. Below-canopy surface temperatures increased significantly with decreasing LAI. A decrease in LAI by one unit (m^2 leaf area per m^2 ground area) increased ground surface temperature by 0.95 °C (confidence interval: 1.07 - 0.83 °C) around noon. Likewise, the temperatures measured on peoples' cap or hijab surfaces under the canopy was strongly affected. For a light-brown hijab, the average noon surface temperature increased by 4.0 °C from forest to oil palm. Thus, in addition to climate warming, land transformation and associated declines in canopy LAI significantly increased below-canopy surface temperatures. Strategies for mitigating such potentially adverse temperature effects may include the integration of more and densely foliated trees into landscapes.

Keywords: LAI, land-use, hijab, cap, surface warming

2.1 Introduction

Climate warming is increasingly recognized as a severe threat to nature. Tropical forest tree canopies are approaching critical temperature thresholds (Doughty et al., 2023) and heat challenges human health in cities and rural areas (Chandrashekhar, 2023; Masuda et al., 2020; Sahu et al., 2013). Forest loss in the tropics increases local and non-local daily temperatures and temperature extremes (McAlpine et al., 2018; Cohn et al., 2019), significantly contributes to global warming and leads to the local warming of land surfaces (Lawrence et al., 2022; Sabajo et al., 2017; Alkama and Cescatti, 2016; Mildrexler et al., 2011). Land surface temperature dynamics can well be monitored from air and spaceborne platforms as long as the surfaces are exposed (Doughty et al., 2023; Donfack et al., 2021; Mildrexler et al., 2011). However, in rural areas, many organisms including humans live sheltered below canopies of forest, agroforests, tree plantations or other tree-based land-use types.

Climate change also affects global vegetation dynamics. Long-term records of leaf area index (LAI) indicate that warming has led to increased greening in high-latitude areas and reduced LAI in tropical regions, often coupled with land transformation (Zhu et al., 2016; Liu et al., 2010). On the other hand, climate-mitigative ecological restoration projects enhance the regional vegetation cover (Peng et al., 2021).

Significant changes in canopy characteristics are found in tropical landscapes undergoing transformation (Rembold et al., 2017; Osen et al., 2021). For example, In the lowlands of Sumatra, airborne laser scanning revealed strong differences in canopy height and foliage density among different land-use types (Camarretta et al., 2021). The transformation of forest to oil palm was also reported to increase daytime air temperatures below the canopy by 2.2 °C (Meijide et al., 2018).

The amount of light mediated by the canopy to the ground surface largely depends on canopy foliage, which is often characterized by the variable LAI. It is a central variable in ecosystem-atmosphere exchange and influences below-canopy energy availability by controlling radiation regime and thermal conditions within the canopy (Fournier et al., 2003), wherein dense tree canopies reduce the severity of warming impacts on biodiversity and ecosystem functioning (De Frenne et al., 2019). The underlying mechanisms controlling surface temperatures are more complex and include components of the radiation balance, latent heat fluxes (evapotranspiration) and vegetation structural complexity (Graham et al., 2010; Yu et al., 2023). LAI thus appears as a particularly promising variable for understanding and predicting dynamics of below-canopy surface temperatures. LAI is the one sided surface area of the total green leaf area per unit ground surface area (Bonan, 1995; Chen and Black, 1992; Qiao et al., 2020). It can be assessed by destructive sampling and analysis of leaf sizes (Fang et al., 2019; Casa et al., 2019), which is however rarely practiced because it is very labor intensive and may go against the principles of nature conservation. Indirect approaches involve the use of optical techniques, e.g. hemispherical photography with specialized plant canopy analysers (e.g. Tian et al., 2017; Raj et al., 2021). LAI estimates are also available from remote sensing products from various platforms, with variable spatial and temporal resolution (e.g. Camarretta et al., 2021; Valdés-Uribe et al., 2023). However, ground-referencing of these products is highly recommended.

Our study was conducted in a landscape of rural lowland Sumatra. The ongoing trend in land cover is transformation of forest to rubber and oil palm plantations (Grass et al., 2020) and includes shrublands, which are forests cleared for plantation establishment or transitions to secondary forest (Camarretta et al., 2021). We expect that LAI decreases and below-canopy surface temperatures increase along this trajectory of land-use transformation. We hypothesize that below-canopy surface temperatures can be predicted by LAI.

2.2 Methods

2.2.1 Study design

The research was conducted in the lowlands of Jambi Province, Sumatra, Indonesia (Fig. 2.1). The study plots are positioned between 102˚56' to 103˚42' latitude and 2˚ 21' to 1˚69' longitude. The average annual air temperature in the region is 26.7 ± 0.2 °C (mean ± SD), and the annual precipitation is 2,235 ± 385 mm (mean ± SD) (Drescher et al., 2016). The dominant soil type is Acrisol (Allen et al., 2015). Over the past decades, the region has witnessed a significant transformation in land use, with the once predominant lowland rainforests giving way to agricultural systems like rubber and oil palm plantations (Clough et al., 2016). The rainforests of Jambi have a long history of exploitation, encompassing both traditional agroforestry practices and the extraction of timber and non-timber products (Andaya, 1993; Kathirithamby, 1993). Previously logged rainforests have often been converted into intensively managed agro-industrial zones to cultivate cash crop trees such as rubber (*Hevea brasiliensis*) and oil palm

(*Elaeis guineensis*) (Gatto et al., 2015). During the 1970s, large commercial logging concessions were issued, marking the onset of significant changes. Subsequently, governmental land and resource use policies were combined with population migration schemes, particularly from densely populated regions to Jambi, aimed at driving economic development (Elmhirst, 2011; Gatto et al., 2015). These transmigrated populations primarily engaged in cash crop production, leading to rapid land-use change and a continuous decrease of rainforest cover. By 2013, rainforests covered only 30% of the province, with forests mainly located in mountainous or protected areas, while agricultural areas accounted for up to 55% of the land, with approximately 10% of degraded or fallow land (mainly waiting for conversion to plantations) (Drescher et al., 2016). As of 2014, Jambi Province witnessed extensive cultivation, with over 590,000 ha of oil palm and more than 650,000 ha of rubber plantations, accounting for 12% and 13% of the land cover, respectively (Badan Pusat Statistik, 2014). Different plantation ages and associated plant sizes as well as different management practises (e.g., related to planting densities) introduce considerable spatial heterogeneity into the landscape.

Our study was part of an interdisciplinary landscape assessment within the framework of the EFForTS project (www.uni-goettingen.de/efforts; Drescher et al., 2016). For this study, four land-use and land-cover classes (Camarretta et al., 2021) were selected: 1) forest: encompassing areas dominated by trees including secondary rainforest and degraded primary rainforest, both with minimum 50% tree canopy closure above the lowest vegetation layer. Forest plots were located in the Bukit Duabelas National Park and the Harapan rainforest, which exhibit near natural conditions, while other forest plots outside of these protected areas typically showed signs of disturbance. 2) shrubland: this broad category comprises shrub dominated fallow areas transitioning to secondary forest or cleared for plantation establishment, with up to 50% tree canopy closure above the lowest vegetation layer; often dominated by rather small-statured trees. 3) rubber plantation: regular monoculture plantations located across smallholder farms and commercial enterprises, covering a wide range of plantation ages (6 to 39 years). Rubber plantations in the region exhibit periodic partial leaf shedding (Niu et al., 2017). 4) oil palm plantation: monoculture plantations located across smallholder farms and commercial enterprises (Wenzel et al., 2024), covering a wide range of plantation ages (4 to 31 years).

A total of 132 plots were selected, with 33 plots in each land-use type (Camarretta et al., 2021, Fig. 2.1). Each plot covered an area of 1000 m^2, was circular in shape and comprised five subplots with an area 25 m^2 (Appendix, Fig. A2.1). Of the 132 plots, our study covered 124 plots (forest = 30, shrubland = 31, rubber = 31 and oil palm = 32) because some plots were inaccessible during the field campaign. The elevation of the study plots is 60 m ± 13 m (mean ± SD) a.m.s.l.

2.2.2 Data

2.2.2.1 Leaf area index

Leaf Area Index (LAI) was assessed using a LAI-2200C Plant Canopy analyzer (LI-COR, Biosciences Inc., Lincoln, USA). This instrument comprises two wands with optical sensors designed to measure radiation, with one wand capturing above-canopy radiation and the other below-canopy radiation. During a single measurement, the device reads canopy light interception at five zenith angles from both inside and outside measurements. The LAI values are then computed by the software FV2200 2.1. Due to the small-sized subplots, we used the 45˚ view-restriction cap while taking the readings. In our study, the above-canopy wand was positioned in an open area near the respective study plot, while on the plot, data collection occurred at all five sub-plots at a height of 1.3 meters with the below-canopy wand. LAI measurements were obtained only once per plot in the early morning (before bright sunlight to avoid scattering effects that could confounding measurements), between June 2021 and March 2022.

2.2.2.2 Below-canopy surface temperature

Below-canopy surface temperature was assessed using a Fluke PTi120 pocket thermal imager, specifically the FLK PTi120 9 Hz model with infrared resolution 120 × 90 (Fluke Corporation, WA, USA). Thermal images were captured for the below-canopy ground surface, a black and white board, a blue worker cap and a light-brown hijab. A hijab is a piece of cloth used by women to cover their head (also see graphical abstract), while male farm workers in Indonesia often wear a cap. The cap and hijab were positioned at 1.5 meters height using a tripod in the morning and remained in place until the conclusion of measurements. Thermal readings were conducted at 11:00 am, 12:00 pm, 1:00 pm, and 2:00 pm of the respective measurement day. Each plot was visited only once during the field campaign (between June 2021 and March 2022). Images were captured at a height of 2.5 meters from the ground which is well within the margins of high accuracy measurements with the device (until 3 m distance from the object) while capturing the maximum possible ground area (2.30 m x 1.72 m). The temperature data were extracted from the thermal images using the Fluke Connect (V1.1.548.0) software. Temperature readings were conducted at an irradiance in the open area ranging from 30 W m^{-2} to 658 W m^{-2} (mean = 314 W m^{-2}; SD = 167 W m^{-2}), but not during or shortly after rainfall.

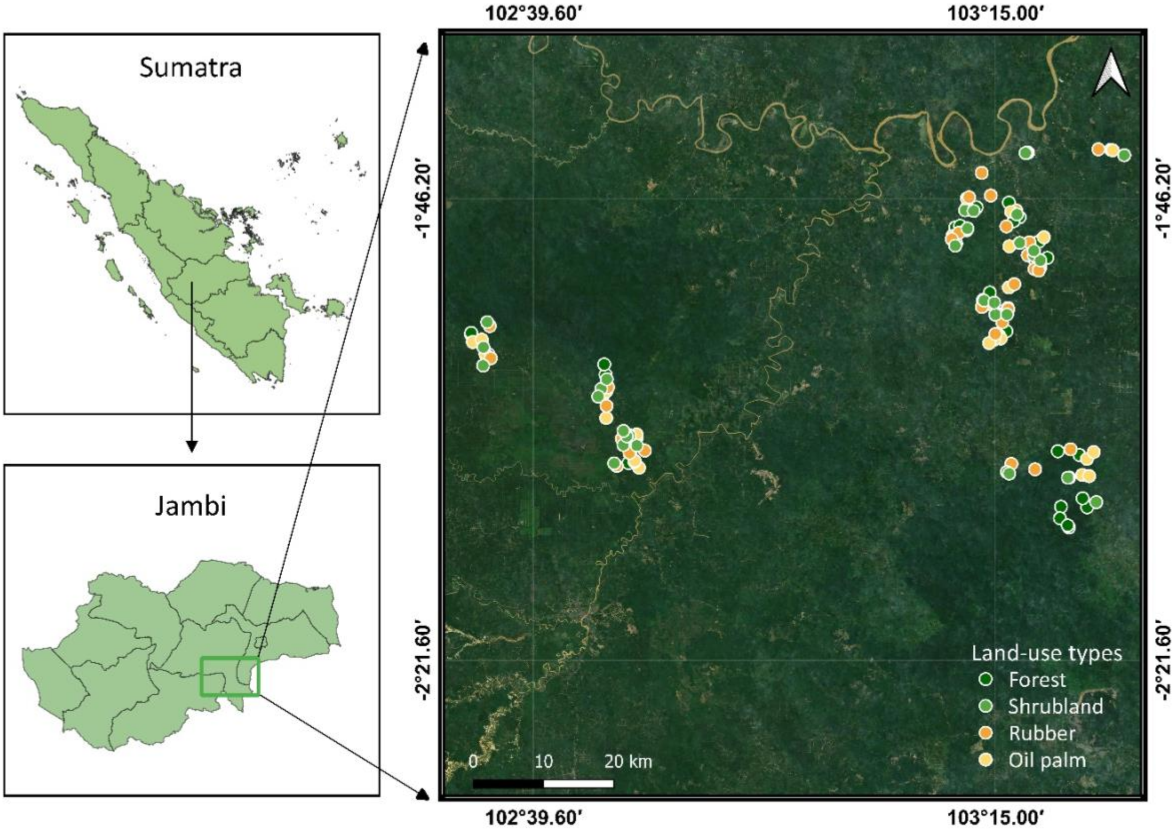


Fig. 2.1. Study landscape in Jambi province, Sumatra, Indonesia with the 132 study plots across the land-use types forest, shrubland, rubber and oil palm plantations. Background map: Sentinel-2 cloudless 2021 by EXO from QGIS 3.28.

2.2.2.3 Below-canopy ground surface

For characterizing the ground surface, we used the RGB images obtained from the abovenamed thermal camera. We categorized the ground surface components as bare soil, vegetation or debris. The point sampling technique was applied, wherein the SamplePoint Software (Booth et al., 2007; Booth and Cox, 2011) was utilized to evenly distribute a grid of 25 points over each digital image.

2.2.2.4 Ambient air temperature and irradiance

Air temperature beneath the canopy was measured employing a thermo-hygrometer (BC06, TROTEC, Germany). Irradiance measurements were conducted using two SpectraPen mini-

PSI25168 devices (Photon System Instruments, Czech Republic), compact and portable spectroradiometers calibrated for visible light as outlined in previous studies (Niedermaier et al., 2020; Wojciechowska et al., 2020). Simultaneous measurements were taken within the plot and in a neighboring open area.

2.2.2.5 Statistical analysis

We employed analysis of variance (ANOVA) with Tukey HSD post hoc tests to examine significant differences in LAI, below-canopy surface temperature, cap and hijab surface temperature, and black and white board temperature and ambient air temperature across the different land-use types. The assumption of normality of the data distribution was confirmed for each land-use type via visual assessments with histogram and QQ plots. The standard deviation for the difference between two mean values for land-use types was calculated according to Lane et. al. (2003). Linear regression analysis was conducted to examine the relationship between below-canopy surface temperature and LAI. Additionally, a linear mixed-effects model, utilizing the R package lme4 (v1.1.33; Bates et al., 2015), was employed to predict below-canopy surface temperature using the variables LAI, solar irradiance, time of day and land-use type as factors. In the mixed-effects model, continuous predictor variables were standardized using the scale function, ensuring a mean of zero and a standard deviation of one. This standardization facilitates the comparison of effect sizes for the estimated coefficients. All data analyses and visualizations were carried out using the R statistical software (v4.3.0; R core team, 2023)

2.3 Results

On the 124 study plots, LAI varied between 0.7 and 7.3 $m^2\ m^{-2}$ (Table 1). LAI in forest was significantly higher than in shrubland, rubber, and oil palm plantations. The coefficient of variation (CV) was higher in rubber, oil palm, and shrubland than in the forest.

In all land-use types, debris and green vegetation dominated the cover of below-canopy ground surface (Appendix, Fig. A2.2). The proportion of bare soil varied between 2% and 15% (Table A.1). The below-canopy ground surface temperatures ranged from 25 °C to 41 °C. It increased with decreasing LAI ($R^2 = 0.4$, Fig. 2.2). The slope of the regression line was 0.95 (Appendix, Table A2.2), indicating that a reduction in LAI by one unit corresponds to a 0.95 °C (confidence interval CI 1.07 - 0.83) increase in ground surface temperature, 1.58 °C (CI 1.79 - 1.37) in cap surface temperature (Appendix, Table A2.3) and 1.15 °C (CI 1.32 - 0.99) in hijab surface temperature (Appendix, Table A2.4). Of the measured surfaces, the ground surface consistently exhibited lower temperatures. The surface temperatures of the cap and hijab were similar at high LAI and diverged with decreasing LAI. The black board surface consistently displayed the highest temperatures among all surfaces, while the white board surface exhibited temperatures higher than the ground surface but lower than those of other surfaces (Appendix, Fig. A2.4).

Table 2.1. Leaf area index (LAI) across different land-use types. The letters attached to the mean indicate significant differences at $p < 0.05$ among land-use types (ANOVA, Tukey's HSD test).

	Leaf area index (m^2 m^{-2})					
	N	Max	Min	Mean	SD	CV%
Forest	30	7.3	4.2	5.9^{a}	0.64	11
Shrubland	31	6.6	1.8	4.3^{b}	1.33	31
Rubber	31	5.1	0.7	2.7^{c}	1.12	42
Oil Palm	32	4.4	0.8	2.9^{c}	0.92	32

A linear mixed-effects model had a conditional R^2 of 0.70 and a marginal R^2 of 0.33; it included the variables LAI, open-area solar irradiance, and time of day (Table 2). Land-use type did not emerge as a significant predictor variable and was thus excluded from the final model (Appendix, Table A2.8). In terms of effect size, LAI emerged as the most impactful predictor variable, followed by open-area solar irradiance, i.e. incoming radiation in an open area nearby the respective plot. Further, time of the day played a role with a peak occurring at 13:00 hrs. Consistent outcomes and similar model performance were also observed for the surface temperatures of the black and white board and of the workers' cap and hijab (see Appendix, Tables A2.9 to A2.12).

Below-canopy surface temperatures increased from forest over shrubland to rubber and oil palm plantations (Fig. 3). Transitioning from an average forest to an average oil palm plantation resulted in a 3.3 ± 0.58°C (mean ± SD) increase in ground surface temperature, a 5.1 ± 1.05°C (mean ± SD) increase in the surface temperature of the dark blue cap and a 4.0 ± 0.88°C (mean ± SD) increase in the surface temperature of the light-brown hijab. The temperatures of the different surfaces varied both within and among the studied land-use types (Appendix, Fig. A2.5).

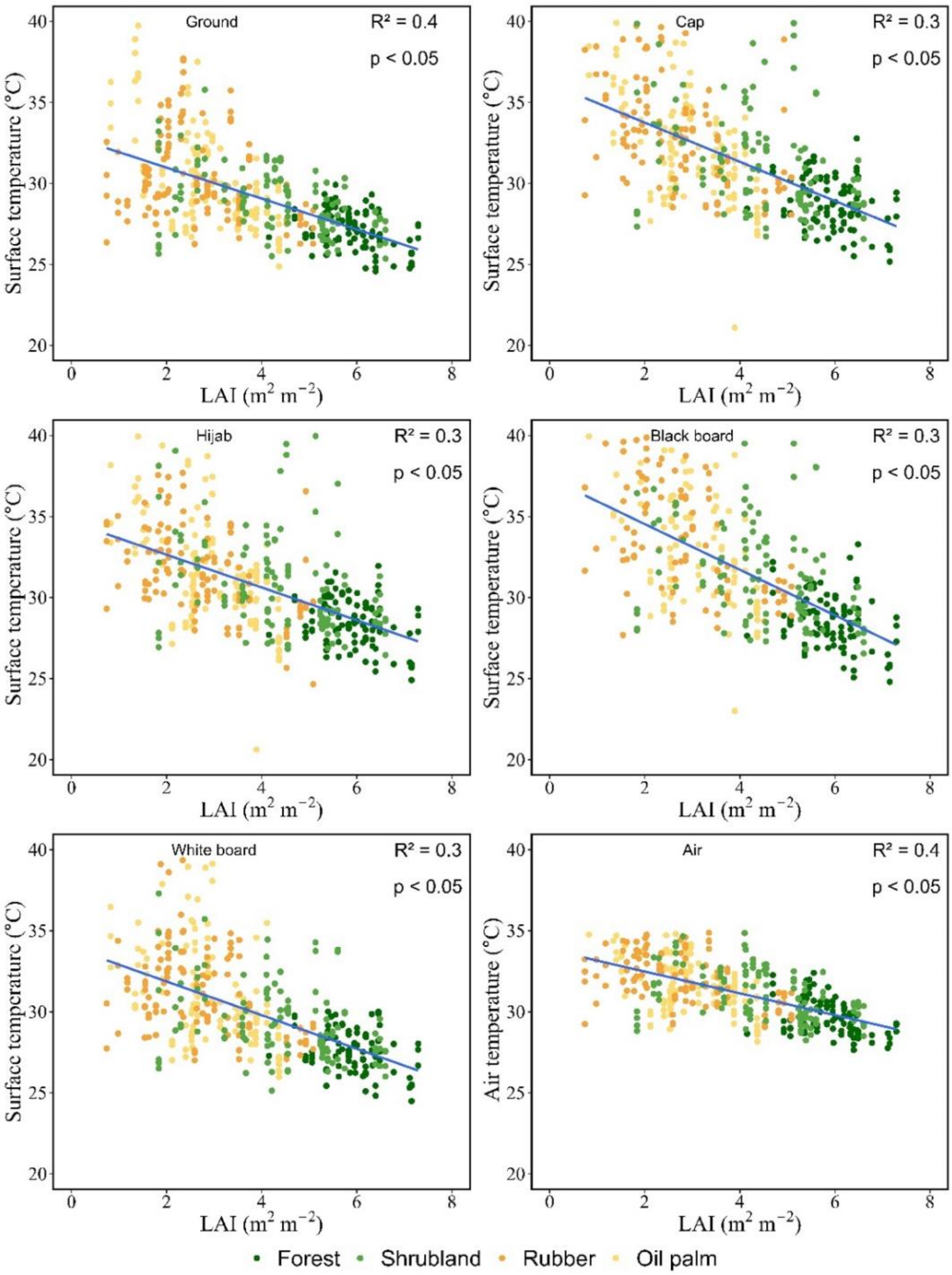


Fig. 2.2. Relationship between leaf area index (LAI) and below-canopy surface temperature for ground, cap, hijab, black board and white board and below-canopy air temperature. N = 124 plots, each with four measurements during the day (time 11:00 am, 12:00 pm, 1:00 pm, and 2:00 pm).

The ground surface, on average, was cooler than the air. The mean difference between below-canopy air temperature and ground-surface temperature was 2.5 ˚C in forest, 2.4 ˚C in shrubland, 1.7 °C in rubber and 1.6 °C in oil pam plantations (Appendix, Table A2.13).

Table 2.2. Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00 hr. 12.00, 13.00, 14.00 hrs.) and the random factor sub-plot. LAI and open-area irradiance (continuous variables) are scaled (non-scaled model output is depicted in Table A.5). Similar model results as here for the sub-plot level were observed for analyses at the plot level (see Appendix, Tables A2.6 and A2.7).

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	28.47	0.10	28.27 - 28.67	< 0.001
LAI	-1.57	0.08	-1.73 - -1.40	< 0.001
IRR (Open area)	0.61	0.05	0.51 - 0.70	< 0.001
Time 12.00 hr.	0.86	0.10	0.66 - 1.05	< 0.001
Time 13.00 hr.	1.08	0.10	0.89 - 1.28	< 0.001
Time 14.00 hr.	0.98	0.11	0.76 - 1.20	< 0.001
Random Effects				
σ^2	2.74			
t_{00} Subplot	3.47			
ICC	0.56			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.327/0.703			

2.4 Discussion

Across the studied landscape in lowland Sumatra, leaf area index per plot varied more than 10-fold. The observed LAI values align well with data from the region and other tropical areas assessed from the ground (Khairiah et al., 2017; Aragão et al., 2005; Osen et al., 2021; Awal et al., 2010; Darras et al., 2019). Our LAI values are however twice as high as the corresponding metric obtained from airborne laser scanning (Camarretta et al., 2021). A strong relationship between the two data sets (R2 = 0.78) provides an opportunity to scale-up LAI from the plot-level to the entire landscapes that were assessed with the airborne LiDAR (Schlund et al., unpublished).

In accordance with our initial expectations and hypothesis, we found a negative correlation between LAI and below-canopy surface temperature in a linear model ($R^2 = 0.4$). It indicates that for every unit decrease in LAI, below-canopy ground surface temperature increases by

0.95°C (CI 1.07 - 0.83). Somewhat comparable to our results, a study conducted in three land use types in Borneo (old growth forest, logged forest, oil palm) identified strong negative correlations between LAI (measured from hemispherical photography) and soil temperature (Hardwick et al., 2015). Notably, our results showed some very high surface temperature values of cap, hijab and black board at moderately high LAI; this may be attributed to direct sun flecks reaching the surface. Surface temperatures varied among the different surface types due to differences in their physical characteristics (e.g. surface color, material).

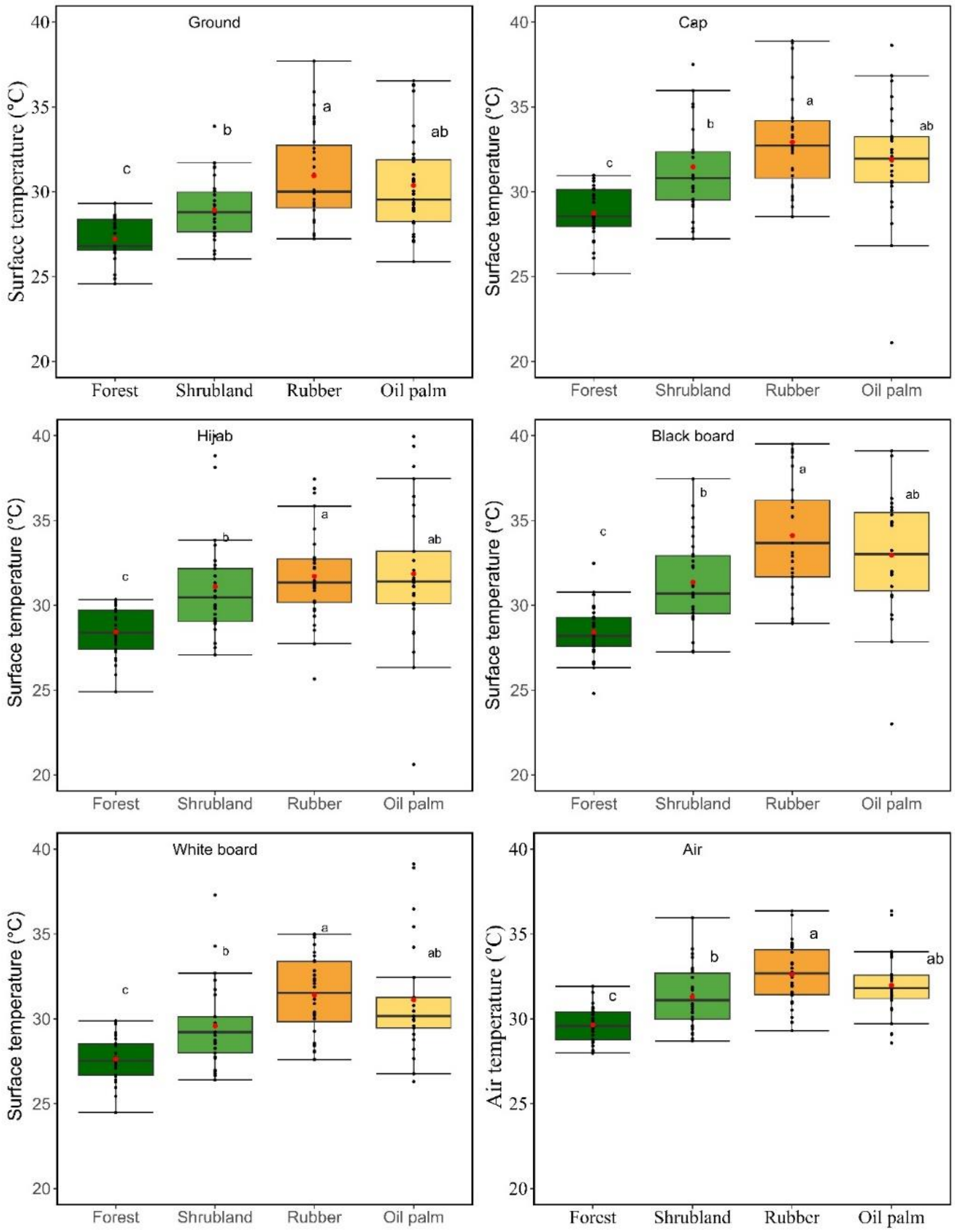


Fig. 2.3. Below-canopy temperature of different surfaces and below-canopy air temperature across land-use types measured at noon. The letters (on top of the boxes) indicate significant differences ($p < 0.05$) among land-use types, based on ANOVA with Tukey's HSD test.

Our mixed-effect model showed an R^2 of 0.7. It indicated that among several predictors the variable LAI was the most influential for predicting below-canopy surface temperatures. Following LAI, open-area irradiance emerged as the second most important variable, aligning with the expectation that energy availability strongly influences surface temperatures. The categorical variable land-use type was not significant in the model, likely due to the high importance of LAI and the substantial variability in LAI within land-use types, particularly in shrubland, rubber and oil palm plantations. The observed high variability of LAI within these land-use types may offer opportunities for management towards higher LAI, and thus lower below-canopy surface temperatures. For example, we observed lower LAI in young plantations than in advanced plantations; therefore, an expanded rotation length of plantations beyond the common 25 years cycle would lead to a higher share of stands with a relatively high LAI.

We found distinct differences in air-to-surface temperatures in forest and shrubland (Appendix, Table A2. 13), indicating surface cooling attributable to evapotranspiration (latent heat flux). This air-to-surface temperature difference was notably smaller in rubber and oil palm plantations. Given the lower LAI values and higher irradiance percentage penetrating through the canopy in rubber and oil palm plantations (Appendix, Fig. A2.3), we infer that the available energy for below-canopy evapotranspiration is considerably higher in rubber and oil palm plantation. While the precise rates of evapotranspiration below the canopy are currently unknown, there is a possibility of a change in energy partitioning, potentially leading to a higher conversion of energy into sensible heat fluxes in rubber and oil palm plantations compared to forests (Sabajo et al., 2017). Future studies could further explore energy partitioning by leveraging data from energy input and thermal images, as demonstrated in previous research (Ellsäßer et al., 2021).

Transitioning from an average forest to an average oil palm plantation resulted in a 3.3 ± 0.58°C (mean ± SD) increase in ground surface temperature, a 5.1 ± 1.05°C increase in the surface temperature of a dark blue cap and a 4.0 ± 0.88°C increase in the surface temperature of a light-brown hijab. Rubber and oil palm plantation types showed a higher variability in surface temperatures than forest. This is attributable to a higher spatial heterogeneity of rubber and oil palm stands in the landscape as compared to the more homogenous, relatively closed canopies of forests, while plantations vary in age and management (particularly planting density) and thus differ in key stand characteristics such as canopy cover, plant size and leaf area (Röll et al., 2019; Meijide et al., 2017; Niu et al., 2017). Rubber plantations in the study region further show temporal variations in canopy and leaf characteristics, as they temporally partially shed their leaves (Niu et al., 2017). Below-canopy surface temperatures and human experiences of temperature may further be influenced by air humidity, wind speed and evapotranspiration, which were not assessed in our study.

An exposure to excessive heat can have adverse effects on human health and well-being, performance and productivity, and such problems are already observed in tropical landscapes (Masuda et al., 2021; Parsons et al., 2021; Wolff et al., 2021; Vargas Zeppetello et al., 2020; Sahu et al., 2013). As such, the conversion of native forest to oil palm plantations increased the frequency of high temperature events (Chapman et al., 2020), and decreased canopy closure in oil palm plantations compared to forests was also associated with generally higher local surface temperatures (Ramdani et al., 2014). Forests provide relatively stable microclimatic habitats that provide a buffer from external climatic conditions. Forest fragmentation increases edge effects and increasingly exposes habitats to external climatic conditions (Ewers and Banks-Leite, 2013). The eventual transformation of forest landscapes to plantations leads to an increase in air temperatures, which influences most organisms and biogeochemical processes and can pose a threat to biodiversity up to the point of causing local extinctions of species while favoring exotic species (Latimer and Zuckerberg, 2021; Fayle et al., 2010). Overall increased temperatures also cause stress to oil palms and rubber trees themselves, thus favoring insect pest and diseases and potentially resulting in critical yield reductions (Abubakar et al., 2021; Paterson, 2019). Landscape cooling is thus not only a social or health-related issue but is also relevant as an economic climate change adaptation measure. Strategies for mitigating such potentially adverse temperature effects may include the integration of more and more densely foliated trees into landscapes. For rubber plantations such systems have a longstanding history on Sumatra, e.g. in the form of so-called jungle rubber systems (see e.g. Hardanto et al., 2017). In an oil palm landscape, Korol et al., (2021) found 10 scattered trees per ha, but these trees were mostly small-statured and there were signs of decreases in the number of such trees over time. One promising approach is to establish diverse tree islands within the 'oceans' of monoculture (oil palm) plantations or to create oil palm agroforests (Zemp et al., 2023). Larger size and structural complexity of planted tree islands were associated with lower average air and surface temperatures than smaller and less complex plots (Donfack et al., 2021). Such tree islands in oil palm landscapes may buffer against rising temperatures and in addition serve as refugia for biodiversity. Riparian buffer zones mainly for hydrological reasons may offer co-benefits for terrestrial biodiversity and improved microclimatic conditions (Williamson et al., 2021). Such landscape elements could thus help to mitigate some of the adverse environmental effects associated with the large-scale expansion of oil palm plantations.

To our knowledge, our study is the first to systematically assess below-canopy surface temperatures in a tropical region across a very large number of study plots (>120) and across key land-use types. It is also the first to evaluate the human temperature experience in tropical transformation landscapes by assessing workers' cap and hijab temperatures under the canopy.

2.5 Conclusions

Land transformation from forest to oil palm and rubber plantations in tropical lowlands increases surface temperatures also below the canopy. Leaf area index is a canopy metric that can reasonably well predict or indicate the ongoing changes in below-canopy surface temperatures, and is also available from remote sensing products. A strategy for mitigating the adverse effects of temperature increases in transformation landscapes may lie in fostering the establishment of tree islands with complex vegetation structure into human-modified landscapes.

2.6 References

Abubakar, A., Ishak, M.Y., Makmom, A.A., 2021. Impacts of and adaptation to climate change on the oil palm in Malaysia: a systematic review. Environ Sci Pollut Res 28, 54339–54361. https://doi.org/10.1007/s11356-021-15890-3

Alkama, R., Cescatti, A., 2016. Biophysical climate impacts of recent changes in global forest cover. Science 351, 600–604. https://doi.org/10.1126/science.aac8083

Allen, K., Corre, M.D., Tjoa, A., Veldkamp, E., 2015. Soil Nitrogen-Cycling Responses to Conversion of Lowland Forests to Oil Palm and Rubber Plantations in Sumatra, Indonesia. PLoS ONE 10, e0133325. https://doi.org/10.1371/journal.pone.0133325

Andaya, B.W., 1993. To live as brothers: southeast Sumatra in the seventeenth and eighteenth centuries. University of Hawaii Press, Honolulu, Hawaii.

Aragão, L.E.O.C., Shimabukuro, Y.E., Espírito Santo, F.D.B., Williams, M., 2005. Landscape pattern and spatial variability of leaf area index in Eastern Amazonia. Forest Ecology and Management 211, 240–256. https://doi.org/10.1016/j.foreco.2005.02.062

Awal, M.A., Ishak, W.I.W., Bockari-Gevao, S.M., 2010. Determination of Leaf Area Index for Oil Palm Plantation Using Hemispherical Photography Technique 18.

Badan Pusat Statistik. Jambi Dalam Angka 2014; Badan Pusat Statistik: Jambi, Indonesia, 2014.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using **lme4**. J. Stat. Soft. 67. https://doi.org/10.18637/jss.v067.i01

Bonan, G.B., 1995. Land-Atmosphere interactions for climate system Models: coupling biophysical, biogeochemical, and ecosystem dynamical processes. Remote Sensing of Environment 51, 57–73. https://doi.org/10.1016/0034-4257(94)00065-U

Booth, D.T., Cox, S.E., 2011. Art to Science: Tools for Greater Objectivity in Resource Monitoring.

Booth, D.T., Cox, S.E., Simonds, G., 2007. Riparian monitoring using 2-cm GSD aerial photography. Ecological Indicators 7, 636–648. https://doi.org/10.1016/j.ecolind.2006.07.005

Camarretta, N., Ehbrecht, M., Seidel, D., Wenzel, A., Zuhdi, Mohd., Merk, M.S., Schlund, M., Erasmi, S., Knohl, A., 2021. Using Airborne Laser Scanning to Characterize Land-Use Systems in a Tropical Landscape Based on Vegetation Structural Metrics. Remote Sensing 13, 4794. https://doi.org/10.3390/rs13234794

Casa, R., Upreti, D., Pelosi, F., 2019. Measurement and estimation of leaf area index (LAI) using commercial instruments and smartphone-based systems. IOP Conf. Ser.: Earth Environ. Sci. 275, 012006. https://doi.org/10.1088/1755-1315/275/1/012006

Chandrashekhar, V., 2023. Heat-proofing India. Science 381, 1393–1397. https://doi.org/10.1126/science.adl0416

Chapman, S., Syktus, J., Trancoso, R., Salazar, A., Thatcher, M., Watson, J.E.M., Meijaard, E., Sheil, D., Dargusch, P., McAlpine, C.A., 2020. Compounding impact of deforestation on Borneo's climate during El Niño events. Environ. Res. Lett. 15, 084006. https://doi.org/10.1088/1748-9326/ab86f5

Chen, J.M., Black, T.A., 1992. Foliage area and architecture of plant canopies from sunfleck size distributions. Agricultural and Forest Meteorology 60, 249–266. https://doi.org/10.1016/0168-1923(92)90040-B

Clough, Y., Krishna, V.V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A.D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., Holtkamp, A.M., Hörandl, E., Irawan, B., Jaya, I.N.S., Jochum, M., Klarner, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Kurniawan, S., Leuschner, C., Maraun, M., Melati, D.N., Opfermann, N., Pérez-Cruzado, C., Prabowo, W.E., Rembold, K., Rizali, A., Rubiana, R., Schneider, D., Tjitrosoedirdjo, S.S., Tjoa, A., Tscharntke, T., Scheu, S., 2016. Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. Nat Commun 7, 13137. https://doi.org/10.1038/ncomms13137

Cohn, A.S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., Thompson, S., 2019. Forest loss in Brazil increases maximum temperatures within 50 km. Environ. Res. Lett. 14, 084047. https://doi.org/10.1088/1748-9326/ab31fb

Darras, K.F.A., Corre, M.D., Formaglio, G., Tjoa, A., Potapov, A., Brambach, F., Sibhatu, K.T., Grass, I., Rubiano, A.A., Buchori, D., Drescher, J., Fardiansah, R., Hölscher, D., Irawan, B., Kneib, T., Krashevska, V., Krause, A., Kreft, H., Li, K., Maraun, M., Polle, A., Ryadin, A.R., Rembold, K., Stiegler, C., Scheu, S., Tarigan, S., Valdés-Uribe, A., Yadi, S., Tscharntke, T., Veldkamp, E., 2019. Reducing Fertilizer and Avoiding Herbicides in Oil Palm Plantations—Ecological and Economic Valuations. Front. For. Glob. Change 2, 65. https://doi.org/10.3389/ffgc.2019.00065

De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B.R., Hylander, K., Luoto, M., Vellend, M., Verheyen, K., Lenoir, J., 2019. Global buffering of temperatures under forest canopies. Nat Ecol Evol 3, 744–749. https://doi.org/10.1038/s41559-019-0842-1

Donfack, L.S., Röll, A., Ellsäßer, F., Ehbrecht, M., Irawan, B., Hölscher, D., Knohl, A., Kreft, H., Siahaan, E.J., Sundawati, L., Stiegler, C., Zemp, D.C., 2021. Microclimate and land surface temperature in a biodiversity enriched oil palm plantation. Forest Ecology and Management 497, 119480. https://doi.org/10.1016/j.foreco.2021.119480

Doughty, C.E., Keany, J.M., Wiebe, B.C., Rey-Sanchez, C., Carter, K.R., Middleby, K.B., Cheesman, A.W., Goulden, M.L., da Rocha, H.R., Miller, S.D., Malhi, Y., Fauset, S., Gloor, E., Slot, M., Oliveras Menor, I., Crous, K.Y., Goldsmith, G.R., Fisher, J.B., 2023. Tropical forests are approaching critical temperature thresholds. Nature 621, 105–111. https://doi.org/10.1038/s41586-023-06391-z

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., Fauzi, A.M., Gunawan, D., Hertel, D., Irawan, B., Jaya, I.N.S., Klarner, B., Kleinn, C., Knohl, A., Kotowska, M.M., Krashevska, V., Krishna, V., Leuschner, C., Lorenz, W., Meijide, A., Melati, D., Nomura, M., Pérez-Cruzado, C., Qaim, M., Siregar, I.Z., Steinebach, S., Tjoa, A., Tscharntke, T., Wick, B., Wiegand, K., Kreft, H., Scheu, S., 2016. Ecological and socio-economic functions across tropical land use systems after rainforest conversion. Phil. Trans. R. Soc. B 371, 20150275. https://doi.org/10.1098/rstb.2015.0275

Ellsäßer, F., Stiegler, C., Röll, A., June, T., Hendrayanto, Knohl, A., Hölscher, D., 2021. Predicting evapotranspiration from drone-based thermography – a method comparison in a tropical oil palm plantation. Biogeosciences 18, 861–872. https://doi.org/10.5194/bg-18-861-2021

Elmhirst, R., 2011. Migrant pathways to resource access in Lampung's political forest: Gender, citizenship and creative conjugality. Geoforum 42, 173–183. https://doi.org/10.1016/j.geoforum.2010.12.004

Ewers, R.M., Banks-Leite, C., 2013. Fragmentation Impairs the Microclimate Buffering Effect of Tropical Forests. PLoS ONE 8, e58093. https://doi.org/10.1371/journal.pone.0058093

Fang, H., Baret, F., Plummer, S., Schaepman-Strub, G., 2019. An Overview of Global Leaf Area Index (LAI): Methods, Products, Validation, and Applications. Reviews of Geophysics 57, 739–799. https://doi.org/10.1029/2018RG000608

Fayle, T.M., Turner, E.C., Snaddon, J.L., Chey, V.K., Chung, A.Y.C., Eggleton, P., Foster, W.A., 2010. Oil palm expansion into rain forest greatly reduces ant biodiversity in canopy, epiphytes and leaf-litter. Basic and Applied Ecology 11, 337–345. https://doi.org/10.1016/j.baae.2009.12.009

Fournier, R.A., Mailly, D., Walter, J.-M.N., Soudani, K., 2003. Indirect Measurement of Forest Canopy Structure from In Situ Optical Sensors, in: Wulder, M.A., Franklin, S.E. (Eds.), Remote Sensing of Forest Environments. Springer US, Boston, MA, pp. 77–113. https://doi.org/10.1007/978-1-4615-0306-4_4

Gatto, M., Wollni, M., Qaim, M., 2015. Oil palm boom and land-use dynamics in Indonesia: The role of policies and socioeconomic factors. Land Use Policy 46, 292–303. https://doi.org/10.1016/j.landusepol.2015.03.001

Graham, E.A., Lam, Y., Yuen, E.M., 2010. Forest understory soil temperatures and heat flux calculated using a Fourier model and scaled using a digital camera. Agricultural and Forest Meteorology 150, 640–649. https://doi.org/10.1016/j.agrformet.2010.02.005

Grass, I., Kubitza, C., Krishna, V.V., Corre, M.D., Mußhoff, O., Pütz, P., Drescher, J., Rembold, K., Ariyanti, E.S., Barnes, A.D., Brinkmann, N., Brose, U., Brümmer, B., Buchori, D., Daniel, R., Darras, K.F.A., Faust, H., Fehrmann, L., Hein, J., Hennings, N., Hidayat, P., Hölscher, D., Jochum, M., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Leuschner, C., Lobite, N.J.S., Panjaitan, R., Polle, A., Potapov, A.M., Purnama, E., Qaim, M., Röll, A., Scheu, S., Schneider, D., Tjoa, A., Tscharntke, T., Veldkamp, E., Wollni, M., 2020. Trade-offs between multifunctionality and profit in tropical smallholder landscapes. Nat Commun 11, 1186. https://doi.org/10.1038/s41467-020-15013-5

Hardanto, A., Röll, A., Hendrayanto, Hölscher, D., 2017. Tree soil water uptake and transpiration in mono-cultural and jungle rubber stands of Sumatra. Forest Ecology and Management 397, 67–77. https://doi.org/10.1016/j.foreco.2017.04.032

Hardwick, S.R., Toumi, R., Pfeifer, M., Turner, E.C., Nilus, R., Ewers, R.M., 2015. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology 201, 187–195. https://doi.org/10.1016/j.agrformet.2014.11.010

Khairiah, R.N., Setiawan, Y., Prasetyo, L.B., Permatasari, P.A., 2017. Leaf Area Index (LAI) in different type of agroforestry systems based on hemispherical photographs in Cidanau Watershed. IOP Conf. Ser.: Earth Environ. Sci. 54, 012050. https://doi.org/10.1088/1755-1315/54/1/012050

Korol, Y., Khokthong, W., Zemp, D.C., Irawan, B., Kreft, H., Hölscher, D., 2021. Scattered trees in an oil palm landscape: Density, size and distribution. Global Ecology and Conservation 28, e01688. https://doi.org/10.1016/j.gecco.2021.e01688

Latimer, C.E., Zuckerberg, B., 2021. Habitat loss and thermal tolerances influence the sensitivity of resident bird populations to winter weather at regional scales. Journal of Animal Ecology 90, 317–329. https://doi.org/10.1111/1365-2656.13332

Lawrence, D., Coe, M., Walker, W., Verchot, L., Vandecar, K., 2022. The Unseen Effects of Deforestation: Biophysical Effects on Climate. Front. For. Glob. Change 5, 756115. https://doi.org/10.3389/ffgc.2022.756115

Liu, S., Liu, R., Liu, Y., 2010. Spatial and temporal variation of global LAI during 1981–2006. J. Geogr. Sci. 20, 323–332. https://doi.org/10.1007/s11442-010-0323-6

Masuda, Y.J., Garg, T., Anggraeni, I., Ebi, K., Krenz, J., Game, E.T., Wolff, N.H., Spector, J.T., 2021. Warming from tropical deforestation reduces worker productivity in rural communities. Nat Commun 12, 1601. https://doi.org/10.1038/s41467-021-21779-z

Masuda, Y.J., Garg, T., Anggraeni, I., Wolff, N.H., Ebi, K., Game, E.T., Krenz, J., Spector, J.T., 2020. Heat exposure from tropical deforestation decreases cognitive performance of rural workers: an experimental study. Environ. Res. Lett. 15, 124015. https://doi.org/10.1088/1748-9326/abb96c

McAlpine, C.A., Johnson, A., Salazar, A., Syktus, J., Wilson, K., Meijaard, E., Seabrook, L., Dargusch, P., Nordin, H., Sheil, D., 2018. Forest loss and Borneo's climate. Environ. Res. Lett. 13, 044009. https://doi.org/10.1088/1748-9326/aaa4ff

Meijide, A., Badu, C.S., Moyano, F., Tiralla, N., Gunawan, D., Knohl, A., 2018. Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event. Agricultural and Forest Meteorology 252, 208–219. https://doi.org/10.1016/j.agrformet.2018.01.013

Meijide, A., Röll, A., Fan, Y., Herbst, M., Niu, F., Tiedemann, F., June, T., Rauf, A., Hölscher, D., Knohl, A., 2017. Controls of water and energy fluxes in oil palm plantations: Environmental variables and oil palm age. Agricultural and Forest Meteorology 239, 71–85. https://doi.org/10.1016/j.agrformet.2017.02.034

Mildrexler, D.J., Zhao, M., Running, S.W., 2011. A global comparison between station air temperatures and MODIS land surface temperatures reveals the cooling role of forests. J. Geophys. Res. 116, G03025. https://doi.org/10.1029/2010JG001486

Niedermaier, S., Schneider, T., Bahl, M.-O., Matsubara, S., Huesgen, P.F., 2020. Photoprotective Acclimation of the Arabidopsis thaliana Leaf Proteome to Fluctuating Light. Front. Genet. 11, 154. https://doi.org/10.3389/fgene.2020.00154

Niu, F., Röll, A., Meijide, A., Hendrayanto, Hölscher, D., 2017. Rubber tree transpiration in the lowlands of Sumatra. Ecohydrology 10, e1882. https://doi.org/10.1002/eco.1882

Osen, K., Soazafy, M.R., Martin, D.A., Wurz, A., März, A., Ranarijaona, H.L.T., Hölscher, D., 2021. Land-use history determines stand structure and tree diversity in vanilla agroforests of northeastern Madagascar. Applied Vegetation Science 24, e12563. https://doi.org/10.1111/avsc.12563

Parsons, L.A., Jung, J., Masuda, Y.J., Vargas Zeppetello, L.R., Wolff, N.H., Kroeger, T., Battisti, D.S., Spector, J.T., 2021. Tropical deforestation accelerates local warming and loss of safe outdoor working hours. One Earth 4, 1730–1740. https://doi.org/10.1016/j.oneear.2021.11.016

Paterson, R., 2019. Ganoderma boninense Disease of Oil Palm to Significantly Reduce Production After 2050 in Sumatra if Projected Climate Change Occurs. Microorganisms 7, 24. https://doi.org/10.3390/microorganisms7010024

Peng, J., Jiang, H., Liu, Q., Green, S.M., Quine, T.A., Liu, H., Qiu, S., Liu, Y., Meersmans, J., 2021. Human activity vs. climate change: Distinguishing dominant drivers on LAI dynamics in karst region of southwest China. Science of The Total Environment 769, 144297. https://doi.org/10.1016/j.scitotenv.2020.144297

Qiao, K., Zhu, W., Xie, Z., 2020. Application conditions and impact factors for various vegetation indices in constructing the LAI seasonal trajectory over different vegetation types. Ecological Indicators 112, 106153. https://doi.org/10.1016/j.ecolind.2020.106153

Raj, R., Walker, J.P., Pingale, R., Nandan, R., Naik, B., Jagarlapudi, A., 2021. Leaf area index estimation using top-of-canopy airborne RGB images. International Journal of Applied Earth Observation and Geoinformation 96, 102282. https://doi.org/10.1016/j.jag.2020.102282

Ramdani, F., Moffiet, T., Hino, M., 2014. Local surface temperature change due to expansion of oil palm plantation in Indonesia. Climatic Change 123, 189–200. https://doi.org/10.1007/s10584-013-1045-4

Rembold, K., Mangopo, H., Tjitrosoedirdjo, S.S., Kreft, H., 2017. Plant diversity, forest dependency, and alien plant invasions in tropical agricultural landscapes. Biological Conservation 213, 234–242. https://doi.org/10.1016/j.biocon.2017.07.020

Röll, A., Niu, F., Meijide, A., Ahongshangbam, J., Ehbrecht, M., Guillaume, T., Gunawan, D., Hardanto, A., Hendrayanto, Hertel, D., Kotowska, M.M., Kreft, H., Kuzyakov, Y., Leuschner, C., Nomura, M., Polle, A., Rembold, K., Sahner, J., Seidel, D., Zemp, D.C., Knohl, A., Hölscher, D., 2019. Transpiration on the rebound in lowland Sumatra. Agricultural and Forest Meteorology 274, 160–171. https://doi.org/10.1016/j.agrformet.2019.04.017

Röll, A., Niu, F., Meijide, A., Hardanto, A., Hendrayanto, Knohl, A., Hölscher, D., 2015. Transpiration in an oil palm landscape: effects of palm age. Biogeosciences 12, 5619–5633. https://doi.org/10.5194/bg-12-5619-2015

Sabajo, C.R., le Maire, G., June, T., Meijide, A., Roupsard, O., Knohl, A., 2017. Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. Biogeosciences 14, 4619–4635. https://doi.org/10.5194/bg-14-4619-2017

Sahu, S., Sett, M., Kjellstrom, T., 2013. Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future. Ind Health 51, 424–431. https://doi.org/10.2486/indhealth.2013-0006

Tian, J., Wang, L., Li, X., Gong, H., Shi, C., Zhong, R., Liu, X., 2017. Comparison of UAV and WorldView-2 imagery for mapping leaf area index of mangrove forest. International Journal of Applied Earth Observation and Geoinformation 61, 22–31. https://doi.org/10.1016/j.jag.2017.05.002

Valdés-Uribe, A., Hölscher, D., Röll, A., 2023. ECOSTRESS Reveals the Importance of Topography and Forest Structure for Evapotranspiration from a Tropical Forest Region of the Andes. Remote Sensing 15, 2985. https://doi.org/10.3390/rs15122985

Vargas Zeppetello, L.R., Parsons, L.A., Spector, J.T., Naylor, R.L., Battisti, D.S., Masuda, Y.J., Wolff, N.H., 2020. Large scale tropical deforestation drives extreme warming. Environ. Res. Lett. 15, 084012. https://doi.org/10.1088/1748-9326/ab96d2

Wenzel, A., Westphal, C., Ballauff, J., Berkelmann, D., Brambach, F., Buchori, D., Camarretta, N., Corre, M.D., Daniel, R., Darras, K., Erasmi, S., Formaglio, G., Hölscher, D., Iddris, N.A.-A., Irawan, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Mulyani, Y., Mußhoff, O., Paterno, G.B., Polle, A., Potapov, A., Röll, A., Scheu, S., Schlund, M., Schneider, D., Sibhatu, K.T., Stiegler, C., Sundawati, L., Tjoa, A., Tscharntke, T., Veldkamp, E., Waite, P.-A., Wollni, M., Zemp, D.C., Grass, I., 2024. Balancing economic and ecological functions in smallholder and industrial oil palm plantations. Proc. Natl. Acad. Sci. U.S.A. 121, e2307220121. https://doi.org/10.1073/pnas.2307220121

Williamson, J., Slade, E.M., Luke, S.H., Swinfield, T., Chung, A.Y.C., Coomes, D.A., Heroin, H., Jucker, T., Lewis, O.T., Vairappan, C.S., Rossiter, S.J., Struebig, M.J., 2021. Riparian buffers act as microclimatic refugia in oil palm landscapes. Journal of Applied Ecology 58, 431–442. https://doi.org/10.1111/1365-2664.13784

Wojciechowska, R., Kunicki, E., Długosz-Grochowska, O., Kołton, A., 2020. Response of Broccoli Transplants to LED Light during Short and Long-Term Storage. Agronomy 10, 1009. https://doi.org/10.3390/agronomy10071009

Wolff, N.H., Zeppetello, L.R.V., Parsons, L.A., Aggraeni, I., Battisti, D.S., Ebi, K.L., Game, E.T., Kroeger, T., Masuda, Y.J., Spector, J.T., 2021. The effect of deforestation and climate change on all-cause mortality and unsafe work conditions due to heat exposure in Berau, Indonesia: a modelling study. The Lancet Planetary Health 5, e882–e892. https://doi.org/10.1016/S2542-5196(21)00279-5

Yu, Y., Fang, S., Zhuo, W., 2023. Revealing the Driving Mechanisms of Land Surface Temperature Spatial Heterogeneity and Its Sensitive Regions in China Based on GeoDetector. Remote Sensing 15, 2814. https://doi.org/10.3390/rs15112814

Zemp, D.C., Guerrero-Ramirez, N., Brambach, F., Darras, K., Grass, I., Potapov, A., Röll, A., Arimond, I., Ballauff, J., Behling, H., Berkelmann, D., Biagioni, S., Buchori, D., Craven, D., Daniel, R., Gailing, O., Ellsäßer, F., Fardiansah, R., Hennings, N., Irawan, B., Khokthong, W., Krashevska, V., Krause, A., Kückes, J., Li, K., Lorenz, H., Maraun, M., Merk, M.S., Moura, C.C.M., Mulyani, Y.A., Paterno, G.B., Pebrianti, H.D., Polle, A., Prameswari, D.A., Sachsenmaier, L., Scheu, S., Schneider, D., Setiajiati, F., Setyaningsih, C.A., Sundawati, L., Tscharntke, T., Wollni, M., Hölscher, D., Kreft, H., 2023. Tree islands enhance biodiversity and functioning in oil palm landscapes. Nature 618, 316–321. https://doi.org/10.1038/s41586-023-06086-5

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. Nature Clim Change 6, 791–795. https://doi.org/10.1038/nclimate3004

Chapter 3

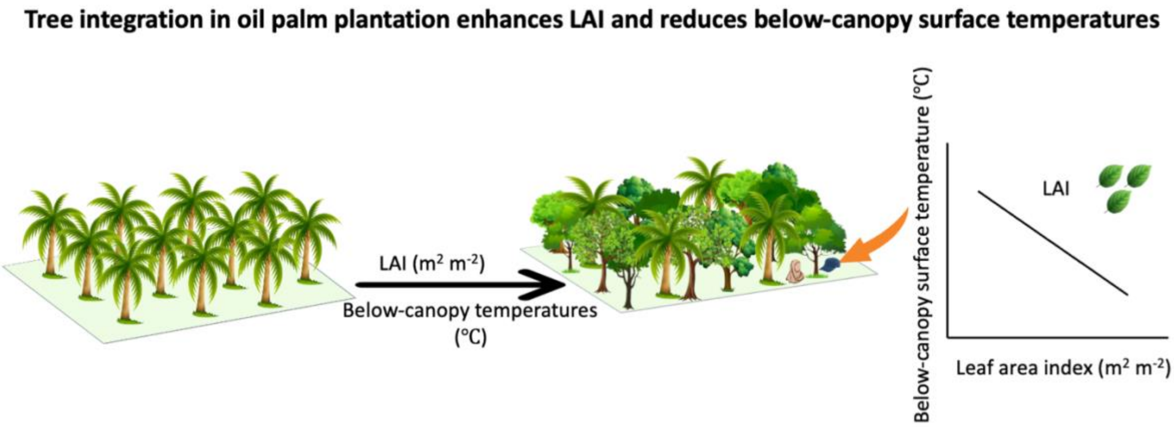
Tree integration in oil palm plantation enhances leaf area index and lowers below-canopy temperatures

Tree integration in oil palm plantation enhances leaf area index and lowers below-canopy temperatures

Pallavi [a], Alexander Röll [b], Gustavo B. Paterno [c], Fabian Brambach [c], Thorge Wintz [a], Delphine Clara Zemp [d], Bambang Irawan [e], Leti Sundawati [f], Hendrayanto [f], Holger Kreft [c, g], Dirk Hölscher [a, g]

[a] *Tropical Silviculture and Forest Ecology, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany*
[b] *Horticultural Sciences, Institute of Crop Science and Resource Conservation, University of Bonn, Germany*
[c] *Biodiversity, Macroecology and Biogeography, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany*
[d] *Conservation Biology, Institute of Biology, Faculty of Sciences, University of Neuchâtel, 2000 Neuchâtel, Switzerland*
[e] *Faculty of Forestry, University of Jambi, 36361 Jambi, Indonesia*
[f] *Department of Forest Management, Bogor Agricultural University, Kampus IPB Darmaga, 16680 Bogor, Indonesia*
[g] *Centre of Biodiversity and Sustainable Land Use, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany*

Graphical abstract



Abstract

Land-use change from forest to agriculture contributes to increasing surface and air temperatures, both in the upper layers of vegetated land and the areas below the canopy. Below the canopy, considerable biodiversity occurs, important ecosystem functions are regulated and humans live and work, but information on how land-use change drives local temperature dynamics, particularly in the context of ecosystem restoration, is scarce. In our study, we tested different modes of tree integration in oil palm monocultures and assessed the factors controlling below-canopy temperatures. The study was conducted nine years after tree planting in a biodiversity enrichment experiment in lowland Sumatra (EFForTS-BEE). Data from nearby forests and monoculture oil palm plantations from a larger-scale landscape assessment were used as a reference for the experiment. Compared to oil palm monocultures, tree integration via planting and natural recruitment in the experiment increased the canopy leaf area index (LAI) by 0.8 $m^2 m^{-2}$ (27%) and reduced below-canopy ground surface temperature at noon by 1.5 ˚C. Similarly, the below-canopy surface temperatures of a worker's hijab and of a black and white reference board were notably reduced. In nearby old-growth forests LAI was much higher and below-canopy temperatures were lower than in the tree integration experiment. On the experimental plots, tree planting plus natural recruitment was more effective in increasing LAI than natural recruitment alone. Mixed-effects models reveal LAI as a key predictor of below-canopy surface temperatures, together with solar irradiance and time of day. Other factors such as tree island size, planted tree diversity, observed tree diversity or stand structural complexity were less important. Our findings indicate that tree integration by planting and natural recruitment offers opportunities to curb high below-canopy temperatures in oil palm cultivation, and that leaf area index is a crucial factor therein.

Key words: Tree island, solar irradiance, observed diversity, stand structural complexity, heat stress, farm workers

3.1 Introduction

Climate change leads to increasing air and land surface temperatures worldwide, posing threats to biodiversity, ecosystem functions and humankind (IPCC 2023). Particularly in tropical regions, ongoing vast land-cover and land-use changes further amplify climate-induced temperature increases at local and regional scale (McAlpine et al., 2018; Cohn et al., 2019). In tropical forests, tree canopies are approaching a critical temperature threshold at which photosynthetic mechanisms may fail (Doughty et al., 2023). Information on land surface temperatures is relatively abundant for the upper and exposed vegetation layer, since it can well be monitored by airborne and spaceborne sensors (Doughty et al., 2023; Donfack et al., 2021; Mildrexler et al., 2011; Sun et al., 2010). Less information is available for below-canopy surface temperatures. Below the canopy, however, considerable biodiversity occurs, important ecosystem functions are regulated, and humans live and work. Hotter temperatures, both outdoors and indoors, are associated with substantial heat-related human mortality and morbidity including heat strokes, cardiovascular diseases, respiratory diseases, microbial infraction and mental health issues (Hondula et al., 2015; Campbell et al., 2018; Lo et al., 2024; Kovats et al., 2004). Below-canopy areas serve as thermal refuges with buffered climatic extremes that help to maintain biodiversity and ecological functions (Ashcroft, 2010; Keppel et al., 2012).

In the tropics, one major trajectory of concurrent land-use change leads from forest to oil palm (*Elaeis guineensis* Jacq.) plantations. Oil palm plantations are highly productive and contribute to rural livelihoods, yet this comes with negative impacts on biodiversity and ecosystem functions (Grass et al., 2020; Qaim et al., 2020; Meijaard et al., 2020). Pathways for a more sustainable future of oil palm cultivation are being discussed and tested, and may include reduced application of agrochemicals, tree integration and maintaining understory vegetation (Iddris et al., 2023; Zemp et al., 2023; Wenzel et al., 2024; Reiss-Woolever et al., 2023; Stone et al., 2023). With regard to below-canopy temperatures, the transformation of forest to monoculture oil palm plantations increased average daytime air temperatures by 2.3 °C (Meijide et al., 2018). For a light-brown hijab, the average noon below-canopy surface temperature increased by 4.0 °C from forest to oil palm (Pallavi et al., 2024). Canopy leaf area index (LAI) was suggested as a key controlling factor; a decrease in LAI by one unit (m^2 leaf area per m^2 ground area) increased surface temperatures of a hijab by 1.2 °C at noon (Pallavi et al., 2024). It was suggested that strategies for mitigating such potentially adverse temperature effects may include the integration of more and densely foliated trees into oil palm cultivation, e.g. by oil palm agroforestry.

Oil palms themselves are sometimes referred to as (palm) trees. However, they lack secondary growth and are therefore not considered trees in a stricter botanical sense (Shugart et al., 2022), which is the tree definition we use in our study. Tree integration in the context of our study comprises both trees originating from planting and from natural recruitment. Generally, management in oil palm plantation suppresses any natural regeneration by herbicide application and/or manual weeding. This might contribute to the high temperatures below oil palm canopies. At global scale, most oil palm cultivation is carried out in monoculture plantations. However, trees often occur scattered in these monoculture landscapes (Teuscher et al., 2015; Korol et al., 2021). One study from lowland Sumatra (Indonesia) reports that these scattered trees typically occur at modest abundances, are mostly small-statured, most likely young, and are derived from natural recruitment or planting along roads (Korol et al., 2021). In contrast to agroforestry systems, they are not an integral part of the cultivation system. In oil palm agroforestry, the palms produce the agricultural crop while the trees constitute the spatially integrated forestry component, which may serve multiple wood and non-wood purposes (Budiadi et al., 2019; Khatun et al., 2020). However, only in the region of oil palm's origin in West Africa can oil palm agroforestry be seen at scale (Khatun et al., 2020; Pashkevich et al., 2024), with productions systems fundamentally differing from the industrial monoculture approach of oil palm cultivation in most other regions of the world. More recently, different types of oil palm agroforestry are being explored in the Amazon region of Brazil, resulting in the achievement of physical capital and economic success at intermediate levels of living standards for households (Braga et al., 2024).

In lowland Sumatra, a region which has undergone large-scale forest conversion to monoculture oil palm cultivation (Margono et al., 2012; Austin et al., 2019), an experiment was established in 2013 to alleviate potential negative effects on biodiversity and ecosystem functions by integrating trees into oil palm plantations (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems - Biodiversity Enrichment Experiment (EFForTS-BEE); Teuscher et al., 2016). The experimental treatments comprise initial planted tree diversity and island area. Planted tree diversity varies between 0 (no planting but allowed for natural regeneration) and 6 species, and the area of tree (agroforestry) islands varies between 25 m^2 and 1600 m^2. Natural tree recruitment is allowed. There are also four control plots with oil palm cultivation as usual (Teuscher et al., 2016). The treatment tree diversity was motivated by the often observed positive effects of tree diversity on ecosystem functions and associated biodiversity (Paquette et al., 2018; Zheng et al., 2024). Enhancing diversity is also postulated as a nature-based solution to the climate crisis (Depauw et al., 2024; Key et al., 2022; Schnabel et al., 2024). The treatment island area was motivated by the theory of island biogeography (MacArthur and Wilson, 1967), which states that bigger islands harbor more species. This theory plays a prominent role in understanding biodiversity patterns in nature conservation (Schrader et al., 2024; Givnish, 2024). Results from EFForTS-BEE so far suggest that the tree islands amidst a sea of oil palms considerably enhance multidiversity and multifunctionality (Zemp et al., 2023). The natural recruitment comprised 52 newly established native woody species, and was promoted by both planted tree diversity and island area (Paterno et al., 2024). Tree planting and natural recruitment enhanced stand structural complexity as derived from terrestrial laser scanning (Zemp et al., 2019; Kikuchi et al., 2024). Structurally complex plots were linked to lower mean and maximum ambient air temperature, and stand structural complexity and tree island area regulate microclimate in EFForTS-BEE (Donfack et al., 2021). Higher stand structural complexity reduces microclimatic temperature in temperate forest (Ehbrecht et al., 2017).

Planted tree diversity promotes tree growth and enhances understory vegetation complexity; creating multi-layered green canopies that provide enhanced canopy cover and transpirational cooling services. This effect becomes more pronounced as the area increases. However, in oil palm monoculture, understorey vegetation is usually cleared with herbicides and weeding, which contributes to rising microclimatic temperatures. Consequently, oil palm plantations are substantially hotter (2.8 °C) than forest (Luskin and Potts, 2011). Overall, tree integration did not impair oil palm yields (Gérard et al., 2017; Zemp et al., 2023). All this points to a large potential of tree integration in oil palm cultivation. However, a more comprehensive analysis examining the effects of tree integration on key vegetation characteristics such as canopy LAI and on below-canopy temperatures is still missing. Such an analysis should be referenced against forests and conventional oil palm monocultures in the wider landscape.

In this study, we assessed canopy LAI and below-canopy temperatures of the air and of different surfaces (ground, workers' cap and hijab, black and white boards) across oil palm agroforests nine years after tree planting. As a reference, we additionally used forest and monoculture oil palm data from a landscape assessment (EFForTS-LA) in the same region

(Pallavi et al., 2024). We hypothesized that H1) Tree integration into oil palm plantations enhances LAI and thereby reduces below-canopy temperatures, H2) Below-canopy temperatures decrease with increasing canopy LAI, stand structural complexity and observed woody diversity, and H3) Planted tree diversity and island area increase LAI and reduce below-canopy temperatures.

3.2 Methods

2.1. Study area

The study was conducted in the lowlands of Jambi Province, Sumatra, Indonesia. Average annual air temperature in the region is 26.7 ± 0.2 °C (mean ± SD), annual precipitation is 2,235 ± 385 mm (1991–2011; measured at Jambi Sultan Thaha airport, Drescher et al., 2016). The dominant soil type is Acrisol (Allen et al., 2015). Over the past decades, the region has witnessed significant land-use transformations, at least partly driven by large commercial logging concessions and a transmigration scheme by the government to enhance economic development in Sumatra. The once predominant lowland rainforests have been largely replaced by rubber and oil palm plantations (Clough et al., 2016). Our study was conducted in the framework of the EFForTS project (www.uni-goettingen.de/efforts; Drescher et al., 2016). We used data from two different project activities, the EFForTS-BEE (Teuscher et al., 2016) and the Landscape Assessment (EFForTS-LA; Pallavi et al., 2024).

3.2.2. Study design

3.2.2.1. Biodiversity enrichment experiment

EFForTS-BEE is located in the PT. Humusindo Makmur Sejati oil palm plantation (01.95◦ S and 103.25◦ E, 47 ± 11 m a.s.l.) near Bungku village in the lowlands of Jambi province, Sumatra (Appendix, Fig. A3.1). It was established in December 2013 (Teuscher et al., 2016). Six native tree species, *Parkia speciosa* Hassk, *Archidendron jiringa* (Jack) I.C.Nielsen, *Durio zibethinus* L., *Peronema canescens* Jack, *Rubroshorea leprosula* (Miq.) P.S.Ashton & J.Heck. and *Dyera polyphylla* (Miq.) Steenis, were planted in 48 of the 56 study plots. The experiment was set in a random partition design (Bell et al., 2009) comprising four partitions with varying plot area, i.e. quadratic tree islands (25 m^2, 100 m^2, 400 m^2, 1600 m^2). Each partition is divided into five blocks representing distinct tree diversity levels (0 = no tree planting, 1, 2, 3, and 6 planted native tree species). Species diversity and species identity were varied across the plots. Within each block, species are randomly selected from the species pool without replacement. This ensures that each species is chosen exactly once at each diversity level. Species compositions are random but subject to the restriction that no repetitions occurred across all plots. Oil palms were planted 6–12 years prior to the establishment of the experiment, on a 9.8 m triangular grid. To enhance light availability for tree establishment, 40% of the oil palms were felled before tree planting, except for the smallest plots where plots were fitted in-between palm rows (Teuscher et al., 2016). In addition to the 48 plots with tree planting, four plots were treated equally but no trees were planted. No agrochemicals such as fertilizers or pesticides have been applied since the establishment of the experiment, but to improve establishment success, fertilizers were applied once inside the planting hole prior to planting (see Teuscher et al., 2016 for detailed method). In 2020, the overall mean tree height of tree island (planted trees and naturally established trees) was 8.8 ± 3.5 m (Mean ± SD) (Montoya-Sánchez et al., 2024). The experiment further comprises four control plots in the commercial oil palm plantation, where no trees were planted and conventional management including the use of herbicides and fertilizers was carried out. Our study was conducted in 2022, nine years after tree planting.

3.2.2.2. Landscape assessment

EFForTS-LA was established across 132 plots in lowland Sumatra, covering four land-use types: forest, shrubland, rubber plantations and oil palm plantations. The plots in the landscape assessment were circular (1000 m^2) with five subplots (25 m^2) (Pallavi et al., 2024). In the present study, we use the forest (n = 30) and oil palm (n = 32) data for comparison to EFForTS-BEE (Appendix, Fig. A3. 2). The forest plots encompassed secondary rainforest and degraded primary rainforest stands with a minimum of 50% tree canopy cover above the lowest vegetation layer. Plots located in the Bukit Duabelas National Park and the Harapan rainforest showed less disturbance than forest plots outside these protected areas. The assessed oil palm plantations were monoculture plantations located across smallholder farms and commercial enterprises (Camarretta et al., 2021). The landscape assessment data already contributed to the publication of Pallavi et al. (2024), which covered more land-use types but did not assess the effects of the tree planting experiment. In the present study, the forest and oil palm data are used as a reference for the tree integration experiment.

3.2.3. Field measurements

3.2.3.1. Leaf area index (LAI)

We used a LAI-2200C Plant Canopy analyzer (LI-COR, Biosciences Inc., Lincoln, USA) to measure canopy leaf area index (LAI, m^2 m^{-2}). This instrument consists of two wands equipped with optical sensors designed for radiation measurement, with one wand capturing above-canopy radiation and the other one below-canopy radiation. Each measurement involves assessing canopy light interception at five zenith angles from both above and below canopy readings. The LAI values are subsequently computed by the software FV2200 (V2.1). We used the 45° view restriction cap while taking readings. In our study, the above-canopy wand was positioned in an open area adjacent to the study plot; on the plot, data collection was done at a height of 1.3 m, both wands capture the data simultaneously. Multiple measurements were obtained per plot (in BEE, the number of measurements varied from 1 to 3; one measurement in 25 m^2 and 100 m^2 plots, two measurements in 400 m^2 plots and three measurements in 1600 m^2 plots) and averaged, measured as recommended in the early morning, between June 2021 and March 2022 (LA) and June 2022 and October 2022 (BEE).

3.2.3.2. Below-canopy surface temperature

We used a Fluke PTi120 9 Hz thermal camera (Fluke Corporation, WA, USA) with an infrared resolution of 120 × 90 to measure below-canopy temperatures of different surfaces, i.e., the ground surface a blue color workers' cap and light brown color hijab (colors were chosen based on the commonly used colors by farm workers in and around the field site) and a black and white board. Cap and hijab were placed at 1.5 m height. Images were captured at a height of 2.5 m from the ground which is well within the margins of high accuracy measurements with the device (until 3 m distance from the object) while capturing the maximum possible ground area (2.30 m x 1.72 m). The distance between the camera and the ground, as well as black and white board was 2.5 m, while for the cap and hijab, the distance was approximately 1 m. The images were captured at 11:00 am, 12:00 pm, 1:00 pm, and 2:00 pm of the respective measurement day. Each plot was visited once during the field campaign (LA: June 2021 to March 2022; BEE: June to October 2022). Ground surface temperature measurements were conducted at sub-plot level and then averaged for each plot. The other assessed surfaces were placed well inside the plot in a given plot in the early mornings and left there undisturbed until the final measurement at 2:00 pm. They were measured at plot level per time interval.

Measurements were never conducted during or shortly after rainfall. The temperature data were extracted from the thermal images using the Fluke Connect (V1.1.548.0) software.

3.2.3.3. Ambient air temperature and radiation

Ambient air temperature below the canopy was measured using a thermo-hygrometer (BC06, TROTEC, Germany) at a height of 1.3 m. Incoming solar radiation was measured using a SpectraPen mini-PSI25168 (Photon System Instruments, Czech Republic), a compact and portable spectroradiometer calibrated for visible light (see e.g. Niedermaier et al., 2020; Wojciechowska et al., 2020). Simultaneous radiation measurements were taken both within the plot (i.e. below the canopy) and in an adjacent open area.

3.2.3.4. Stand structural complexity index (SSCI)

Between December 2022 and January 2023, terrestrial laser scans were conducted in each plot to capture the 3D distribution of foliage and woody components using a FARO Focus terrestrial laser scanner (Faro Technologies Inc., Lake Mary, USA). The laser scanner was placed on a tripod at a height of 1.3 m, and it was raised by up to 20 cm to position the instrument above the understory vegetation if necessary. The instrument was set to scan with a field of view of 360° horizontally and 300° vertically, with a step width of 0.035° (Zemp et al., 2019). The single laser scans, made at the center of each plot (Kikuchi et al., 2024), were then processed and used to calculate the stand structural complexity index (SSCI) as described by Ehbrecht et al. (2017).

3.2.3.5. Observed species diversity

In EFForTS-BEE, inventories are conducted biennially to record naturally recruiting woody species and the total stem count, along with an inventory of the originally planted trees (Paterno et al., 2024). In this study, we used the observed diversity (planted tree diversity plus naturally recruited diversity) per plot recorded in 2022 (after nine years of establishment). A total of 79 species belonging to 35 families were recorded, accounting for 3,564 stems.

3.2.4. Statistical analysis

We employed Kruskal-Wallis with Dunn's post hoc tests to examine significant differences of LAI, below-canopy surface temperatures (ground, cap and hijab, black and white board), and ambient air temperature across the studied plots in EFForTS-LA and EFForTS-BEE. We further calculated mean and standard deviation for each land-use type.

To predict below-canopy surface temperatures, we first employed a linear mixed-effects model utilizing the R package lme4 (v1.1.33; Bates et al., 2015), with the fixed variables LAI, solar irradiance, SSCI, observed diversity and time of day; plot ID entered as a random factor. Continuous variables were standardized using the scale function, resulting in a mean of zero and a standard deviation of one. This standardization allows for easier comparison of effect sizes among variables. We performed stepwise selection (using the function dredge in the R package MuMIn version 1.48.4, Bartoń, 2024) to select the best-performing model according to their AIC values.

We used linear regression analysis to study the relationship between different surface temperatures and LAI in EFForTS-BEE. In line with the EFForTS-BEE study design, we further applied a random partition analysis (Bell et al. 2009) to examine effects of island area and planted diversity on LAI and on below-canopy temperatures. All analyses and visualizations were performed with R statistical software (v4.3.0; R core team, 2023).

3.3 Results

3.3.1 Leaf area index (LAI)

There was a significant difference in LAI among the land-use types (Kruskal-Wallis χ^2 = 197.87, df=4, $p < 0.05$). The LAI in the oil palm control plots of EFForTS-BEE (2.9 ± 0.3 m^2 m^{-2}, mean ± SD, n = 4) was statistically indistinguishable from the LAI of oil palm plantations in EFForTS-LA (2.9 ± 0.9 m^2 m^{-2}, n = 30) (Fig. 1). LAI in plots without tree planting (n = 4) and with tree planting (n = 48) did not differ significantly; in plots with tree planting it ranged from 1.7 to 5.6 m^2 m^{-2} and had a mean of 3.7 m^2 m^{-2} (SD ± 1.0), which was significantly higher than in monoculture oil palm but lower than in forest plots (5.9 ± 0.6 m^2 m^{-2}).

3.3.2 Below-canopy temperatures

Below-canopy ground surface temperature varied significantly among the land-use types (Kruskal-Wallis χ^2 = 52.32, df=4, $p < 0.05$). The below-canopy ground surface temperature in the oil palm control plots of the EFForTS-BEE (29.5 ± 1.6 ˚C, n = 4) did not differ significantly from to the below-canopy ground surface temperature of oil palms in the EFForTS-LA (30.1 ± 3.0 ˚C, n = 32) (Fig. 2). Similarly, plots with no tree planting (n = 4) showed no significant difference (29.3 ± 1.6°C) compared to oil palm plots. Plots with tree planting (n = 48) had significantly lower temperature (28.6 ± 2.0 ˚C) than oil palm plantations but higher than forest plots (27.2 ± 1.2, n = 30).

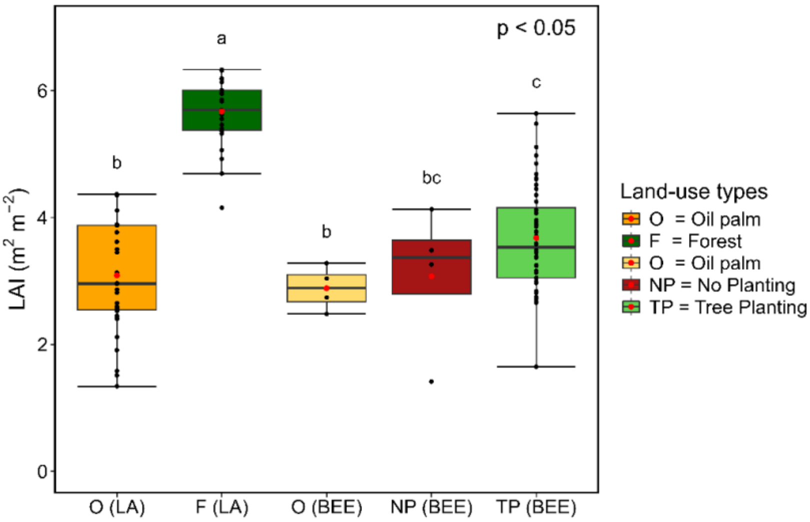


Fig. 3.1. Leaf area index (LAI) across plots in EFForTS-LA and EFForTS-BEE. Plots comprise forest (F, n = 30) and conventional oil palm monocultures (O, n = 32) from the landscape assessment, and in BEE oil palm control plots (O, n = 4), no tree planting with natural recruitment plots (NP, n = 4) and tree planting with natural recruitment plots (TP, n = 48). Different letters indicate significant differences at P < 0.05 (Kruskal-Wallis test with Dunn's post-hoc test). Red dots indicate mean values.

Worker cap and hijab surface temperature differed significantly among the land-use types (Kruskal-Wallis $\chi^2 = 85.53$, df=4, $p < 0.05$ and $\chi^2 = 68.63$, df = 4, $p < 0.05$ respectively). Worker cap surface temperatures in tree planting plots (32.30 ± 4.5 ˚C) were similar to oil palm (32.47 ± 2.7 ˚C) but significantly higher than in forest (28.74 ± 1.5˚C). Hijab surface temperature in tree planting plots (30.6 ± 2.6 ˚C) were significantly lower than oil palm (32.0 ± 3.7 ˚C) and higher than in forest (28.5 ± 41.5 ˚C). Similar trends were observed for the white and black reference board. Below-canopy air temperature did not differ significantly among experimental plots with or without tree planting and oil palm monocultures, but was significantly lower in forest.

3.3.3 Predictors of below-canopy temperature

The below-canopy temperature measurements in the BEE were conducted under varying environmental conditions, with open-area solar irradiance at the time of measurement ranging from 30 W m^{-2} to 658 W m^{-2} (mean: 314 W m^{-2}; SD: 167 W m^{-2}). We thus applied linear mixed-effect models to the data from the 52 experimental BEE plots (No planting and Tree planting plots), with the predictor variables solar irradiance and time of day and the vegetation characteristics LAI, stand structural complexity (SSCI) and observed tree species diversity. Here, the models with ground surface temperature as the response variable are presented. Among 64 models (Appendix, Table A3.1), we selected the best supported one (Model 36), with the lowest AIC (763.0) and BIC (789.5). This model included the variables LAI, open-area irradiance and time of day. The model had a conditional R^2 of 0.60 and a marginal R^2 of 0.30 (Table 1). The standardized model coefficient (Table 2) revealed a strong negative effect of LAI on below-canopy ground surface temperature (β = -0.64, CI: -1.00 - -0.27), and a strong positive effect of solar irradiance (β = 0.59, CI: 0.36 - 0.82). Time of day also had a positive effect, with significantly increased temperatures at 1:00 pm (β = 0.77, CI: 0.29 - 1.24) and 2:00 pm (β = 0.83, CI: 0.35 - 1.32) compared to (pre-) noon measurements. SSCI and observed tree diversity had a small negative effect on below-canopy ground surface temperature (β = -0.08, CI: -0.51 - 0.34 and β = -0.68, CI: -1.53 – 0.17 respectively) which was not statistically significant. Island area was not statistically significant either (Appendix, Table A3.2) and was thus not retained in the best model. The random factor (plot) accounted for 30% of the variation in below-canopy ground surface temperature (Table 2).

In a linear regression analysis, below-canopy temperatures of the ground significantly increased with decreasing LAI ($R^2 = 0.15$, $P < 0.05$, Fig. 3.3). The slope of the regression line was 0.9, indicating that a decrease in LAI by one unit on average corresponds to a 0.90 °C increase (CI: 1.20 - 0.61 °C) in ground surface temperature. For the workers' cap and hijab, a one unit decrease of LAI corresponds to temperature increases of 1.22 °C (CI: 1.92 - 0.53 °C) and 0.76 °C (CI: 1.17 - 0.35 °C), respectively. Similarly, a unit decrease in LAI corresponded to respective 0.72 °C (CI: 1.04 - 0.41 °C) and 1.20 °C (CI: 1.84 - 0.56 °C) increases in white board and black board surface temperature. Ambient air temperature below the canopy increased by 0.62 °C (CI: 0.84 - 0.41 °C) for every unit decrease in LAI (Fig. 3.3, Appendix, Table A3.3). All models were significant ($P < 0.05$), but the explained variance was small for all six below-canopy temperature variables (R^2 = 0.15 (ground), 0.05 (cap), 0.06 (hijab), 0.08 (white board), 0.06 (black board), and 0.13 (air)). Below-canopy temperatures also increased with decreasing SSCI, but again the explained variance by the model was small ($R^2 = 0.04$). The observed tree diversity (planted trees and natural woody recruitment) did not show significant effects on below-canopy surface temperatures.

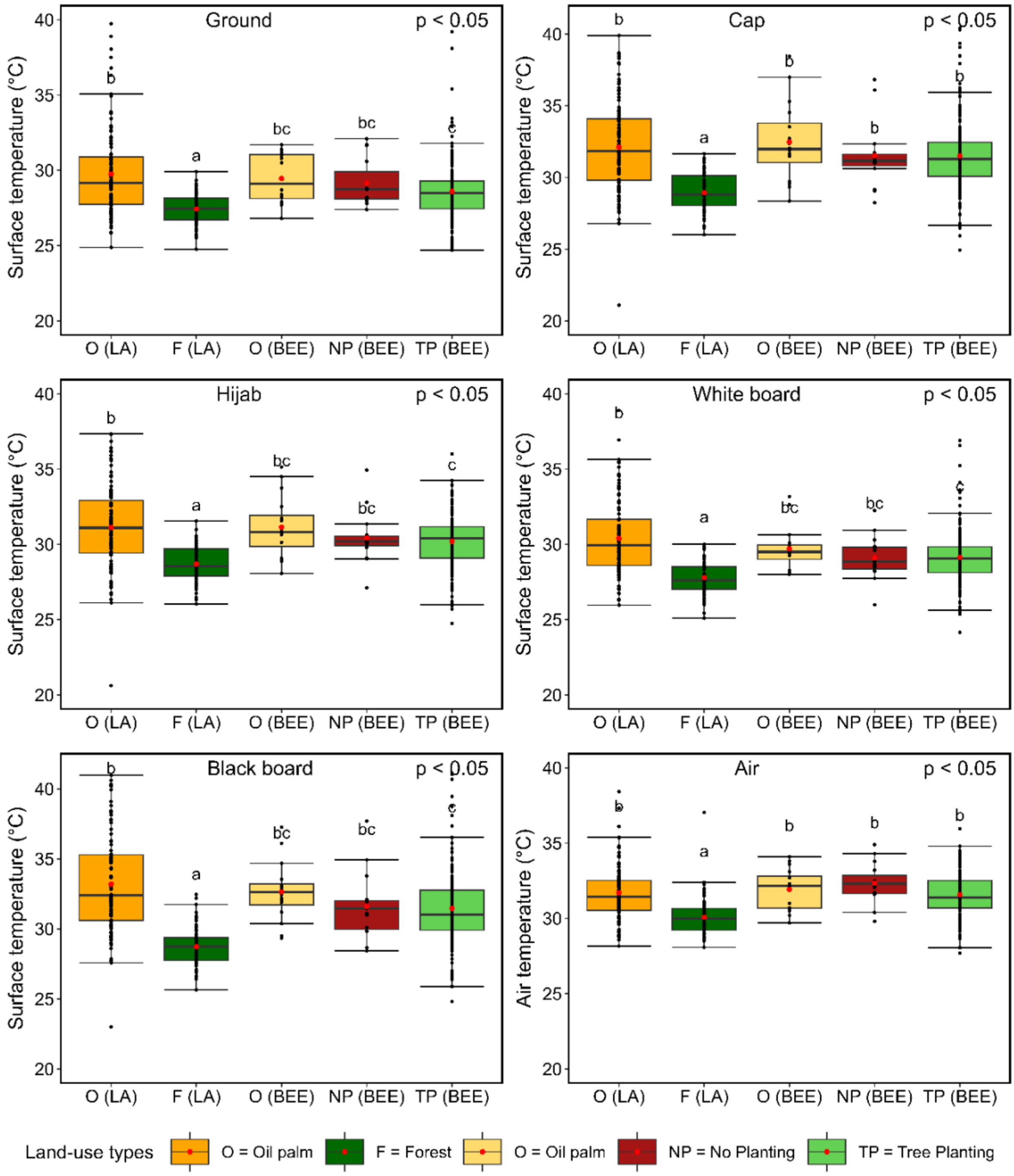


Fig. 3.2. Below-canopy temperatures across plots in the wider landscape (EFForTS-LA) and in the biodiversity enrichment experiment (EFForTS-BEE). Below-canopy temperatures of different surfaces (ground, workers' cap and hijab, reference black and white board) and of the air are presented. Plots comprise forest (F, n = 30) and conventional oil palm monocultures (O, n = 32) from the landscape assessment, and in BEE oil palm control plots (O, n = 4), no tree planting with natural recruitment plots (NP, n = 4) and tree planting with natural recruitment plots (TP, n = 48). Different letters indicate significant differences at p < 0.05 (Kruskal-Wallis test with Dunn's post-hoc test). Red dots indicate mean values.

Table 3.1 Performance of linear mixed-effect models for the target variable below-canopy ground surface temperature (n = 52). Model performance is evaluated in terms of Akaike information criterion (AIC), Bayesian information criterion (BIC), conditional and marginal coefficient of determination (R^2) and root mean square error (RMSE) for the null model (no fixed factor), the full model (all fixed factors) and the best model (based on model performance). Model selection was by stepwise selection using the R function 'dredge'. All continuous variables were scaled. BCGST: below-canopy ground surface temperature, LAI: leaf area index, IRR: irradiance, SSCI: stand structural complexity index.

Model type	Variables	Model performance				
		AIC	BIC	R^2 (cond.)	R^2 (marg.)	RMSE
Best	BCGST ~ LAI + IRR + Time + (1|Plot)	763.0	789.5	0.62	0.25	1.077
Full	BCGST ~ LAI + IRR +Time + SSCI + Observed diversity + Island area (1|Plot)	768.8	812.0	0.63	0.28	1.073
Null	BCGST ~ 1 + (1|Plot)	794.7	804.7	0.54	0.00	1.185

3.3.4 Effects of planted tree diversity and island area

In EFForTS-BEE, planted tree diversity and island area are the initial experimental treatments. The random partition design allowed for testing their effects on LAI and below-canopy temperatures (No planting plus Tree planting; n = 52). For LAI, the random partition ANOVA showed no significant effects of planted species richness, species identity or species interaction, but a marginally significant effect of island area on LAI (P = 0.056). The effect was positive, i.e. larger tree islands tend to have higher LAI (Appendix, Table A3.4). For all six below-canopy temperature variables, there were no significant effects of planted species richness or island area. For the workers' cap surface temperature, there was a marginally significant effect of species identity (P = 0.052), and for the hijab surface temperature there were marginally significant effects of species identity (P = 0.071) and species interaction (P = 0.087).

Table 2. Model estimates and statistics of the best performing linear mixed-effect model for the target variable below-canopy ground surface temperature. Leaf area index (LAI), solar irradiance (IRR) and time of day are the fixed factors, plot is the random factor. All continuous variables were scaled. Estimates are provided with standard errors (SE), 95% confidence intervals (CI) and significance level (P). A version of the model with stand structural complexity index (SSCI) and observed diversity as additional (but non-significant) predictors can be found in Appendix, Table A3.1.

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	28.24	0.24	27.77 - 28.71	< 0.001
LAI	-0.64	0.19	-1.00 - -0.27	0.001
IRR (Open area)	0.59	0.12	0.36 - 0.82	< 0.001
Time 12.00 pm	0.22	0.24	-0.26 - 0.70	0.376
Time 1.00 pm	0.77	0.24	0.29 - 1.24	0.002
Time 2.00 pm	0.83	0.25	0.35 - 1.32	0.001
Random Effects				
σ^2	1.49			
t_{00}	1.40			
ICC	0.48			
N	52			
Observations	205			
Marginal R^2/Conditional R^2	0.3/0.6			

3.4 Discussion

Tree integration into conventional monoculture oil palm cultivation increased LAI and reduced below-canopy temperatures. The results point to LAI as a key predictor of below-canopy surface temperatures among vegetation characteristics. Other factors such as observed tree diversity, stand structural complexity or planted tree diversity and tree island area were less important.

3.4.1 H1: Tree integration into oil palm cultivation enhances LAI and reduces below-canopy temperatures

The LAI of tree island with tree planting and natural recruitment (3.7 m^2 m^{-2} ± 0.8 SD) was higher than that of oil palm monocultures (2.9 ± 0.3) but smaller than that of forests (5.93 ± 0.6). Other studies from tropical forests reported mean LAIs between 5.07 and 5.5 m^2 m^{-2} (Malhado et al., 2009; Olivas et al., 2013). Our observed LAI in plots with tree planting aligns with LAI values observed in other agroforestry systems (1–5.3 m^2) in tropical landscapes (Khairiah et al., 2017; Mendes dos Santos et al., 2020). It is at the lower range of values for young secondary forests (4–5 m^2), as e.g. recovering after shifting cultivation (Hölscher et al., 2005; Aragão et al., 2005). This indicates that there might still be potential for further enhancement of LAI by tree growth and forest recovery. Reasons for the relatively modest LAI nine years after tree planting may include the relatively high share and canopy cover of oil palms on the plots (Khokthong et al., 2019) and the high mortality of some planted species (*Rubroshorea leprosula*, *Durio zibethinus*). Further, there was a relatively low share of forests and trees in the landscape surrounding the plots that could have served as seed sources (Korol et al., 2021; Paterno et al., 2024), as well as high land-use intensity prior to the establishment of the experiment, e.g. compared to shifting cultivation.

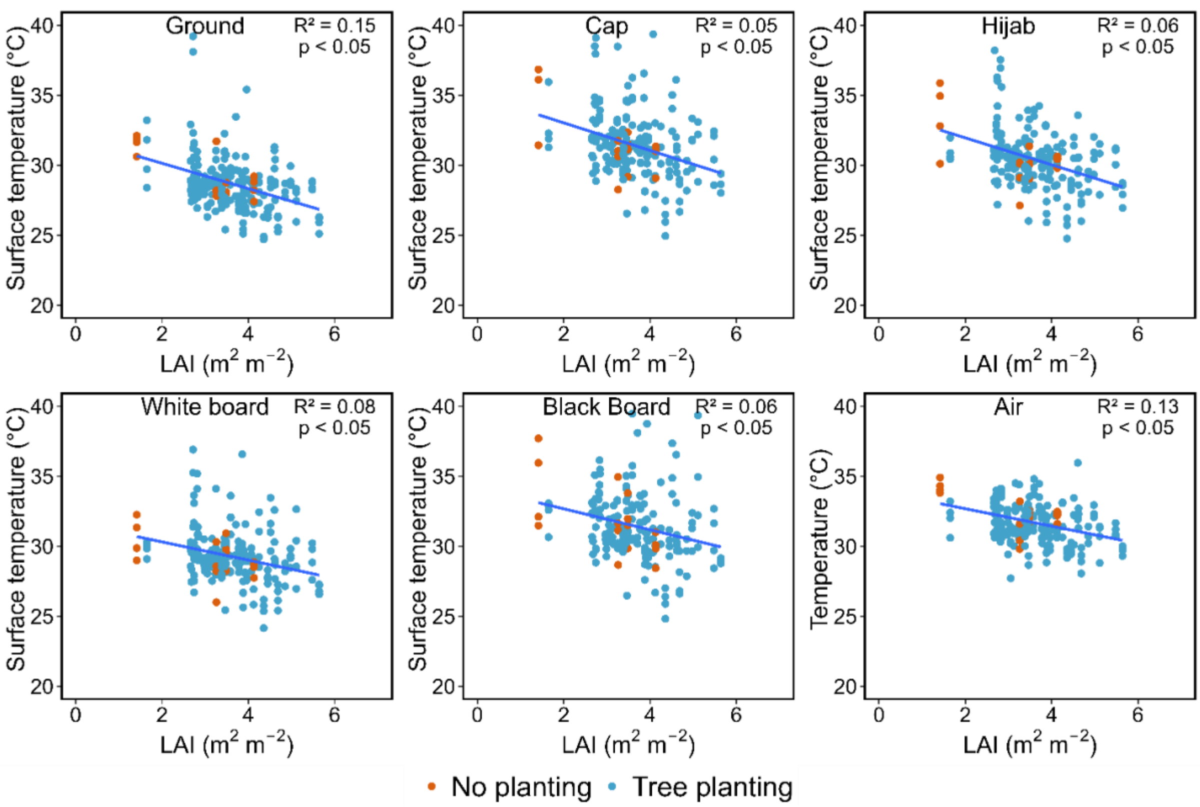


Fig. 3.3 Relationship between leaf area index (LAI) and different below-canopy temperatures in the tree enrichment experiment (n = 52). Linear regressions show the association between LAI and temperatures measured on different surfaces: ground, workers' cap, hijab, whiteboard, blackboard, and ambient air below the canopy. Green dots represent plots with tree planting (n = 48), while red dots indicate plots without tree planting (n = 4). Data are pooled across measurement times (11:00 AM, 12:00 PM, 1:00 PM, and 2:00 PM).

The ground surface around noon was 1.5 ± 0.6 °C cooler in tree islands than in oil palm monocultures, but higher than in forests. Similar trends were observed for other measured surfaces (hijab, cap, white and black board). Our results are supported by studies that showed air and surface temperature beneath the canopy in forest are cooler than oil palm (Hardwick et al., 2015; Meijide et al., 2018; Pallavi et al., 2024). We found that air temperature in tree islands is 0.3 ± 0.1 °C lower than in oil palm. In a previous study, five years after tree planting, ambient air temperature and land surface temperatures in EFForTS-BEE were not clearly different between mixed-species plantations and natural regeneration (Donfack et al., 2021), but were generally higher in natural regeneration compared to in oil palm monocultures. Despite differences in methods (temporal and spatial replications) this points to an increased cooling effect over time via successional advancement of the vegetation. The findings suggest that tree integration buffers temperatures, which is in line with the observation that forests buffer temperature extremes (De Lombaerde et al., 2022). Overall, the results support our hypothesis H1, i.e. that tree integration into oil palm cultivation enhances LAI and reduces below-canopy temperatures.

3.4.2 H2: Below-canopy temperatures decrease with increasing canopy LAI, stand structural complexity and observed woody plant diversity

Our best mixed effect model for the response variable below-canopy ground surface temperature explained a substantial amount of variation, with a conditional R^2 of 0.6 and a marginal R^2 of 0.3. It included the predictor variables LAI, open-area irradiance and time of day. Below-canopy ground temperature decreased with increasing LAI, increased with increasing irradiance, and increased from 11 am towards 2 pm. Under such ambient conditions, more energy is available by solar irradiance and preceding warming of the ground increases ground temperature. Since increasing LAI means that the ground area is increasingly covered by several leaf layers, such a relationship is expected and confirms former observations (Pallavi et al., 2024). Looking at the key predictor in the final model, LAI, our study shows a one unit increase in LAI corresponding to a 0.9 °C (CI 1.20 – 0.61) decrease in below-canopy ground surface temperature, which is consistent (0.95 °C) with the findings by Pallavi et al. (2024). A stand structural complexity index (SSCI) and the observed tree diversity were not statistically significant and thus not retained in the best model. This partially stands in contrast to previous studies. As such, in temperate European forest Ehbrecht et al. (2017) found that SSCI significantly influenced daily fluctuations in below-canopy air temperatures, with lower temperatures around noon at high SCCI. Also in our study, SSCI was related to below-canopy temperatures in a simple linear regression. However, it was not selected into the best mixed-effect model because LAI is another, yet more powerful predictor among vegetation characteristics; the two variables are correlated and to some extent probably explain part of the same variation (Spearman's R = 0.24). Regarding tree diversity, a comprehensive analysis across TreeDivNet plots by Schnabel et al. (2024) found that increasing tree diversity reduced soil temperatures. The buffering effect of tree diversity, however, was mediated through canopy density and structural diversity, as measured by LAI and SSCI (Schnabel et al., 2023). In our study, LAI was part of the final model and probably already incorporated effects of structural diversity and tree diversity, which were both removed from the final model due to their statistical insignificance. Furthermore, the woody species richness (n = 79 spp., unpublished data from EFForTS 2022 inventory) and observed diversity per plot in EFForTS-BEE is relatively high and higher than in most tree diversity experiments, as the planted diversity is substantially increased by the allowed recruited diversity. Changes at such high levels of diversity may have only minor effects, suggesting an effect of diminishing returns. We conclude that our hypothesis H2 is partly supported with respect to LAI, but rejected with regard to SSCI and observed tree diversity.

3.4.3 H3: Planted tree diversity and island area increase LAI and reduce below-canopy temperatures

The direct treatments in EFForTS-BEE were planted tree diversity and island area, which are motivated by positive biodiversity-ecosystem function relationships (Tilman et al., 2014; Zheng et al., 2024) and the theory of island biogeography (MacArthur and Wilson, 1967; Schrader et al., 2024). In a random partition analysis, we found no effect of planted tree diversity on LAI or below-canopy surface temperatures. There was a marginally significant effect of island area ($P = 0.056$) for LAI and no significant effect for below-canopy surface temperatures. As discussed before, this contrasts with the recent finding that tree species diversity increases temperature buffering below the canopy and prevents soil heating in hot weather (Schnabel et al., 2023; Huang et al., 2024). Both planted tree diversity and island area were significant predictors of the recruitment of woody species in EFForTS-BEE, with a larger weight of island area (Paterno et al., 2024). The marginally significant effects of island area on LAI could be in line with this finding. However, overall, hypothesis H3 is rejected.

3.4.4 Considerations for a healthier rural thermal environment

We found that integrating trees into oil palm cultivation enhances LAI and reduces below-canopy surface temperatures. The reduction of 1.5 °C around noon seems modest in view of the increasing heat stress imposed on nature and humans, given the steep increase in global temperatures and the additional direct effects of land-use change on below-canopy surfaces. However, for nature and people exposed to tropical heat and its adverse effects on health, tree integration appears as a potential way to mitigate such effects. It is thus far more acknowledged in urban environments but should also get more attention in rural areas (Chandrashekhar, 2023; Li et al., 2024; Wolff et al., 2018). Rising heat is expected to surpass pollution as a major health burden including mortality by the end of this century, as indicated in a recent modelling study (Pozzer et al., 2024). The adverse effects of deforestation on below-canopy temperatures and human heat stress are reversible to their original state after restoration, without permanently altering the system's ability to regulate temperature. Our study does not indicate a specific effect of tree diversity at high levels, but since positive effects of tree diversity are widespread, e.g. for early tree survival or natural regeneration (Blondeel et al., 2024; Paterno et al. 2024) and general biodiversity and ecosystem functions (Zemp et al. 2023; Messier et al., 2022), we would maintain the suggestion of developing diverse tree communities. In this context, tree planting combined with natural regeneration was more effective than natural regeneration alone, thus calling for active tree planting. The areas should not be too small, as suggested by the marginally significant results on island area. Thus, in addition to well-known effects of tree planting on biodiversity and ecosystem functions, it also has positive effect on human health.

3.5 References

Allen, K., Corre, M.D., Tjoa, A., Veldkamp, E., 2015. Soil Nitrogen-Cycling Responses to Conversion of Lowland Forests to Oil Palm and Rubber Plantations in Sumatra, Indonesia. PLoS ONE 10, e0133325. https://doi.org/10.1371/journal.pone.0133325

Aragão, L.E.O.C., Shimabukuro, Y.E., Espírito Santo, F.D.B., Williams, M., 2005. Landscape pattern and spatial variability of leaf area index in Eastern Amazonia. Forest Ecology and Management 211, 240–256. https://doi.org/10.1016/j.foreco.2005.02.062

Ashcroft, M.B., 2010. Identifying refugia from climate change. Journal of Biogeography 37, 1407–1413. https://doi.org/10.1111/j.1365-2699.2010.02300.x

Austin, K.G., Schwantes, A., Gu, Y., Kasibhatla, P.S., 2019. What causes deforestation in Indonesia? Environ. Res. Lett. 14, 024007. https://doi.org/10.1088/1748-9326/aaf6db

Bartoń K (2024). MuMIn: Multi-Model Inference. R package version 1.48.4, https://CRAN.R-project.org/package=MuMIn

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using **lme4**. J. Stat. Soft. 67. https://doi.org/10.18637/jss.v067.i01

Bell, T., Lilley, A.K., Hector, A., Schmid, B., King, L., Newman, J.A., 2009. A Linear Model Method for Biodiversity–Ecosystem Functioning Experiments. The American Naturalist 174, 836–849. https://doi.org/10.1086/647931

Blondeel, H., Guillemot, J., Martin-StPaul, N., Druel, A., Bilodeau-Gauthier, S., Bauhus, J., Grossiord, C., Hector, A., Jactel, H., Jensen, J., Messier, C., Muys, B., Serrano-León, H., Auge, H., Barsoum, N., Birhane, E., Bruelheide, H., Cavender-Bares, J., Chu, C., Cumming, J.R., Damtew, A., Eisenhauer, N., Ferlian, O., Fiedler, S., Ganade, G., Godbold, D.L., Gravel, D., Hall, J.S., Hölscher, D., Hulvey, K.B., Koricheva, J., Kreft, H., Lapadat, C., Liang, J., Liu, X., Meredieu, C., Mereu, S., Montgomery, R., Morillas, L., Nock, C., Paquette, A., Parker, J.D., Parker, W.C., Paterno, G.B., Perring, M.P., Ponette, Q., Potvin, C., Reich, P.B., Rentch, J., Rewald, B., Sandén, H., Sinacore, K., Standish, R.J., Stefanski, A., Tobin, P.C., van Breugel, M., Fagundes, M.V., Weih, M., Williams, L.J., Zhou, M., Scherer-Lorenzen, M., Verheyen, K., Baeten, L., 2024. Tree diversity reduces variability in sapling survival under drought. Journal of Ecology 112, 1164–1180. https://doi.org/10.1111/1365-2745.14294

Braga, D.P.P., Miccolis, A., Ramos, H.M.N., Cunha, L.F., de Sousa, L.V.F., Marques, H.R., 2024. Implications of smallholder livelihoods for scaling oil palm agroforestry in Brazilian Eastern Amazon. World Development Sustainability 4, 100128. https://doi.org/10.1016/j.wds.2024.100128

Budiadi, Susanti, A., Marhaento, H., Ali Imron, M., Permadi, D.B., Hermudananto, 2019. Oil palm agroforestry: an alternative to enhance farmers' livelihood resilience. IOP Conf. Ser.: Earth Environ. Sci. 336, 012001. https://doi.org/10.1088/1755-1315/336/1/012001

Camarretta, N., Ehbrecht, M., Seidel, D., Wenzel, A., Zuhdi, Mohd., Merk, M.S., Schlund, M., Erasmi, S., Knohl, A., 2021. Using Airborne Laser Scanning to Characterize Land-Use Systems in a Tropical Landscape Based on Vegetation Structural Metrics. Remote Sensing 13, 4794. https://doi.org/10.3390/rs13234794

Campbell, S., Remenyi, T.A., White, C.J., Johnston, F.H., 2018. Heatwave and health impact research: A global review. Health & Place 53, 210–218. https://doi.org/10.1016/j.healthplace.2018.08.017

Chandrashekhar, V., 2023. Heat-proofing India. Science 381, 1393–1397. https://doi.org/10.1126/science.adl0416

Clough, Y., Krishna, V.V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A.D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., Holtkamp, A.M., Hörandl, E., Irawan, B., Jaya, I.N.S., Jochum, M., Klarner, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Kurniawan, S., Leuschner, C., Maraun, M., Melati, D.N., Opfermann, N., Pérez-Cruzado, C., Prabowo, W.E., Rembold, K., Rizali, A., Rubiana, R., Schneider, D., Tjitrosoedirdjo, S.S., Tjoa, A., Tscharntke, T., Scheu, S., 2016. Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. Nat Commun 7, 13137. https://doi.org/10.1038/ncomms13137

Cohn, A.S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., Thompson, S., 2019. Forest loss in Brazil increases maximum temperatures within 50 km. Environ. Res. Lett. 14, 084047. https://doi.org/10.1088/1748-9326/ab31fb

De Lombaerde, E., Vangansbeke, P., Lenoir, J., Van Meerbeek, K., Lembrechts, J., Rodríguez-Sánchez, F., Luoto, M., Scheffers, B., Haesen, S., Aalto, J., Christiansen, D.M., De Pauw, K., Depauw, L., Govaert, S., Greiser, C., Hampe, A., Hylander, K., Klinges, D., Koelemeijer, I., Meeussen, C., Ogée, J., Sanczuk, P., Vanneste, T., Zellweger, F., Baeten, L., De Frenne, P., 2022. Maintaining forest cover to enhance temperature buffering under future climate change. Science of The Total Environment 810, 151338. https://doi.org/10.1016/j.scitotenv.2021.151338

Depauw, L., De Lombaerde, E., Dhiedt, E., Blondeel, H., Abdala-Roberts, L., Auge, H., Barsoum, N., Bauhus, J., Chu, C., Damtew, A., Eisenhauer, N., Fagundes, M.V., Ganade, G., Gendreau-Berthiaume, B., Godbold, D., Gravel, D., Guillemot, J., Hajek, P., Hector, A., Hérault, B., Jactel, H., Koricheva, J., Kreft, H., Liu, X., Mereu, S., Messier, C., Muys, B., Nock, C.A., Paquette, A., Parker, J.D., Parker, W.C., Paterno, G.B., Perring, M.P., Ponette, Q., Potvin, C., Reich, P.B., Rewald, B., Scherer-Lorenzen, M., Schnabel, F., Sousa-Silva, R., Weih, M., Zemp, D.C., Verheyen, K., Baeten, L., 2024. Enhancing Tree Performance Through Species Mixing: Review of a Quarter-Century of TreeDivNet Experiments Reveals Research Gaps and Practical Insights. Curr. For. Rep. 10, 1–20. https://doi.org/10.1007/s40725-023-00208-y

Donfack, L.S., Röll, A., Ellsäßer, F., Ehbrecht, M., Irawan, B., Hölscher, D., Knohl, A., Kreft, H., Siahaan, E.J., Sundawati, L., Stiegler, C., Zemp, D.C., 2021. Microclimate and land surface temperature in a biodiversity enriched oil palm plantation. Forest Ecology and Management 497, 119480. https://doi.org/10.1016/j.foreco.2021.119480

Doughty, C.E., Keany, J.M., Wiebe, B.C., Rey-Sanchez, C., Carter, K.R., Middleby, K.B., Cheesman, A.W., Goulden, M.L., da Rocha, H.R., Miller, S.D., Malhi, Y., Fauset, S., Gloor, E., Slot, M., Oliveras Menor, I., Crous, K.Y., Goldsmith, G.R., Fisher, J.B., 2023. Tropical forests are approaching critical temperature thresholds. Nature 621, 105–111. https://doi.org/10.1038/s41586-023-06391-z

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., Fauzi, A.M., Gunawan, D., Hertel, D., Irawan, B., Jaya, I.N.S., Klarner, B., Kleinn, C., Knohl, A., Kotowska, M.M., Krashevska, V., Krishna, V., Leuschner, C., Lorenz, W., Meijide, A., Melati, D., Nomura, M., Pérez-Cruzado, C., Qaim, M., Siregar, I.Z., Steinebach, S., Tjoa, A., Tscharntke, T., Wick, B., Wiegand, K., Kreft, H., Scheu, S., 2016. Ecological and socio-economic functions across tropical land use systems after rainforest conversion. Phil. Trans. R. Soc. B 371, 20150275. https://doi.org/10.1098/rstb.2015.0275

Ehbrecht, M., Schall, P., Ammer, C., Seidel, D., 2017. Quantifying stand structural complexity and its relationship with forest management, tree species diversity and microclimate. Agricultural and Forest Meteorology 242, 1–9. https://doi.org/10.1016/j.agrformet.2017.04.012

Gérard, A., Wollni, M., Hölscher, D., Irawan, B., Sundawati, L., Teuscher, M., Kreft, H., 2017. Oil-palm yields in diversified plantations: Initial results from a biodiversity enrichment experiment in Sumatra, Indonesia. Agriculture, Ecosystems & Environment 240, 253–260. https://doi.org/10.1016/j.agee.2017.02.026

Givnish, T.J., 2024. Global conservation priorities for island plant diversity. Nature d41586-024-02921–5. https://doi.org/10.1038/d41586-024-02921-5

Grass, I., Kubitza, C., Krishna, V.V., Corre, M.D., Mußhoff, O., Pütz, P., Drescher, J., Rembold, K., Ariyanti, E.S., Barnes, A.D., Brinkmann, N., Brose, U., Brümmer, B., Buchori, D., Daniel, R., Darras, K.F.A., Faust, H., Fehrmann, L., Hein, J., Hennings, N., Hidayat, P., Hölscher, D., Jochum, M., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Leuschner, C., Lobite, N.J.S., Panjaitan, R., Polle, A., Potapov, A.M., Purnama, E., Qaim, M., Röll, A., Scheu, S., Schneider, D., Tjoa, A., Tscharntke, T., Veldkamp, E., Wollni, M., 2020. Trade-offs between multifunctionality and profit in tropical smallholder landscapes. Nat Commun 11, 1186. https://doi.org/10.1038/s41467-020-15013-5

Hardwick, S.R., Toumi, R., Pfeifer, M., Turner, E.C., Nilus, R., Ewers, R.M., 2015. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology 201, 187–195. https://doi.org/10.1016/j.agrformet.2014.11.010

Hölscher, D., Mackensen, J., Roberts, J.-M., 2005. Forest recovery in the humid tropics: changes in vegetation structure, nutrient pools and the hydrological cycle, in: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, pp. 598–621. https://doi.org/10.1017/CBO9780511535666.031

Hondula, D.M., Balling, R.C., Vanos, J.K., Georgescu, M., 2015. Rising Temperatures, Human Health, and the Role of Adaptation. Curr Clim Change Rep 1, 144–154. https://doi.org/10.1007/s40641-015-0016-4

Huang, Y., Stein, G., Kolle, O., Kübler, K., Schulze, E.-D., Dong, H., Eichenberg, D., Gleixner, G., Hildebrandt, A., Lange, M., Roscher, C., Schielzeth, H., Schmid, B., Weigelt, A., Weisser, W.W., Shadaydeh, M., Denzler, J., Ebeling, A., Eisenhauer, N., 2024. Enhanced stability of grassland soil temperature by plant diversity. Nat. Geosci. 17, 44–50. https://doi.org/10.1038/s41561-023-01338-5

Iddris, N.A.-A., Formaglio, G., Paul, C., von Groß, V., Chen, G., Angulo-Rubiano, A., Berkelmann, D., Brambach, F., Darras, K.F.A., Krashevska, V., Potapov, A., Wenzel, A., Irawan, B., Damris, M., Daniel, R., Grass, I., Kreft, H., Scheu, S., Tscharntke, T., Tjoa, A., Veldkamp, E., Corre, M.D., 2023. Mechanical weeding enhances ecosystem multifunctionality and profit in industrial oil palm. Nat Sustain 6, 683–695. https://doi.org/10.1038/s41893-023-01076-x

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.

Keppel, G., Van Niel, K.P., Wardell-Johnson, G.W., Yates, C.J., Byrne, M., Mucina, L., Schut, A.G.T., Hopper, S.D., Franklin, S.E., 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. Global Ecology and Biogeography 21, 393–404. https://doi.org/10.1111/j.1466-8238.2011.00686.x

Key, I.B., Smith, A.C., Turner, B., Chausson, A., Girardin, C.A.J., Macgillivray, M., Seddon, N., 2022. Biodiversity outcomes of nature-based solutions for climate change adaptation: Characterising the evidence base. Front. Environ. Sci. 10, 905767. https://doi.org/10.3389/fenvs.2022.905767

Khairiah, R.N., Setiawan, Y., Prasetyo, L.B., Permatasari, P.A., 2017. Leaf Area Index (LAI) in different type of agroforestry systems based on hemispherical photographs in Cidanau Watershed. IOP Conf. Ser.: Earth Environ. Sci. 54, 012050. https://doi.org/10.1088/1755-1315/54/1/012050

Khatun, K., Maguire-Rajpaul, V.A., Asante, E.A., McDermott, C.L., 2020. From Agroforestry to Agroindustry: Smallholder Access to Benefits From Oil Palm in Ghana and the Implications for Sustainability Certification. Front. Sustain. Food Syst. 4, 29. https://doi.org/10.3389/fsufs.2020.00029

Khokthong, W., Zemp, D.C., Irawan, B., Sundawati, L., Kreft, H., Hölscher, D., 2019. Drone-Based Assessment of Canopy Cover for Analyzing Tree Mortality in an Oil Palm Agroforest. Front. For. Glob. Change 2, 12. https://doi.org/10.3389/ffgc.2019.00012

Kikuchi, T., Seidel, D., Ehbrecht, M., Zemp, D.C., Brambach, F., Irawan, B., Sundawati, L., Hölscher, D., Kreft, H., Paterno, G.B., 2024. Combining planting trees and natural regeneration promotes long-term structural complexity in oil palm landscapes. Forest Ecology and Management 569, 122182. https://doi.org/10.1016/j.foreco.2024.122182

Korol, Y., Khokthong, W., Zemp, D.C., Irawan, B., Kreft, H., Hölscher, D., 2021. Scattered trees in an oil palm landscape: Density, size and distribution. Global Ecology and Conservation 28, e01688. https://doi.org/10.1016/j.gecco.2021.e01688

Kovats, R.S., Hajat, S., Wilkinson, P., 2004. Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. Occup Environ Med 61, 893–898. https://doi.org/10.1136/oem.2003.012047

Li, Y., Svenning, J.-C., Zhou, W., Zhu, K., Abrams, J.F., Lenton, T.M., Ripple, W.J., Yu, Z., Teng, S.N., Dunn, R.R., Xu, C., 2024. Green spaces provide substantial but unequal urban cooling globally. Nat Commun 15, 7108. https://doi.org/10.1038/s41467-024-51355-0

Lo, Y.T.E., Vosper, E., Higgins, J.P.T., Howard, G., 2024. Heat impacts on human health in the Western Pacific Region: an umbrella review. The Lancet Regional Health - Western Pacific 42, 100952. https://doi.org/10.1016/j.lanwpc.2023.100952

Luskin, M.S., Potts, M.D., 2011. Microclimate and habitat heterogeneity through the oil palm lifecycle. Basic and Applied Ecology 12, 540–551. https://doi.org/10.1016/j.baae.2011.06.004

MacArthur, R. H., & Wilson, E. O., 1967. *The Theory of Island Biogeography* (REV-Revised). Princeton University Press. http://www.jstor.org/stable/j.ctt19cc1t2

Malhado, A.C.M., Costa, M.H., de Lima, F.Z., Portilho, K.C., Figueiredo, D.N., 2009. Seasonal leaf dynamics in an Amazonian tropical forest. Forest Ecology and Management 258, 1161–1165. https://doi.org/10.1016/j.foreco.2009.06.002

Margono, B.A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., Goetz, S., Hansen, M.C., 2012. Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. Environ. Res. Lett. 7, 034010. https://doi.org/10.1088/1748-9326/7/3/034010

McAlpine, C.A., Johnson, A., Salazar, A., Syktus, J., Wilson, K., Meijaard, E., Seabrook, L., Dargusch, P., Nordin, H., Sheil, D., 2018. Forest loss and Borneo's climate. Environ. Res. Lett. 13, 044009. https://doi.org/10.1088/1748-9326/aaa4ff

Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Macfarlane, N., Hoffmann, R., Persio, M., Descals, A., Szantoi, Z., Sheil, D., 2020. The environmental impacts of palm oil in context. Nat. Plants 6, 1418–1426. https://doi.org/10.1038/s41477-020-00813-w

Meijide, A., Badu, C.S., Moyano, F., Tiralla, N., Gunawan, D., Knohl, A., 2018. Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the

2015 ENSO event. Agricultural and Forest Meteorology 252, 208–219. https://doi.org/10.1016/j.agrformet.2018.01.013

Mendes dos Santos, L., Ferraz, G.A. e S., Barbosa, B.D. de S., Diotto, A.V., Andrade, M.T., Conti, L., Rossi, G., 2020. Determining the Leaf Area Index and Percentage of Area Covered by Coffee Crops Using UAV RGB Images. IEEE J. Sel. Top. Appl. Earth Observations Remote Sensing 13, 6401–6409. https://doi.org/10.1109/JSTARS.2020.3034193

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., Bruelheide, H., Caldwell, B., Cavender-Bares, J., Dhiedt, E., Eisenhauer, N., Ganade, G., Gravel, D., Guillemot, J., Hall, J.S., Hector, A., Hérault, B., Jactel, H., Koricheva, J., Kreft, H., Mereu, S., Muys, B., Nock, C.A., Paquette, A., Parker, J.D., Perring, M.P., Ponette, Q., Potvin, C., Reich, P.B., Scherer-Lorenzen, M., Schnabel, F., Verheyen, K., Weih, M., Wollni, M., Zemp, D.C., 2022. For the sake of resilience and multifunctionality, let's diversify planted forests! CONSERVATION LETTERS 15, e12829. https://doi.org/10.1111/conl.12829

Mildrexler, D.J., Zhao, M., Running, S.W., 2011. A global comparison between station air temperatures and MODIS land surface temperatures reveals the cooling role of forests. J. Geophys. Res. 116, G03025. https://doi.org/10.1029/2010JG001486

Montoya-Sánchez, V., Camarretta, N., Ehbrecht, M., Schlund, M., Brant Paterno, G., Seidel, D., Guerrero-Ramírez, N., Brambach, F., Hölscher, D., Kreft, H., Irawan, B., Sundawati, L., Zemp, D.C., 2024. Comparing airborne and terrestrial LiDAR with ground-based inventory metrics of vegetation structural complexity in oil palm agroforests. Ecological Indicators 166, 112306. https://doi.org/10.1016/j.ecolind.2024.112306

Niedermaier, S., Schneider, T., Bahl, M.-O., Matsubara, S., Huesgen, P.F., 2020. Photoprotective Acclimation of the Arabidopsis thaliana Leaf Proteome to Fluctuating Light. Front. Genet. 11, 154. https://doi.org/10.3389/fgene.2020.00154

Olivas, P.C., Oberbauer, S.F., Clark, D.B., Clark, D.A., Ryan, M.G., O'Brien, J.J., Ordoñez, H., 2013. Comparison of direct and indirect methods for assessing leaf area index across a tropical rain forest landscape. Agricultural and Forest Meteorology 177, 110–116. https://doi.org/10.1016/j.agrformet.2013.04.010

Pallavi, Röll, A., Marques, I., Ramadhani, D.N., Valdes-Uribe, A., Hendrayanto, H., Hölscher, D., 2024. Changes in leaf area index by tropical forest transformation to plantations increase below-canopy surface temperatures. Global Ecology and Conservation 53, e03001. https://doi.org/10.1016/j.gecco.2024.e03001

Paquette, A., Hector, A., Castagneyrol, B., Vanhellemont, M., Koricheva, J., Scherer-Lorenzen, M., Verheyen, K., TreeDivNet, Abdala-Roberts, L., Auge, H., Barsoum, N., Bauhus, J., Baum, C., Bruelheide, H., Castagneyrol, B., Cavender-Bares, J., Eisenhauer, N., Ferlian, O., Ganade, G., Godbold, D., Gravel, D., Hall, J., Hector, A., Hobbs, R., Hoelscher, D., Hulvey, K.B., Huxham, M., Jactel, H., Koricheva, J., Kreft, H., Liang, J., Mereu, S., Messier, C., Montgomery, R., Muys, B., Nock, C., Paquette, A., Parker, J., Parker, W., Parra-Tabla, V., Perring, M.P., Ponette, Q., Potvin, C., Reich, P.B., Rewald, B., Sandén, H., Scherer-Lorenzen, M., Smith, A., Standish, R., Vanhellemont, M., Verheyen, K., Weih, M., Wollni, M., Zemp, D.C., 2018. A million and more trees for science. Nat Ecol Evol 2, 763–766. https://doi.org/10.1038/s41559-018-0544-0

Pashkevich, M.D., Marshall, C.A.M., Freeman, B., Reiss-Woolever, V.J., Caliman, J.-P., Drewer, J., Heath, B., Hendren, M.T., Saputra, A., Stone, J., Timperley, J.H., Draper, W., Gbarway, A., Geninyan, B., Goll, B., Guahn, M., Gweh, A.N., Hadfield, P., Jah, M.T., Jayswen, S., Jones, T., Kandie, S., Koffa, D., Korb, J., Koon, N., Manewah, B., Medrano, L.M., Palmeirim, A.F., Pett, B., Rocha, R., Swope-Nyantee, E., Tue, J., Tuolee, J., Van Dessel, P., Vincent, A., Weah, R., Widodo, R., Yennego, A.J., Yonmah, J., Turner, E.C., 2024. The socioecological benefits and consequences of oil palm cultivation in its native range: The Sustainable Oil Palm in West Africa (SOPWA) Project. Science of The Total Environment 926, 171850. https://doi.org/10.1016/j.scitotenv.2024.171850

Paterno, G.B., Brambach, F., Guerrero-Ramírez, N., Zemp, D.C., Cantillo, A.F., Camarretta, N., Moura, C.C.M., Gailing, O., Ballauff, J., Polle, A., Schlund, M., Erasmi, S., Iddris, N.A., Khokthong, W., Sundawati, L., Irawan, B., Hölscher, D., Kreft, H., 2024a. Diverse and larger tree islands promote native tree diversity in oil palm landscapes. Science 386, 795–802. https://doi.org/10.1126/science.ado1629

Paterno, G.B., Brambach, F., Guerrero-Ramírez, N., Zemp, D.C., Cantillo, A.F., Camarretta, N., Moura, C.C.M., Gailing, O., Ballauff, J., Polle, A., Schlund, M., Erasmi, S., Iddris, N.A., Khokthong, W., Sundawati, L., Irawan, B., Hölscher, D., Kreft, H., 2024b. Diverse and larger tree islands promote native tree diversity in oil palm landscapes. Science 386, 795–802. https://doi.org/10.1126/science.ado1629

Pozzer, A., Steffens, B., Proestos, Y., Sciare, J., Akritidis, D., Chowdhury, S., Burkart, K., Bacer, S., 2024. Atmospheric health burden across the century and the accelerating impact of temperature compared to pollution. Nat Commun 15, 9379. https://doi.org/10.1038/s41467-024-53649-9

Qaim, M., Sibhatu, K.T., Siregar, H., Grass, I., 2020. Environmental, Economic, and Social Consequences of the Oil Palm Boom. Annu. Rev. Resour. Econ. 12, 321–344. https://doi.org/10.1146/annurev-resource-110119-024922

Reiss-Woolever, V.J., Advento, A.D., Aryawan, A.A.K., Caliman, J.-P., Foster, W.A., Naim, M., Pujianto, Purnomo, D., Soeprapto, Suhardi, Tarigan, R.S., Wahyuningsih, R., Rambe, T.D.S., Ps, S., Widodo, R.H., Luke, S.H., Snaddon, J.L., Turner, E.C., 2023. Understory vegetation supports more abundant and diverse butterfly communities in oil palm plantations. Front. For. Glob. Change 6, 1205744. https://doi.org/10.3389/ffgc.2023.1205744

Schnabel, F., Beugnon, R., Yang, B., Richter, R., Eisenhauer, N., Huang, Y., Liu, X., Wirth, C., Cesarz, S., Fichtner, A., Perles-Garcia, M.D., Hähn, G.J.A., Härdtle, W., Kunz, M., Izaguirre, N.C.C., Niklaus, P.A., von Oheimb, G., Schmid, B., Trogisch, S., Wendisch, M., Ma, K., Bruelheide, H., 2023. Tree diversity increases forest temperature buffering. https://doi.org/10.1101/2023.09.11.556807

Schnabel, F., Guillemot, J., Barry, K.E., Brunn, M., Cesarz, S., Eisenhauer, N., Gebauer, T., Guerrero-Ramirez, N.R., Handa, I.T., Madsen, C., Mancilla, Lady, Monteza, J., Moore, T., Oelmann, Y., Scherer-Lorenzen, M., Schwendenmann, L., Wagner, A., Wirth, C., Potvin, C., 2024. Tree diversity increases carbon stocks and fluxes above- but not belowground in a tropical forest experiment. https://doi.org/10.1101/2024.06.20.599915

Schrader, J., Weigelt, P., Cai, L., Westoby, M., Fernández-Palacios, J.M., Cabezas, F.J., Plunkett, G.M., Ranker, T.A., Triantis, K.A., Trigas, P., Kubota, Y., Kreft, H., 2024. Islands are key for protecting the world's plant endemism. Nature. https://doi.org/10.1038/s41586-024-08036-1

Shugart, H., White, P., Saatchi, S., Chave, J., 2022. The world atlas of trees and forests. Princeton University Press. ISBN 978-0-691-22674-3

Stone, J., Advento, A.D., Pashkevich, M.D., Aryawan, A.A.K., Caliman, J., Hood, A.S.C., Foster, W.A., Naim, M., Pujianto, Purnomo, D., Suhardi, Tarigan, R.S., Rambe, T.D.S., Widodo, R.H., Luke, S.H., Snaddon, J.L., Turner, E.C., 2023. Maintaining understory vegetation in oil palm plantations supports higher assassin bug numbers. Ecol Sol and Evidence 4, e12293. https://doi.org/10.1002/2688-8319.12293

Sun, C., Wu, Z., Lv, Z., Wei, J., Lv, Z., 2010. Spatial-Temporal Analysis of Land Surface Temperature and Its Interplay with Land Use Change, in: 2010 2nd International Conference on Information Engineering and Computer Science. IEEE, Wuhan, China, pp. 1–4. https://doi.org/10.1109/ICIECS.2010.5677797

Teuscher, M., Gérard, A., Brose, U., Buchori, D., Clough, Y., Ehbrecht, M., Hölscher, D., Irawan, B., Sundawati, L., Wollni, M., Kreft, H., 2016. Experimental Biodiversity Enrichment in Oil-Palm-Dominated Landscapes in Indonesia. Front. Plant Sci. 07. https://doi.org/10.3389/fpls.2016.01538

Teuscher, M., Vorlaufer, M., Wollni, M., Brose, U., Mulyani, Y., Clough, Y., 2015. Trade-offs between bird diversity and abundance, yields and revenue in smallholder oil palm plantations in Sumatra, Indonesia. Biological Conservation 186, 306–318. https://doi.org/10.1016/j.biocon.2015.03.022

Tilman, D., Isbell, F., Cowles, J.M., 2014. Biodiversity and Ecosystem Functioning. Annu. Rev. Ecol. Evol. Syst. 45, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

Wenzel, A., Westphal, C., Ballauff, J., Berkelmann, D., Brambach, F., Buchori, D., Camarretta, N., Corre, M.D., Daniel, R., Darras, K., Erasmi, S., Formaglio, G., Hölscher, D., Iddris, N.A.-A., Irawan, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Mulyani, Y., Mußhoff, O., Paterno, G.B., Polle, A., Potapov, A., Röll, A., Scheu, S., Schlund, M., Schneider, D., Sibhatu, K.T., Stiegler, C., Sundawati, L., Tjoa, A., Tscharntke, T., Veldkamp, E., Waite, P.-A., Wollni, M., Zemp, D.C., Grass, I., 2024. Balancing economic and ecological functions in smallholder and industrial oil palm plantations. Proc. Natl. Acad. Sci. U.S.A. 121, e2307220121. https://doi.org/10.1073/pnas.2307220121

Wojciechowska, R., Kunicki, E., Długosz-Grochowska, O., Kołton, A., 2020. Response of Broccoli Transplants to LED Light during Short and Long-Term Storage. Agronomy 10, 1009. https://doi.org/10.3390/agronomy10071009

Wolff, N.H., Masuda, Y.J., Meijaard, E., Wells, J.A., Game, E.T., 2018. Impacts of tropical deforestation on local temperature and human well-being perceptions. Global Environmental Change 52, 181–189. https://doi.org/10.1016/j.gloenvcha.2018.07.004

Zemp, D.C., Gérard, A., Hölscher, D., Ammer, C., Irawan, B., Sundawati, L., Teuscher, M., Kreft, H., 2019. Tree performance in a biodiversity enrichment experiment in an oil palm landscape. Journal of Applied Ecology 56, 2340–2352. https://doi.org/10.1111/1365-2664.13460

Zemp, D.C., Guerrero-Ramirez, N., Brambach, F., Darras, K., Grass, I., Potapov, A., Röll, A., Arimond, I., Ballauff, J., Behling, H., Berkelmann, D., Biagioni, S., Buchori, D., Craven, D., Daniel, R., Gailing, O., Ellsäßer, F., Fardiansah, R., Hennings, N., Irawan, B., Khokthong, W., Krashevska, V., Krause, A., Kückes, J., Li, K., Lorenz, H., Maraun, M., Merk, M.S., Moura, C.C.M., Mulyani, Y.A., Paterno, G.B., Pebrianti, H.D., Polle, A., Prameswari, D.A., Sachsenmaier, L., Scheu, S., Schneider, D., Setiajiati, F., Setyaningsih, C.A., Sundawati, L., Tscharntke, T., Wollni, M., Hölscher, D., Kreft, H., 2023. Tree islands enhance biodiversity and functioning in oil palm landscapes. Nature 618, 316–321. https://doi.org/10.1038/s41586-023-06086-5

Zheng, L., Barry, K.E., Guerrero-Ramírez, N.R., Craven, D., Reich, P.B., Verheyen, K., Scherer-Lorenzen, M., Eisenhauer, N., Barsoum, N., Bauhus, J., Bruelheide, H., Cavender-Bares, J., Dolezal, J., Auge, H., Fagundes, M.V., Ferlian, O., Fiedler, S., Forrester, D.I., Ganade, G., Gebauer, T., Haase, J., Hajek, P., Hector, A., Hérault, B., Hölscher, D., Hulvey, K.B., Irawan, B., Jactel, H., Koricheva, J., Kreft, H., Lanta, V., Leps, J., Mereu, S., Messier, C., Montagnini, F., Mörsdorf, M., Müller, S., Muys, B., Nock, C.A., Paquette, A., Parker, W.C., Parker, J.D., Parrotta, J.A., Paterno, G.B., Perring, M.P., Piotto, D., Wayne Polley, H., Ponette, Q., Potvin, C., Quosh, J., Rewald, B., Godbold, D.L., van Ruijven, J., Standish, R.J., Stefanski, A., Sundawati, L., Urgoiti, J., Williams, L.J., Wilsey, B.J., Yang, B., Zhang, L., Zhao, Z., Yang, Y., Sandén, H., Ebeling, A., Schmid, B., Fischer, M., Kotowska, M.M., Palmborg, C., Tilman, D., Yan, E., Hautier, Y., 2024. Effects of plant diversity on productivity strengthen over time due to trait-dependent shifts in species overyielding. Nat Commun 15, 2078. https://doi.org/10.1038/s41467-024-46355-z

Chapter 4
Synthesis

4.1 Overview

Global south experiencing continuous transformation of remaining tropical forest into agricultural monoculture. Particularly in Indonesia, conversion of rainforest into oil palm monoculture plantations are continuous from decades. The knowledge about this conversion linked temperature changes are limited, specifically below canopy surface temperature (microclimatic surface temperature) and a practicable restoration approach to buffer the rising temperature in oil palm plantation. This work intends acquire thus far limited knowledge on effect of forest transformation into monoculture on below-canopy surface temperature (Chapter 1). Four land use types in lowland Sumatra, Indonesia – forest, shrubland, rubber and oil palm were compared regarding their canopy leaf area index and below-canopy surface temperature for different surfaces. The results are elaborately discussed (chapter 2). Restoring the habitat and ecosystem functions in monoculture plantations generally focused on biodiversity enrichment, however the crucial role of tree integration in monoculture plantation in curbing the below-canopy surface temperature is largely unknown. Our work investigated the effects of tree integration in conventional oil palm monoculture and results are explicitly discussed (chapter 3).

4.2 Forest conversion to monocultures alters LAI and below-canopy surface temperatures

As a first step (chapter 2), leaf area index (LAI), solar irradiance (IRR) and below-canopy surface temperatures were measured in four land-use types (i.e., forest, shrubland, rubber and oil palm) across 132 study plots located in a dynamic and mosaic landscape of lowland Sumatra. Below-canopy thermal conditions are often unstudied (Cheung et al., 2021). Tree covered area usually provide cooling effect than the open area. A study by Su et al., (2023) found that in many forests, the cooling effect from increased evapotranspiration due to tree cover is more significant than the warming caused by the loss of tree cover. However, the knowledge gap still exists to understand the influence of canopy leaf area index on below-canopy surface temperature under present meteorological conditions in mosaic landscape. Our study revealed the LAI is significantly reduced over land-use trajectory from forest to shrubland to rubber and oil palm. The LAI value within the forest plots not varied largely but shrubland, rubber and oil palm plantation showed large variation within types (Chapter 2). In rubber and oil palm monoculture the canopy LAI largely depends on age of the plantations and management practice followed (spacing, fertilizer application, plant selection, etc.). Though, rubber trees have synchronous phenological (Azizan et al., 2023) leaf shedding behavior, this behavior is seen asynchronous and sheds partial leaves in Indonesian landscape (Niu et al., 2017). This could be one of the reliable reasons for variation in LAI.

Whereas the shrubland is heterogenous in nature, it includes shrub-dominated fallow areas in the process of transitioning to secondary forest or being cleared for plantation development, featuring up to 50% tree canopy closure above the lower vegetation layer, often characterized by relatively small-statured trees. In the current study, LAI emerged as most important variable to predict below-canopy surface temperature. Study showed that land-use type as a factor did not have significant effect on below-canopy surface temperature that means land-use type itself did not emerge as a predictor to predict surface temperature. It opens up a discussion on any land-use type is potential to reduce the temperature by increasing the LAI.

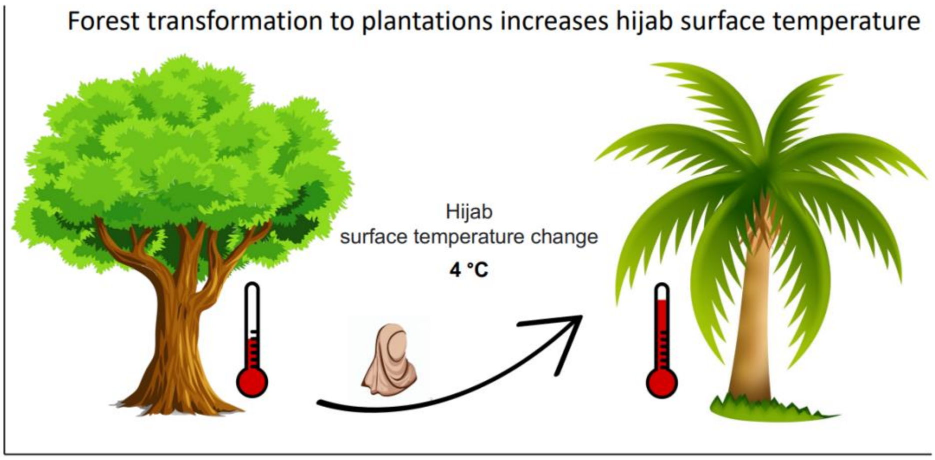


Fig. 4.1. Graphical abstract indicates conversion of forest into oil palm monoculture increased the hijab surface temperature by 4 °C.

4.3 Tree integration to reduce rising microclimatic temperatures

Considering the ongoing global ecological crisis, land use and ecosystem functions have become a major topic in restoration and landscape planning (Santos et al., 2022). Agroforestry system is majorly debated and discussed approach to enhance the tree cover and to restore the biodiversity along with conventional forest conservation. However, there is still lack of knowledge to successfully manage agroforestry in perineal cash crops without compromising the yield. EFForTS-BEE (Biodiversity enrichment experiment), one of the few existing tree integration experiments provided an opportunity to study effect of tree planting on biodiversity and ecosystem functions. As a result, multidiversity increased to 250% (across 10 biodiversity indicators) and multifunctionality increased to 75 % (across 19 indicators of ecosystem function) while reporting no yield reductions at landscape level (Zemp et al., 2023). Thus, pointing to large potential of tree integration in oil palm plantations. However, a thorough analysis of LAI and below-canopy surface temperatures had not yet been conducted. The current study evaluated canopy LAI and below-canopy temperatures across various surfaces (ground, workers' caps and hijabs, reference boards) as well as air temperature within the 56 fixed experimental plots of EFForTS-BEE, additionally incorporated data from a large-scale landscape assessment in the same region (chapter 3). The study revealed that tree integration into oil palm increased LAI and reduced below-canopy surface temperatures. A study by Su et al., (2023) found that achieving the goal of no biophysical warming from tree cover changes is possible by restoring a fraction of previously lost tree cover areas. The warming caused by tree cover loss is smaller in magnitude than the cooling effect from tree cover restoration. Overlooking this asymmetric temperature response to fine-scale changes in tree cover ignores the continued impact of biophysical feedbacks on surface temperatures, even under the net-zero cover change. In this direction, tree integration into monoculture plantation has great potential in restoring the impaired ecosystem function and multifunctionality along with tree cover gain. The hysteresis of warming and cooling by monoculture plantation and tree integration will be the future way.

The success of tree planting effort is more when right species are selected. In this study, planted tree species diversity did not show combined effect on LAI ($p > 0.05$) or below-canopy temperatures ($p > 0.05$). However, Sungkai significantly influenced ground surface temperature ($p = 0.01$), and Jelutung had a significant effect on both cap surface temperature ($p = 0.02$) and hijab surface temperature ($p = 0.02$). Species were chosen based on their intended use, such as for fruit production or timber. Species selection is generally influenced by the preferences of landowners. A consistently cooler microclimate is more likely when selected species are evergreen and have denser canopies.

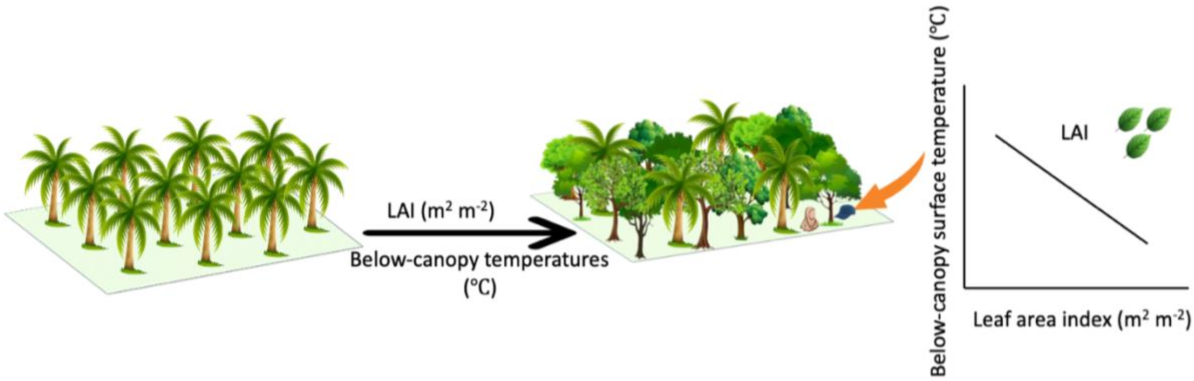


Fig. 4.2. Graphical representation of tree integration in oil palm plantation enhances LAI and reduces below-canopy surface temperatures

4.4 Jungle rubber/rubber agroforestry in the landscape

Rubber is traditionally grown along with forest trees or in forests in many tropical countries, Indonesia is not an exception (Cahyo et al., 2024). Rubber agroforestry has primarily been practiced before the commercialization of the crop through monocropping (Penot and Ilahang, 2021). In Indonesia, smallholder farmers continue to practice this traditional method, which is often called "jungle rubber." In our landscape assessment study, although we included jungle rubber (n = 4) and conventional rubber monoculture (n = 25), we did not separately analyze their effects on LAI and below-canopy surface temperature. However, now we explicitly investigated the jungle rubber and rubber monoculture plots. The average LAI in jungle rubber is 4.5 ± 0.54 whereas it is 2.28 ± 0.75 in monoculture rubber. Below-canopy ground surface temperature decreases by 1.99 °C from monoculture rubber (30.52 ± 2.62) to jungle rubber (28.53 ± 1.50). Other surfaces, such as caps and hijabs, are 4.42 °C and 3.54 °C cooler in jungle rubber compared to rubber monoculture. Similarly, the air temperature below jungle rubber canopy (30.48 ± 1.07) is 2.03 °C cooler than in rubber monoculture (32.51 ± 1.70).

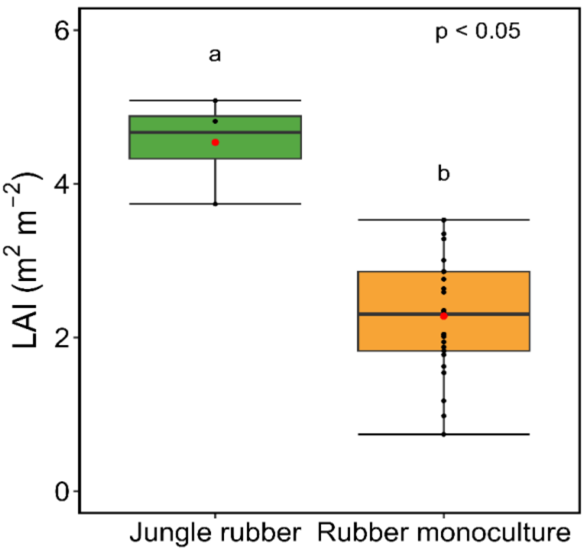


Fig. 4.3. Leaf area index (LAI) across plots in the jungle rubber (n=4) and in the commercial rubber monoculture (n=25). Different letters indicate significant differences at $p < 0.05$ (Kruskal-Wallis test with Dunn's post-hoc test). Red dots indicate mean values.

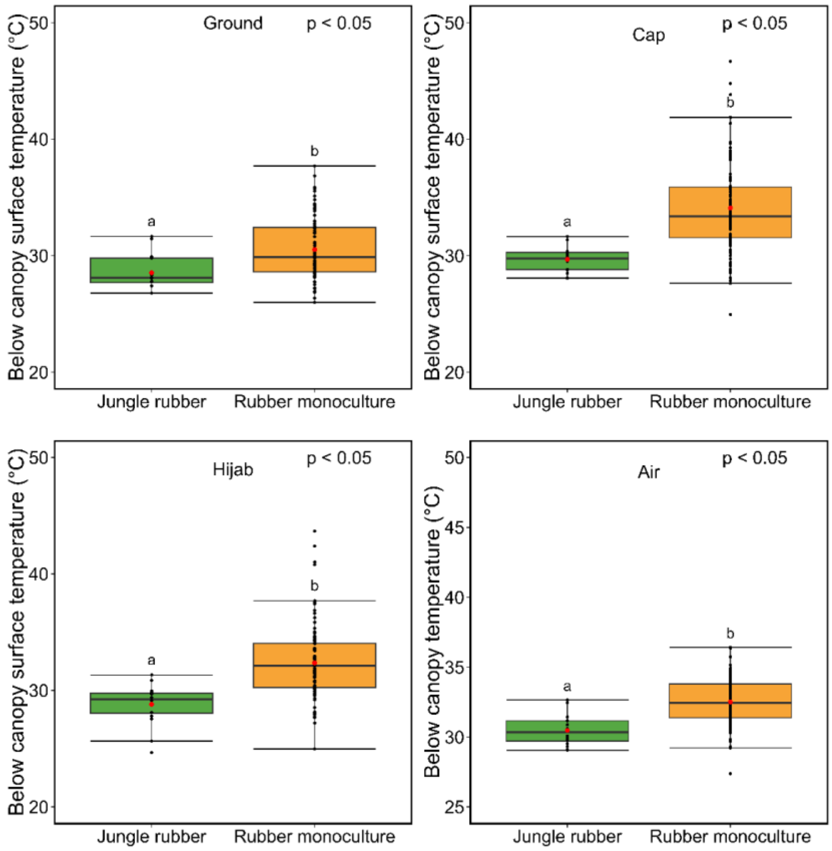


Fig. 4.4. Below-canopy temperatures for different surfaces (ground, cap, and hijab) and ambient air across plots in the jungle rubber (n=4) and in the commercial rubber monoculture (n=25). Data is pooled across measurement times (11:00 AM, 12:00 PM, 1:00 PM, and 2:00 PM). Different letters indicate significant differences at $p < 0.05$ (Kruskal-Wallis test with Dunn's post-hoc test). Red dots indicate mean values.

4.5 Land-use trajectories and below-canopy surface temperature dynamics at the landscape scale

Over the decades, land-use transitions from forests to monoculture plantations in lowland Sumatra have significantly impacted biodiversity and ecosystem functions. This study synthesizes knowledge about the extent of changes in below-canopy surface temperatures across existing land-use trajectories at the landscape level. Below-canopy surface temperatures increased from forests to rubber and oil palm plantations. The extent of temperature change from forests to shrubland and jungle rubber was relatively lower than in rubber and oil palm plantations. Interestingly, the study found that below-canopy surface temperatures in jungle rubber were identical to those in tree-integrated oil palm plantations. This finding highlights the potential of integrating trees into rubber plantations to mitigate below-canopy surface temperature increases. However, the landscape remains highly dynamic, with possible multidirectional transformations (Fig. 4.5).

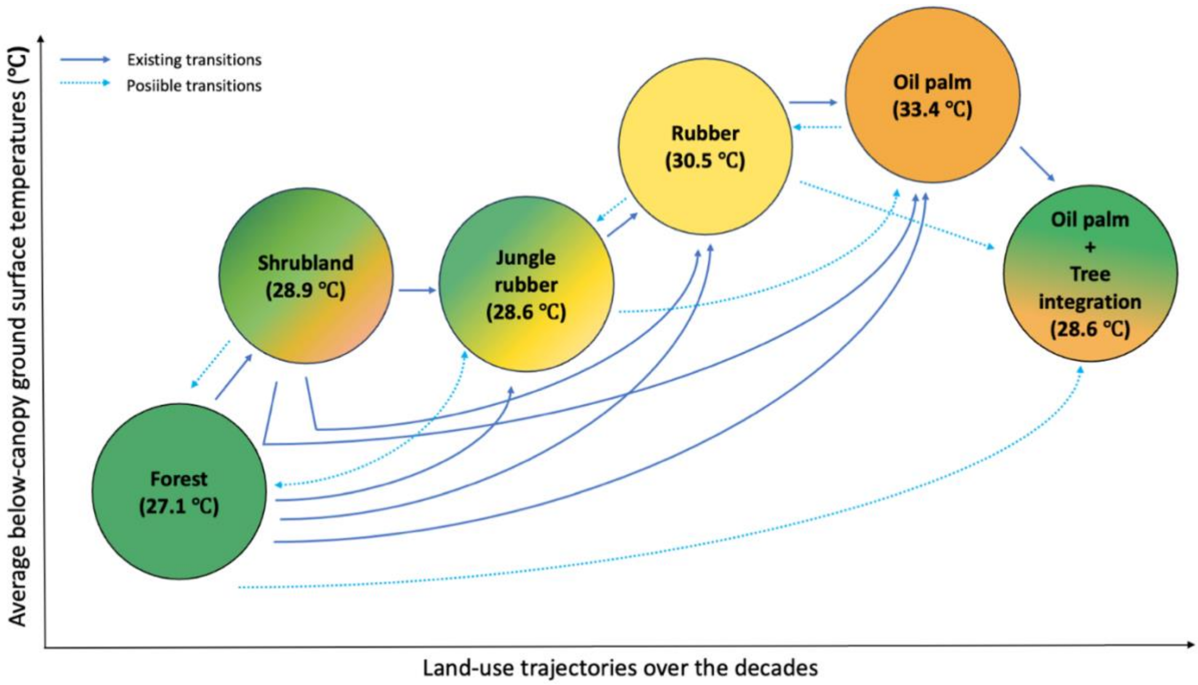


Fig. 4.5. Schematic representation of land-use trajectories at landscape level in the lowland Sumatra. Position of the different land-use types on the y-axis indicates respective below-canopy ground surface temperatures. Solid dark-blue arrows show transitions that already been seen and also ongoing in the landscape. The light-blue dotted arrows indicate a possible transition. Tree integration into oil palm (upper right circle) are a special landscape element established within oil palm monoculture.

The management and rubber harvesting practices in smallholder plantations are largely influenced by the market value of rubber. When market prices decline, smallholders often abandon management activities, particularly weed control, due to low or non-existent profits during these periods. As a result, these neglected rubber plantations partially resemble jungle rubber. This represents a possible transition from rubber to jungle rubber, although this is not always the case.

4.6 Effect of temperature on farm workers in a dynamic landscape

In the tropics, millions of people work outdoors throughout the year. Exposure to rising temperatures caused by climate change and global warming is inevitable. Prolonged heat exposure leads to numerous health issues, reduced work efficiency, and shorter working hours (Wolff et al., 2018; Chandrashekhar, 2023; Sahu et al., 2013). At a global scale, the effects of heat stress on human health have been extensively studied in urban areas. However, in rural tropical regions, millions of people are engaged in agriculture or plantation work, where the working environment is often more severe. Furthermore, global disparities—particularly in the Global South—persist in terms of climate-related incentives, infrastructure support, and work-life flexibility. Despite this, the impact of climate change and land-use changes on farm workers has largely been overlooked. We recommend more research to better understand the challenges of rural life in the context of ongoing climate change.

4.7 Limitation of the study

Despite the good results presented, our study has a few limitations that could add more strength to the results and discussions. By selecting a highly heterogeneous variable, temperature, which is often affected by several factors, we focused on measuring only a few variables, namely, LAI (a vegetation index), SSCI, observed diversity and IRR (a meteorological factor), as explanatory variables to explain the hypothesis.

We collected data from 132 plots for the landscape assessment and 56 plots for the biodiversity enrichment experiment, providing a high level of spatial replication to ensure robust data collection. However, temporal replication considered in our study restricted to within a day per plot, particularly for solar radiation and surface temperature measurements. Temperature and radiation were recorded four times per day, with each plot visited only once during the data collection period. Although repeated visits over several days would have improved the temporal resolution, this was not implemented. Data collection took place from June 2021 to December 2022, but seasonal variability (wet and dry seasons) was not accounted for in the analysis. Temperature, one of the most heterogeneous variables, is influenced by various factors such as wind, humidity, solar radiation, cloud cover and precipitation, which are dynamic in nature.

It was tedious to measure below-canopy surface temperatures since there is no established method for doing so. Airborne and spaceborne tools currently do not measure below-canopy surface temperatures. Therefore, we used a handheld thermal camera, the Fluke PTi120, which is a compact pocket camera developed for industrial inspection. Despite the its beneficial specifications, the temperature measurement accuracy above 0°C is ± 2°C or ± 2%. This accuracy could result in overestimating or underestimating the actual surface temperature below the canopy. Furthermore, the camera does not include GPS, and the images are not geo-referenced. Georeferenced thermal images could provide more valuable information for studying spatial variability, scaling up studies, or comparing with land surface temperatures captured by airborne or spaceborne data.

The ground area covered by the image from a height of 2.5 m is 2.30 m x 1.72 m (3.96 m^2), which represents only a small portion of the subplot (25 m^2). A larger area coverage would be preferable. Additionally, there may be a shift in camera position and angle of capture since it is handheld and not static, which could introduce possible errors due to operational shake. Furthermore, we used a thermo-hygrometer (BC06, TROTEC, Germany) with an accuracy of ±1 °C for the measuring range of 0–40 °C. Although changes tend to be minimal under microclimatic conditions, even slight variations in temperature could have a negative effect.

4.8 Management of tree integrated plots

After 9 years of tree planting treatments, despite the natural regeneration of 79 woody species across the tree islands, species diversity did not strongly affect below-canopy surface temperatures. A study by Paterno et al., (2024) also showed that lianas are growing in the tree-planted islands; by nature, lianas climb over the trees and can strangle them, hampering tree growth. Additionally, lianas will not grow as a canopy or enhance the leaf area index. Therefore, cutting lianas could improve tree growth. Furthermore, exotic woody species may compete with native species that regenerate naturally. Implementing the removal of exotic species as a management practice could be considered. Weed control would catalyst the native tree species growth in early period.

4.9 Future outlook

Examining the leaf area index (LAI) and below-canopy surface temperature across a wider landscape and experimental settings provides valuable insights into the impacts of rainforest conversion to oil palm and rubber monocultures on LAI and temperature dynamics (Chapter 2). Furthermore, it highlights how these effects can be mitigated by integrating trees into oil palm monocultures (Chapter 3). We were able to assess and discuss the relationship between LAI and below-canopy surface temperature under current meteorological conditions in lowland Sumatra. Additionally, we provided initial information on using thermography to estimate below-canopy surface temperature. However, we only used a device that captures thermal images of a smaller ground area. Future studies should aim to cover larger areas and include temporal replications to better understand the dynamics of temperature. Further major step will explore analyzing eddy covariance data alongside below-canopy surface temperature data to estimate evapotranspiration at both the canopy level and beneath the canopy. This approach aims to understand the variation of these measurements across the different layers of the forest, thereby providing a more comprehensive understanding of water fluxes. Estimating evapotranspiration at a regional scale will enhance our comprehension of water cycles and energy balance within forest ecosystems, which is of paramount importance for climate modeling and resource management. Other compelling area of investigation is the influence of below-canopy surface temperatures on the diversity and functionality of flora and fauna, both at the surface and within sub-surface ecosystems. Potential alterations to microhabitats, stemming from changes in temperature beneath the canopy, could affect the growth, distribution, and survival of various plant species. Furthermore, these temperature variations might influence the behavior, abundance, and interactions of soil-dwelling organisms. Studying these dynamics could offer valuable insights into broader ecological processes and the resilience of these systems.

In the EFForTS BEE project, ecological restoration was the driving concept. The future integration of trees into monocultures could become economically viable by selecting species that yield both timber and non-timber products, coupled with appropriate silvicultural practices. This approach would address both economic and ecological interests. The potential for tree integration is not limited to oil palm; it could also be explored in other palm species, such as betel nut (Areca catechu), which is a major cash crop cultivated extensively in the Western Ghats of India.

4.10 Reference

Azizan, F.A., Astuti, I.S., Young, A., Abdul Aziz, A., 2023. Rubber leaf fall phenomenon linked to increased temperature. Agriculture, Ecosystems & Environment 352, 108531. https://doi.org/10.1016/j.agee.2023.108531

Cahyo, A.N., Dong, Y., Taryono, Nugraha, Y., Junaidi, Sahuri, Penot, E., Hairmansis, A., Purwestri, Y.A., Akbar, A., Asywadi, H., Ardika, R., Prasetyo, N.E., Agustina, D.S., Alam, T., Oktavia, F., Subandiyah, S., Montoro, P., 2024. Rubber-Based Agroforestry Systems Associated with Food Crops: A Solution for Sustainable Rubber and Food Production? Agriculture 14, 1038. https://doi.org/10.3390/agriculture14071038

Chandrashekhar, V., 2023. Heat-proofing India. Science 381, 1393–1397. https://doi.org/10.1126/science.adl0416

Cheung, P.K., Jim, C.Y., Hung, P.L., 2021. Preliminary study on the temperature relationship at remotely-sensed tree canopy and below-canopy air and ground surface. Building and Environment 204, 108169. https://doi.org/10.1016/j.buildenv.2021.108169

Niu, F., Röll, A., Meijide, A., Hendrayanto, Hölscher, D., 2017. Rubber tree transpiration in the lowlands of Sumatra. Ecohydrology 10, e1882. https://doi.org/10.1002/eco.1882

Paterno, G.B., Brambach, F., Guerrero-Ramírez, N., Zemp, D.C., Cantillo, A.F., Camarretta, N., Moura, C.C.M., Gailing, O., Ballauff, J., Polle, A., Schlund, M., Erasmi, S., Iddris, N.A., Khokthong, W., Sundawati, L., Irawan, B., Hölscher, D., Kreft, H., 2024. Diverse and larger tree islands promote native tree diversity in oil palm landscapes. Science 386, 795–802. https://doi.org/10.1126/science.ado1629

Penot, E., Ilahang, 2021. Rubber Agroforestry Systems (RAS) in West Kalimantan, Indonesia: An historical perspective. E3S Web Conf. 305, 02001. https://doi.org/10.1051/e3sconf/202130502001

Sahu, S., Sett, M., Kjellstrom, T., 2013. Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future. Ind Health 51, 424–431. https://doi.org/10.2486/indhealth.2013-0006

Santos, M., Cajaiba, R.L., Bastos, R., Gonzalez, D., Petrescu Bakış, A.-L., Ferreira, D., Leote, P., Barreto da Silva, W., Cabral, J.A., Gonçalves, B., Mosquera-Losada, M.R., 2022. Why Do Agroforestry Systems Enhance Biodiversity? Evidence From Habitat Amount Hypothesis Predictions. Front. Ecol. Evol. 9, 630151. https://doi.org/10.3389/fevo.2021.630151

Su, Y., Zhang, C., Ciais, P., Zeng, Z., Cescatti, A., Shang, J., Chen, J.M., Liu, J., Wang, Y.-P., Yuan, W., Peng, S., Lee, X., Zhu, Z., Fan, L., Liu, X., Liu, L., Lafortezza, R., Li, Y., Ren, J., Yang, X., Chen, X., 2023. Asymmetric influence of forest cover gain and loss on land surface temperature. Nat. Clim. Chang. 13, 823–831. https://doi.org/10.1038/s41558-023-01757-7

Wolff, N.H., Masuda, Y.J., Meijaard, E., Wells, J.A., Game, E.T., 2018. Impacts of tropical deforestation on local temperature and human well-being perceptions. Global Environmental Change 52, 181–189. https://doi.org/10.1016/j.gloenvcha.2018.07.004

Zemp, D.C., Guerrero-Ramirez, N., Brambach, F., Darras, K., Grass, I., Potapov, A., Röll, A., Arimond, I., Ballauff, J., Behling, H., Berkelmann, D., Biagioni, S., Buchori, D., Craven, D., Daniel, R., Gailing, O., Ellsäßer, F., Fardiansah, R., Hennings, N., Irawan, B., Khokthong, W., Krashevska, V., Krause, A., Kückes, J., Li, K., Lorenz, H., Maraun, M., Merk, M.S., Moura, C.C.M., Mulyani, Y.A., Paterno, G.B., Pebrianti, H.D., Polle, A., Prameswari, D.A., Sachsenmaier, L., Scheu, S., Schneider, D., Setiajiati, F., Setyaningsih, C.A., Sundawati, L., Tscharntke, T., Wollni, M., Hölscher, D., Kreft, H., 2023. Tree islands enhance biodiversity and functioning in oil palm landscapes. Nature 618, 316–321. https://doi.org/10.1038/s41586-023-06086-5

Appendix

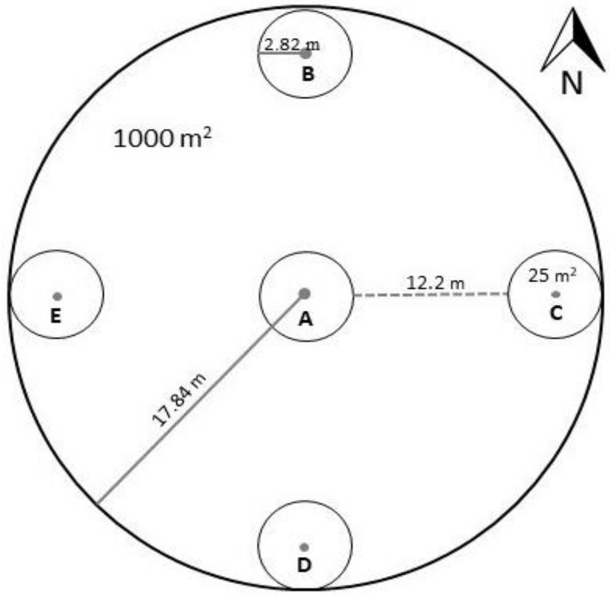


Fig. A2.1 Study plot with five sub-plots (A-E). The plot has a total area of 1000 m^2.

Fig. A2.2 Below-canopy ground surface of different land-use types

Table A2.1 Below-canopy ground surface across the different land-use types. Means and standard deviations (SD) are provided for each land-use type in the categories bare soil, green vegetation and debris. The superscripted letters indicate significant differences ($p < 0.05$) among land-use types as based on ANOVA with post-hoc test.

		Below-canopy ground surface cover (%)					
		Bare soil		Green vegetation		Debris	
	N	Mean	SD	Mean	SD	Mean	SD
Forest	30	2.2 ^{bc}	2.8	35.2 ^{c}	10.9	62.6 ^{a}	10.2
Shrubland	31	4.4 ^{b}	8.5	32.4 ^{c}	19.0	59.7 ^{a}	20.2
Rubber	31	1.3 ^{c}	3.6	53.1 ^{a}	19.4	45.6 ^{b}	18.1
Oil palm	32	15.1 ^{a}	13.6	46.4 ^{b}	24.0	38.4 ^{c}	20.3

Table A2.2 Outcome of simple linear regression model for the response variable below-canopy ground surface temperature with the explanatory variable leaf area index (LAI)

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	32.88	0.26	32.38 – 33.39	< 0.001
LAI	-0.95	0.06	-1.07 – -0.83	< 0.001
Observations	451			
R^2	0.4			

Table A2.3 Outcome of simple linear regression model for the response variable cap surface temperature with the explanatory variable leaf area index (LAI)

	Cap surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	32.23	0.44	37.35 – 39.11	< 0.001
LAI	-1.58	0.10	-1.79 – -1.37	< 0.001
Observations	451			
R^2	0.3			

Table A2.4 Outcome of simple linear regression model for the response variable hijab ground surface temperature with the explanatory variable leaf area index (LAI)

	Hijab surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	35.50	0.35	34.80 – 36.20	< 0.001
LAI	-1.15	0.08	-1.32 – -0.99	< 0.001
Observations	451			
R^2	0.3			

Table A2.5 Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor sub-plot. The continuous variables are non-scaled.

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	30.78	0.24	30.31 – 31.24	< 0.001
LAI	-0.89	0.05	-0.98 – -0.80	< 0.001
IRR (Open area)	0.00	0.00	0.00 – 0.00	< 0.001
Time 12.00 hr.	0.85	0.10	0.66 – 1.05	< 0.001
Time 13.00 hr.	1.08	0.10	0.88 – 1.27	< 0.001
Time 14.00 hr.	0.98	0.11	0.76 – 1.19	< 0.001
Random Effects				
σ^2	2.73			
t_{00} Subplot	3.49			
ICC	0.56			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.328/0.705			

Table A2.6 Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor plot. The continuous variables are non-scaled.

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	31.05	0.44	30.18 – 31.92	< 0.001
LAI	-0.94	0.09	-1.12 – -0.75	< 0.001
IRR (Open area)	0.00	0.00	0.00 – 0.00	< 0.001
Time 12.00 hr.	0.85	0.14	0.59 – 1.12	< 0.001
Time 13.00 hr.	1.07	0.14	0.80 – 1.35	< 0.001
Time 14.00 hr.	0.94	0.16	0.63 – 1.24	< 0.001
Random Effects				
σ^2	1.07			
t_{00} Subplot	2.78			
ICC	0.72			
$N_{Subplot}$	124			
Observations	451			
Marginal R^2/Conditional R^2	0.431/0.842			

Table A2.7 Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor plot. The continuous variables are scaled

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	28.49	0.18	28.13 – 28.84	< 0.001
LAI	-1.54	0.16	-1.85 – -1.24	< 0.001
IRR (Open area)	0.57	0.07	0.43– 0.72	< 0.001
Time 12.00 hr.	0.85	0.14	0.59 – 1.12	< 0.001
Time 13.00 hr.	1.07	0.14	0.80 – 1.35	< 0.001
Time 14.00 hr.	0.94	0.16	0.63 – 1.24	< 0.001
Random Effects				
σ^2	1.07			
t_{00} Subplot	2.78			
ICC	0.72			
$N_{Subplot}$	124			
Observations	451			
Marginal R^2/Conditional R^2	0.431/0.842			

Table A2.8 Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.), land use and the random factor subplot. The continuous variables are scaled.

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	28.21	0.23	27.76 – 28.66	< 0.001
LAI	-1.44	0.12	-1.68 – -1.21	< 0.001
IRR (Open area)	0.61	0.05	0.51– 0.70	< 0.001
Time 12.00 hr.	0.85	0.10	0.66 – 1.05	< 0.001
Time 13.00 hr.	1.08	0.10	0.88 – 1.27	< 0.001
Time 14.00 hr.	0.97	0.11	0.75 – 1.19	< 0.001
Shrubland	0.19	0.26	-0.32– 0.70	0.470
Rubber	0.44	0.32	-0.19– 1.08	0.171
Oil palm	0.39	0.31	-0.22 – 1.01	0.210
Random Effects				
σ^2	2.73			
t_{00} Subplot	3.48			
ICC	0.56			
N_{Subplot}	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.329/0.705			

Table A2.9 Outcome of a linear mixed effect model for the response variable worker cap surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor sub-plot. The continuous variables are scaled.

	Worker cap surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	31.20	0.14	30.92– 31.48	< 0.001
LAI	-2.34	0.11	-2.55 – -2.14	< 0.001
IRR (Open area)	1.32	0.08	1.17 – 1.47	< 0.001
Time 12.00 hr.	0.99	0.15	0.69 – 1.29	< 0.001
Time 13.00 hr.	1.46	0.16	1.15 – 1.76	< 0.001
Time 14.00 hr.	1.14	0.17	0.80 – 1.48	< 0.001
Random Effects				
σ^2	6.75			
t_{00} Subplot	5.15			
ICC	0.43			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.390/0.654			

Table A2.10 Outcome of a linear mixed effect model for the response variable worker hijab surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor sub-plot. The continuous variables are scaled.

	Worker hijab surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	30.07	0.11	29.85– 30.30	< 0.001
LAI	-1.72	0.09	-1.89 – -1.55	< 0.001
IRR (Open area)	0.97	0.06	0.86 – 1.09	< 0.001
Time 12.00 hr.	0.95	0.12	0.72 – 1.19	< 0.001
Time 13.00 hr.	1.55	0.12	1.31 – 1.78	< 0.001
Time 14.00 hr.	1.39	0.13	1.12 – 1.65	< 0.001
Random Effects				
σ^2	3.95			
t_{00} Subplot	3.64			
ICC	0.48			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.356/0.665			

Table A2.11 Outcome of a linear mixed effect model for the response variable black board surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor sub-plot. The continuous variables are scaled.

	Black board surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	33.62	0.23	33.17– 34.08	< 0.001
LAI	-3.79	0.16	-4.10 – -3.48	< 0.001
IRR (Open area)	1.84	0.13	1.59 – 2.09	< 0.001
Time 12.00 hr.	0.20	0.27	-0.33 – 0.74	< 0.457
Time 13.00 hr.	0.80	0.28	0.26 – 1.34	< 0.004
Time 14.00 hr.	-0.07	0.30	-0.67– 0.53	< 0.823
Random Effects				
σ^2	21.21			
t_{00} Subplot	9.64			
ICC	0.31			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.376/0.571			

Table A2.12 Outcome of a linear mixed effect model for the response variable white board surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00, 12.00, 13.00 and 14.00 hr.) and the random factor sub-plot. The continuous variables are scaled.

	White board surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	29.55	0.11	29.33– 29.77	< 0.001
LAI	-1.82	0.08	-1.98 – -1.66	< 0.001
IRR (Open area)	0.97	0.06	0.85 – 1.08	< 0.001
Time 12.00 hr.	1.02	0.12	0.78 – 1.26	< 0.001
Time 13.00 hr.	0.91	0.12	0.67 – 1.16	< 0.001
Time 14.00 hr.	0.66	0.14	0.39 – 0.93	< 0.001
Random Effects				
σ^2	4.27			
t_{00} Subplot	2.97			
ICC	0.41			
$N_{Subplot}$	620			
Observations	2247			
Marginal R^2/Conditional R^2	0.386/0.638			

Table A2.13. Difference between below-canopy air temperature and various surface temperatures (air temperature – surface temperature), i.e. below-canopy ground surface temperature, worker cap surface temperature, worker hijab surface temperature, whiteboard surface temperature, and blackboard surface temperature. The depicted results are mean differences and standard deviations (SD) at noon. The negative sign associated with mean values indicates that surface temperature is higher than air temperature.

	Difference in air to surface temperature (˚C)									
	Ground		Cap		Hijab		Whiteboard		Blackboard	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Forest	2.5	0.5	0.8	0.9	1.1	0.8	2.0	0.8	1.3	0.9
Shrubland	2.4	0.7	-1.6	4.9	-0.4	3.5	1.3	2.5	-2.0	7.1
Rubber	1.7	2.0	-1.4	3.4	0.6	2.2	0.2	3.1	-3.9	6.0
Oil palm	1.6	1.6	-1.9	4.4	-0.5	3.5	-0.6	4.8	-5.8	8.1

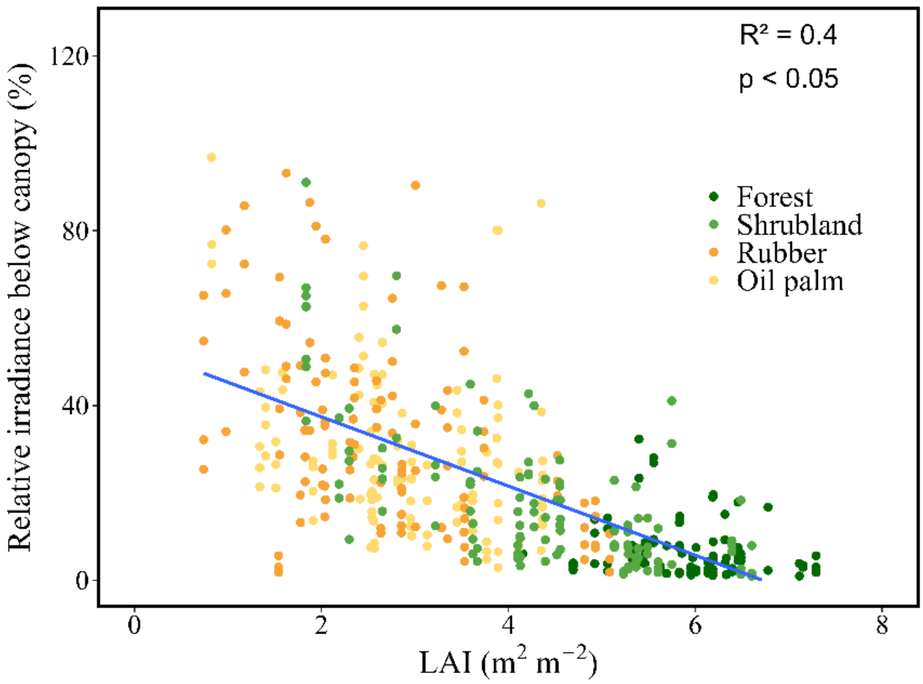


Fig. A2.3 Relationship between leaf area index (LAI) and relative irradiance below-canopy. N = 124 plots, each with four measurements the day (Time 11.00, 12.00, 13.00 and 14.00 hr.)

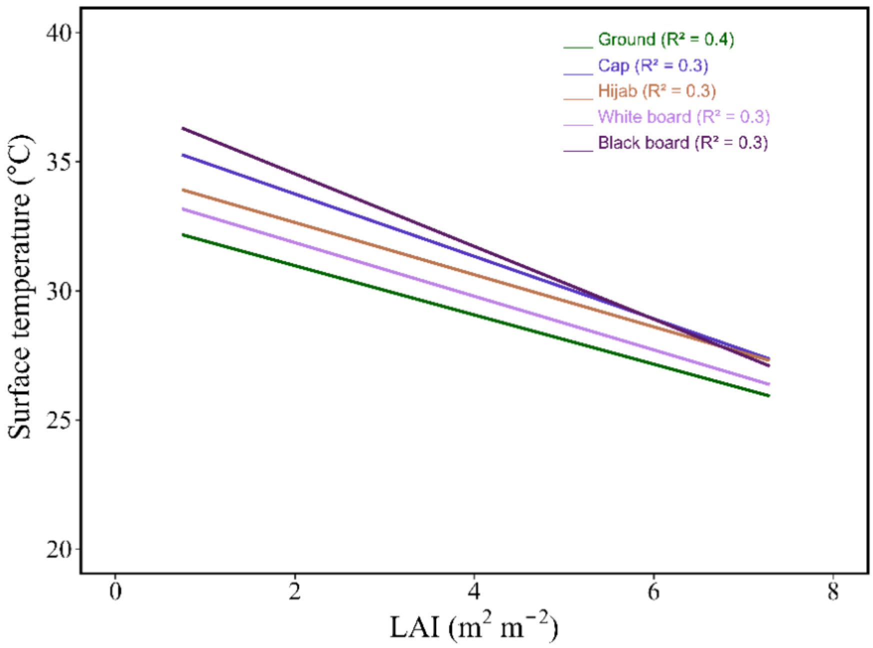


Fig. A2.4 Relationship between LAI and temperatures of five different surfaces (ground, cap, hijab, black and white board). The lines are derived from the 124 plots (N), each plot with four measurements during the day (time 11:00 am, 12:00 pm, 1:00 pm, and 2:00 pm of the day), observations include all four land-use types. But the individual observations not shown here.

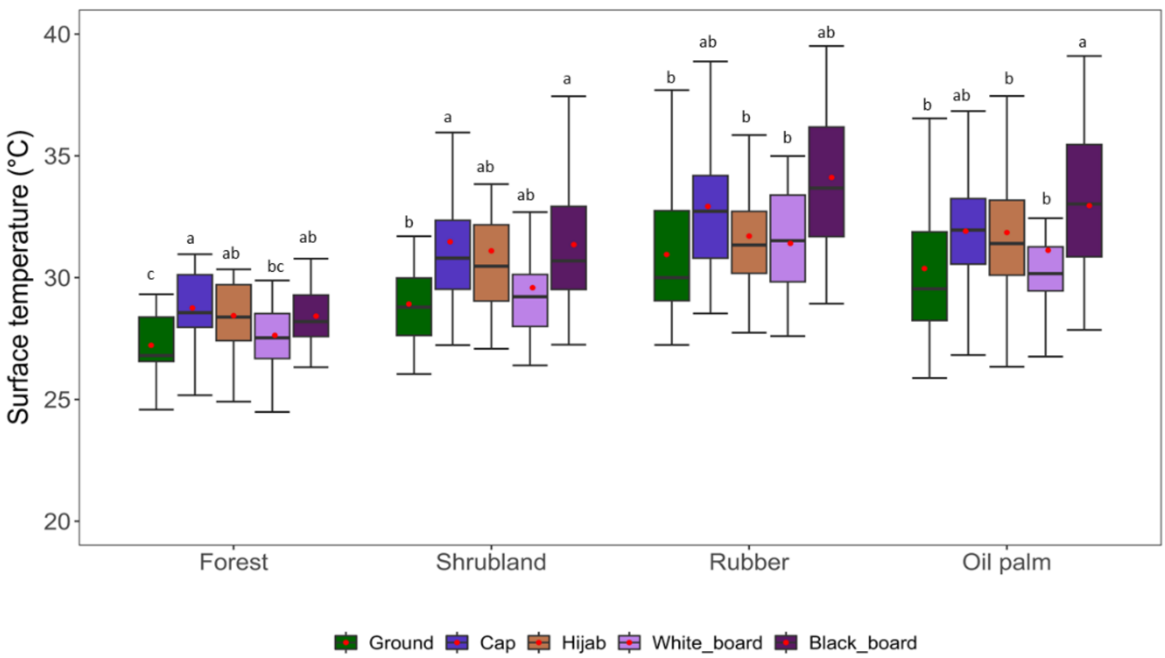


Fig. A2.5 Below-canopy surface temperature of different surfaces as measured at noon varied within and among the studied land-use types. Different letters (on top of the box) indicate significant differences ($p < 0.05$) among the surfaces within a given land-use type, as based on ANOVA with Tukey's HSD test.

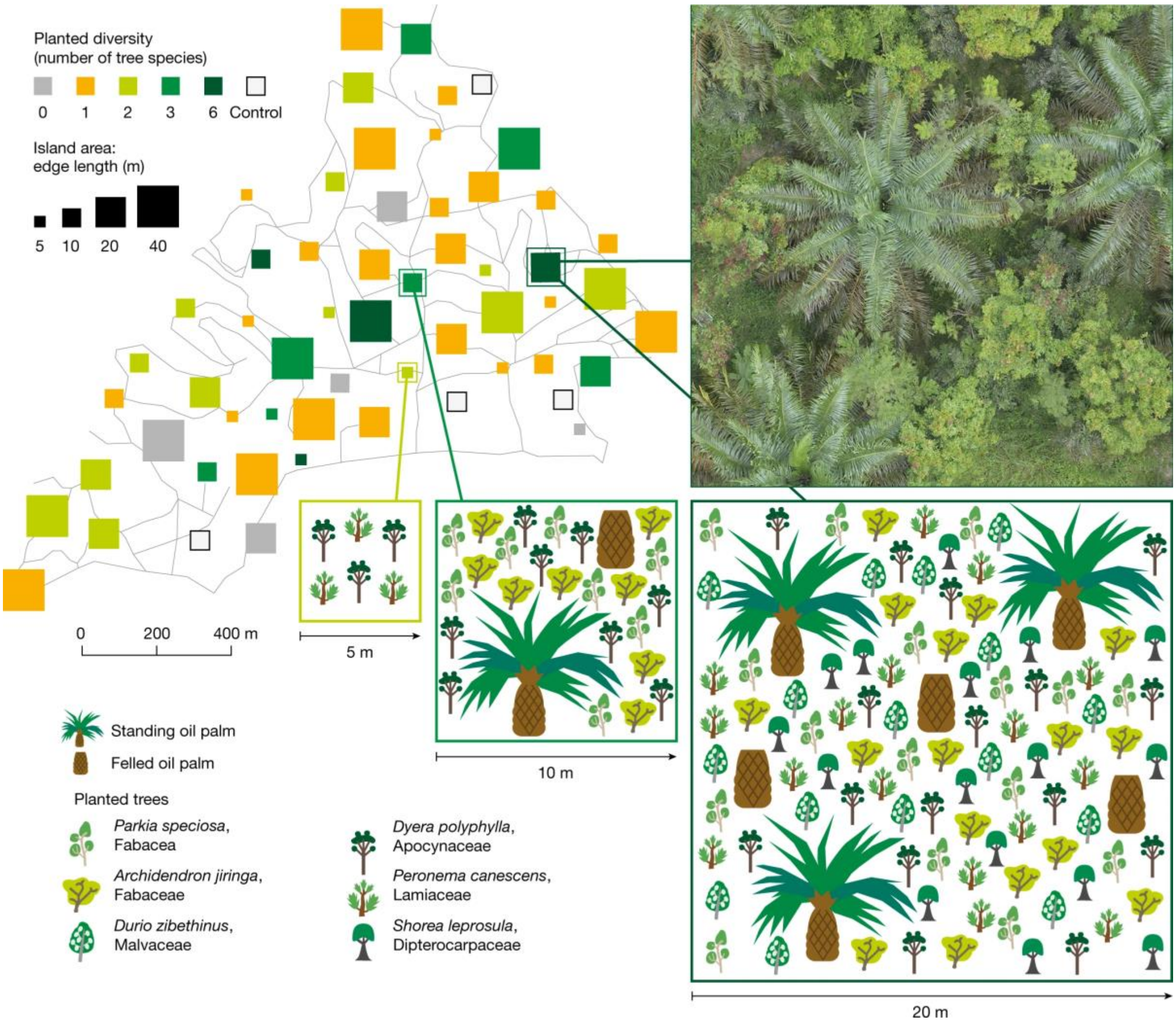


Fig. A3.1 Experimental design that tests the ecological restoration outcomes of tree island establishment in oil palm-dominated landscapes. Tree islands vary in area (25–1,600 m2) and planted tree diversity (none to six species), with a total of 52 tree islands established in an industrial oil palm plantation in Sumatra, Indonesia. Control plots represent conventionally managed oil palm monocultures. Note that the islands in the map are not at scale. (Source: Zemp et al., 2023).

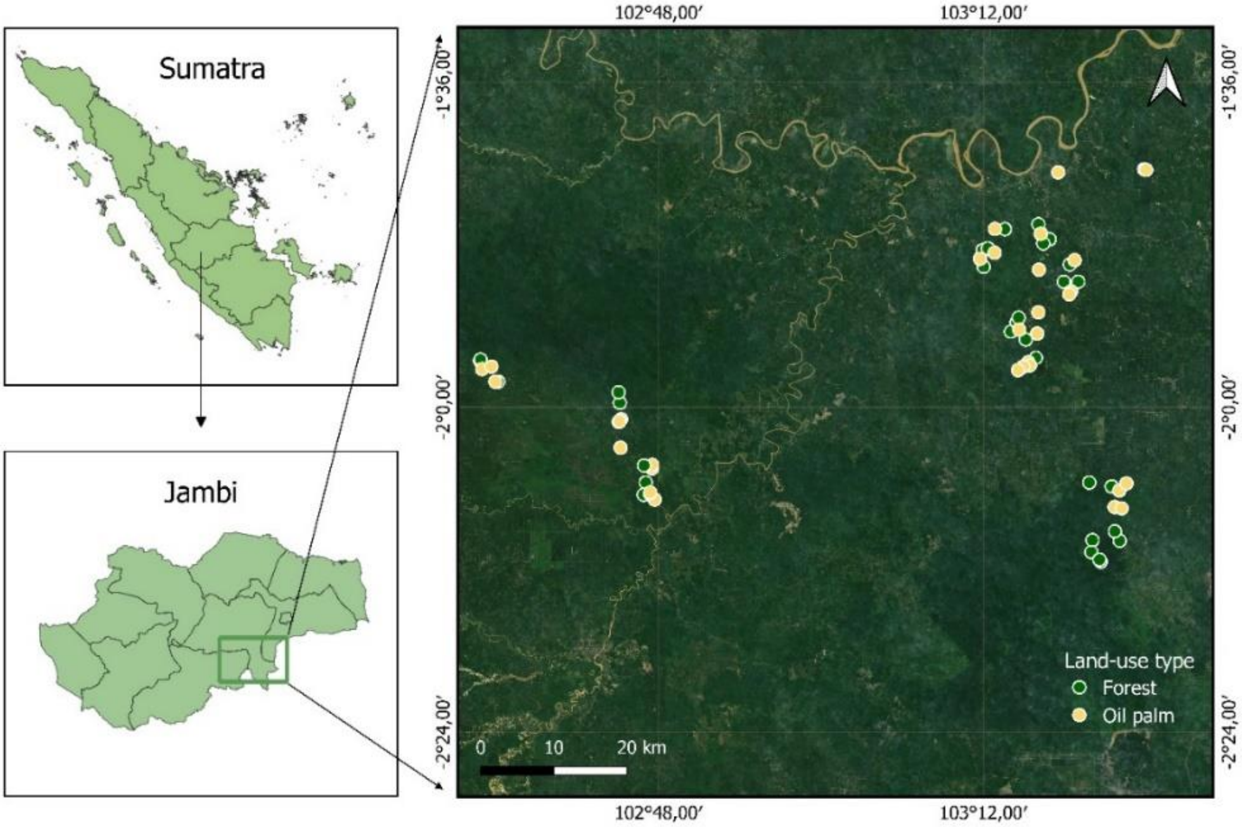


Fig. A3.2. Map of landscape assessment plots selected for current study in Jambi province, Sumatra, Indonesia with the 62 study plots across the land-use types forest and oil palm plantations. Each plot has 5 subplots of 5m X 5m area. Background map: Sentinel-2 cloudless 2021 by EXO from QGIS 3.28.

Table A3.1 Mixed effect model selection following the stepwise selection to select best model support by using the function dredge. Best fit models are ranked based on the selecting criteria AIC and weights. Null model (model 33), full model (model 48) and the best fit model (model 36) is presented in main results.

Model	Intercept	IRR	LAI	Island area	observed diversity	SSCI	Time	AIC	AICc	Weight
36	28.24	0.59	-0.64				+	763.0	763.7	0.619
44	28.24	0.59	-0.64		-0.16		+	765.8	766.7	0.138
52	28.24	0.59	-0.61			-0.08	+	766.2	767.1	0.114
4	28.69	0.52	-0.66					769.5	769.8	0.030
60	28.24	0.58	-0.60		-0.18	-0.13	+	768.7	769.8	0.029
34	28.24	0.63					+	770.1	770.7	0.019
50	28.24	0.61				-0.30	+	771.3	772	0.010
48	27.54	0.58	-0.68	-0.04	-0.61		+	771.4	772.5	0.007
40	28.30	0.59	-0.63	-0.003			+	771.6	772.6	0.007
12	28.69	0.52	-0.66		-0.15			772.3	772.7	0.007
20	28.69	0.52	-0.63			-0.09		772.6	773.1	0.006
42	28.23	0.63			-0.14		+	773.3	773.7	0.004
58	28.24	0.61			-0.23	-0.35	+	773.5	774.4	0.003
28	28.69	0.51	-0.62		-0.18	-0.14		775.2	775.8	0.001
56	28.34	0.59	-0.59	-0.005		-0.11	+	774.6	775.8	0.001
64	27.58	0.58	-0.65	0.04	-0.56	-0.08	+	774.5	775.9	0.001
2	28.69	0.56						777.4	777.6	0.001
16	27.98	0.51	-0.71	0.04	-0.61			777.9	778.5	0.000
8	28.74	0.52	-0.66	-0.003				778.1	778.6	0.000
18	28.69	0.54				-0.32		778.3	778.6	0.000
38	28.35	0.63		0.006			+	778.5	779.3	0.000
54	28.47	0.61		-0.12		-0.34	+	779.2	780.1	0.000
10	28.69	0.55			-0.13			780.3	780.6	0.000
46	27.93	0.63		0.02	-0.34		+	779.7	780.6	0.000
26	28.69	0.53			-0.21	-0.37		780.5	781.0	0.000
62	28.06	0.61		0.01	-0.33	-0.34	+	780.4	781.5	0.000
24	28.79	0.51	-0.61	-0.005		-0.11		781.1	781.7	0.000
32	28.03	0.51	-0.67	0.04	-0.59	-0.09		781.0	781.8	0.000
35	28.23		-0.75				+	783.3	783.8	0.000
3	28.69		-0.76					784.6	784.8	0.000
6	28.80	0.55		-0.006				785.8	786.1	0.000
22	28.92	0.53		-0.01		-0.36		786.2	786.6	0.000
43	28.23		-0.75		-0.17		+	785.9	786.7	0.000

Cont. Table A3.1

51	28.23		-0.69			-0.16	+	785.9	786.7	0.000
14	28.39	0.55		0.02	-0.33			786.9	787.4	0.000
19	28.69		-0.69			-0.16		787.3	787.6	0.000
11	28.69		-0.76		-0.17			787.3	787.6	0.000
30	28.52	0.53		0.01	-0.32	-0.36		787.4	788.0	0.000
59	28.23		-0.68		-0.22	-0.21	+	788.2	789.1	0.000
27	28.69		-0.68		-0.21	-0.21		789.6	790.0	0.000
47	27.44		-0.80	0.04	-0.68		+	791.2	792.2	0.000
39	28.29		-0.75	-0.003			+	791.8	792.6	0.000
15	27.90		-0.81	0.04	-0.67			792.7	793.1	0.000
49	28.22					-0.42	+	792.7	793.3	0.000
7	28.74		-0.75	-0.003				793.2	793.5	0.000
33	28.22							793.1	793.6	0.000
17	28.69						+	794.3	794.5	0.000
1	28.69					-0.42		794.7	794.9	0.000
63	27.54		-0.74	0.04	-0.65	-0.16	+	793.9	795.0	0.000
55	28.36		-0.67	-0.007		-0.19	+	794.3	795.2	0.000
57	28.22				-0.26	-0.47	+	794.5	795.3	0.000
31	28.00		-0.74	0.04	-0.64	-0.16		795.3	795.9	0.000
23	28.82		-0.68	-0.007		-0.19		795.7	796.1	0.000
41	28.22				-0.15		+	795.8	796.4	0.000
25	28.69				-0.25	-0.47		796.2	796.5	0.000
9	28.69				-0.15			797.5	797.7	0.000
53	28.51			-0.02		-0.47	+	800.2	800.9	0.000
37	28.35			-0.007			+	801.4	801.9	0.000
21	28.97			-0.02		-0.47		801.8	802.1	0.000
61	28.07			0.008	-0.35	-0.47	+	801.3	802.2	0.000
45	27.89			0.02	-0.37		+	802.4	803.1	0.000
5	28.80			-0.006				802.9	803.2	0.000
29	28.54			0.008	-0.34	-0.47		802.9	803.4	0.000
13	28.36			0.02	-0.35			804.0	804.3	0.000

Table A3.2. Outcome of a linear mixed effect model for the response variable below-canopy ground surface temperature with the fixed factors leaf area index (LAI), open-area irradiance (IRR) and time of day (Time 11.00 am. 12.00 pm, 1.00 pm, 2.00 pm.) SSCI and observed diversity, Island area and the random factor plot. LAI and open-area irradiance (continuous variables) are scaled. BCST - below-canopy surface temperature, LAI - leaf area index, IRR – irradiance, SSCI - stand structural complexity index

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	27.33	0.59	26.15 - 28.51	< 0.001
LAI	-0.63	0.22	-1.06 - -0.20	0.004
IRR (Open area)	0.58	0.12	0.36 - 0.81	< 0.001
SSCI	-0.08	0.21	-0.51 - 0.34	0.695
Observed diversity	-0.68	0.43	-1.53 – 0.17	0.118
Island area 100 m^2	0.88	0.57	-0.24 – 2.00	0.122
Island area 400 m^2	1.12	0.76	-0.38 – 2.63	0.143
Island area 1600 m^2	1.66	1.17	-0.65 – 3.98	0.158
Time 12.00 pm	0.22	0.24	-0.26 - 0.70	0.365
Time 1.00 pm	0.77	0.24	0.29 - 1.24	0.002
Time 2.00 pm	0.84	0.25	0.35 - 1.32	0.001
Random Effects				
σ^2	1.49			
t_{00}	1.43			
ICC	0.49			
N	52			
Observations	205			
Marginal R^2/Conditional R^2	0.3/0.6			

Table A3.3 Outcome of simple linear regression model for the response variable below-canopy temperatures with the explanatory variable LAI within BEE (N=52), where tree planting and no planting plot data were used which included all diversity level, species composition and plot size.

	Below-canopy ground surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	31.94	0.55	30.86 – 33.02	< 0.001
LAI	-0.90	0.15	-1.20 – -0.61	< 0.001
Observations	205			
R^2	0.15			
	Below-canopy cap surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	36.72	1.31	34.13 – 39.31	< 0.001
LAI	-1.22	0.35	-1.92 – -0.53	0.001
Observations	205			
R^2	0.05			
	Below-canopy hijab surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	33.37	0.77	31.86 – 34.88	< 0.001
LAI	-0.76	0.21	-1.17 – -0.35	< 0.001
Observations	205			
R^2	0.06			
	Below-canopy white board surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	31.89	0.60	30.70 – 33.08	< 0.001
LAI	-0.72	0.16	-1.04 – -0.41	< 0.001
Observations	205			
R^2	0.08			

Cont. Table A3.3

	Below-canopy black board surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	36.53	1.20	34.16 – 38.91	< 0.001
LAI	-1.20	0.32	-1.84– -0.56	< 0.001
Observations	205			
R^2	0.06			
	Below-canopy air surface temperature (˚C)			
Predictors	Estimates	SE	CI	P
(Intercept)	33.92	0.40	33.12– 34.72	< 0.001
LAI	-0.62	0.11	-0.84 – -0.41	< 0.001
Observations	205			
R^2	0.13			

Table A3.4: ANOVA results of the random partition analysis for leaf area index (LAI) and different surface temperatures (ST) and air temperature in the tree enrichment experiment. The design allows to test for effects of planted species richness (linear richness, levels: 0 to 6 species), species identity (of the 6 different tree species), interaction among species in different mixtures (non-linear richness) and plot size (5 x 5, 10 x 10, 20 x 20, 40 x 40 m). Statistical significances are indicated as '*' For $P < 0.1$, Df: degrees of freedom, Sq: square.

	Df	Sum Sq	Mean Sq	F-value	*p*-value
LAI					
Linear richness	1	0.001	0.00149	0.0015	0.96924
Species identity	5	2.974	0.59477	0.6027	0.69815
Non-linear richness	2	0.330	0.16523	0.1674	0.84649
Plot size	3	8.168	2.72276	2.7591	0.05627 *
Below-canopy ST					
Linear richness	1	0.414	0.41443	0.3986	0.5318
Species identity	5	7.596	1.51911	1.4612	0.2266
Non-linear richness	2	0.723	0.36143	0.3476	0.7087
Plot size	3	0.839	0.27981	0.2691	0.8472
Cap ST					
Linear richness	1	0.1183	0.11833	0.1415	0.70898
Species identity	5	10.2379	2.04759	2.4489	0.05216 *
Non-linear richness	2	3.8273	1.91364	2.2887	0.11596
Plot size	3	2.7161	0.90537	1.0828	0.36870
Hijab ST					
Linear richness	1	0.3811	0.38107	0.4538	0.50486
Species identity	5	9.4011	1.88022	2.2389	0.07142 *
Non-linear richness	2	4.3946	2.19732	2.6165	0.08691 *
Plot size	3	2.5901	0.86335	1.0280	0.39171
White board ST					
Linear richness	1	0.164	0.16447	0.1608	0.6908
Species identity	5	6.372	1.27442	1.2462	0.3082
Non-linear richness	2	2.057	1.02871	1.0060	0.3757
Plot size	3	1.592	0.53073	0.5190	0.6719

Cont. Table A3.4

Black board ST					
Linear richness	1	0.030	0.03040	0.0304	0.8627
Species identity	5	7.272	1.45432	1.4522	0.2296
Non-linear richness	2	1.679	0.83944	0.8382	0.4407
Plot size	3	1.967	0.65555	0.6546	0.5853
Air Temp.					
Linear richness	1	0.007	0.00679	0.0058	0.9396
Species identity	5	1.330	0.26607	0.2282	0.9478
Non-linear richness	2	1.436	0.71789	0.6157	0.5458
Plot size	3	2.253	0.75095	0.6441	0.5917

Indexes

Index of Figures

Index of Tables

Supporting Documents________________________

Declaration of honor

Declaration of honor

I hereby declare that I am the sole author of this dissertation entitled “Land-use trajectories in lowland Sumatra - impact on leaf area index and below-canopy temperatures” and that all references and data sources have been acknowledges as such. I further declare that this work has never been submitted in any form as part of any other dissertation procedure.

Göttingen, January 2025 ___________________________________