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EFFECTS OF SOIL NUTRIENT AVAILABILITY ON ECTOMYCORRHIZAL COMMUNITIES' DISTRIBUTION IN TWO DIPTEROCARP SPECIES UNDER ELEVATED ATMOSPHERIC CARBON DIOXIDE

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The consequences of rising atmospheric carbon dioxide (CO_2) level on belowground communities in tropical rainforests continues to be a subject of debate. The main objective of this study was to investigate the distribution of ectomycorrhizal (ECM) fungi and relationship between soil nutrients availability under two different CO_2 concentrations. Free Air Carbon Dioxide Enrichment (FACE) hexagon plot was designed to monitor the impact of CO_2 in tropical rainforest ecosystems at Tekam Forest Reserve, Pahang, Malaysia. Twelve roots and soil samples were collected from two dipterocarp saplings (*Shorea lepidota* and *S. leprosula*) in both elevated CO_2 (FACE plot) and control plot conditions. Five soil properties: nitrogen (N), phosphorus (P), potassium (K), carbon (C), and the C:N ratio were analysed. In terms of species distribution, only four species of ECM were found in the FACE plot as opposed to five in the control plot. Unlike *Geastrum* sp. which was observed in the control plot, *Lactarius* sp., *Russula* sp., *Tomentella* sp., and *Cenococcum* sp. exist in both control and FACE plots, indicating their adaptability to varying soil nutrient and CO_2 conditions. Then the Detrended Correspondence Analysis (DCA), Principal Component Analysis (PCA), and Canonical Correspondence Analysis (CCA) were employed to establish the relationship between ECM fungi and their host plant, soil nutrient composition and host plant, and combining all parameters, respectively. *Shorea lepidota* displayed a tendency towards phosphorus in the control plot while *S. leprosula* showed a preference for higher carbon contents. *Tomentella* sp. and *Cenococcum* sp. showed strong association with nitrogen and potassium contents, respectively. Whilst, both *Lactarius* sp. and *Russula* sp. were highly associated with C:N ratio. Conclusively, our findings emphasize the need to understand the complex relationship between soil nutrient availability, ECM distribution and elevated atmospheric CO_2 in tropical rainforest ecosystems.

Keywords: Atmospheric CO_2, dipterocarpaceae, ECM fungi, soil nutrients

INTRODUCTION

Forest ecosystems are home to a diverse range of organisms, including the valuable players known as ectomycorrhizal fungi (ECM), which form beneficial connections with many plant species. They form associations with approximately 60% of plant stems on Earth (Steidinger et al. 2019) and provide host plants with approximately 80% of their annual nitrogen requirements (Leake et al. 2004). These root-symbionts are prolific hyphae producers and significantly enhance the soil volume explored by fine roots (Smith & Read 2010). They constitute over 30% of the soil microbial biomass in boreal and temperate forest ecosystems (Högberg & Högberg 2002).

The establishment and maintenance of ECM symbiosis are influenced by various factors such as the unique traits of plants studied by Bauman *et al.* (2016), Chot and Reddy (2022), López-García et al. (2017) and Shi et al. (2023), and the intriguing exudate profiles investigated by Soudzilovskaia et al. (2015) and Wong-Bajracharya et al. (2020). Additionally, researchers like Veach et al. (2018) have shed light on the importance of resource allocation in these mutually beneficial relationships.

The primary benefits of ECM fungi to the host plant are an increased range for the uptake of nutrients such as phosphorus (P) and nitrogen (N), as well as increase in drought and disease resistance (Augé 2001, Domínguez-Núñez et al. 2019, Hagenbo et al. 2020, Lehto & Zwiazek 2011, Smith & Read 2010). In return, the fungi received carbon (C) in the form of photosynthate. The establishment and functioning of such symbioses are influenced by various factors including photosynthetic rates (Gardner et al. 2021), carbon allocation (Naing et al. 2016, Pan et al. 2020), and modifications in root exudates composition (Bardgett et al. 2014, Bernard et al. 2022, Finzi et al. 2015, Huang et al. 2014).

Among these factors, the concentration of CO_2 in the atmosphere has emerged as a key driver that shapes plant-soil interactions and belowground communities. Elevated CO_2 levels not only affect aboveground vegetation but also induce notable changes in plant physiology (Bhargava & Mitra 2020), morphology (Barickman et al. 2021, Luo et al. 2020), growth patterns (Brito et al. 2020, Piñero et al. 2017), and root architecture (Ziegler et al. 2023). Consequently, the intricate connections between plants and the belowground environment, particularly ECM fungi, are significantly influenced by elevated CO_2 concentrations.

Increased atmospheric CO_2 not only affects the plant but also has profound impacts on the physical and chemical properties of the soil. Changes in CO_2 levels can influence soil moisture (Burkart et al. 2011, Lemordant et al. 2018), nutrient availability (Madhu & Hatfield 2013, Wong-Bajracharya et al. 2020), soil carbon stocks (Terrer et al. 2021, Walker et al. 2021), organic matter decomposition rates (Li et al. 2023) and nutrient cycling processes (Jiang et al. 2020a, Liu et al. 2018). These modifications in soil properties form a dynamic feedback loop that further influences plant responses and the availability of resources for ECM fungi (Daza et al. 2005, Zak et al. 2019).

Currently, little is known about the actual relationships and the real interplay between changes in plant communities and the properties of the soil under different climates. Further, as the colonisation dynamics, diversity and functioning of ECM fungi are intricately linked to the quality and quantity of resources they can access in soil, this study aimed to investigate the relationship between soil nutrient availability and the distribution of ectomycorrhizal (ECM) fungi under two different CO_2 concentrations (0 and 100–300 ppm). By examining the responses of ECM fungi to changing CO_2 levels, adaptations and shifts in plant-microbe interactions that may occur in future high-CO_2 environments can be predicted.

MATERIALS AND METHODS

Study site

The study was conducted within the Tekam Forest Reserve in Jerantut, Pahang, a hill dipterocarp forest characterised by its diverse soil composition. The soil in this area predominantly consists of pyroclastic and volcanic rocks, evident by historical volcanic activity (Khoo 1977, Marryanna et al. 2019). The soil texture ranges from clay (42%) to sandy (37%) (Amir Husni et al. 1989) providing a varied substrate for plant growth and nutrient dynamics. Tekam Forest Reserve experiences a bimodal rainfall pattern, with peaks in precipitation occurring in November and May (Marryanna et al. 2019). The average annual precipitation in the study area is approximately 2987 mm (Weather and Climate 2022).

Free Air Carbon Enrichment (FACE) plot description

Within the Tekam Forest Reserve, the FACE system was implemented to investigate the effect of elevated atmospheric CO_2 levels on the forest ecosystems. The FACE system was hexagonally designed with a side length of 6.0 m on each side. Functioning as an open-chamber plot, CO_2 gas is released into the experimental area at desired levels (100–300 ppm) within 24 hours (Norsheilla et al. 2018). These concentrations were chosen to mimic the high levels of atmospheric CO_2 concentrations under natural field conditions. The system was also designed to maintain air temperature and humidity while the CO_2 concentration was elevated above normal levels. To ensure accurate reading of selected parameters, the FACE system is integrated with a control panel house and computerised data monitoring, providing real-time insights into the environmental conditions and CO_2 levels within the experimental plot.

Ectomycorrhizal (ECM) diversity identification

The roots of three selected saplings of both *Shorea lepidota* and *S. leprosula* in both conditions (control and FACE plot) were meticulously traced and excised using a sharp knife. To minimise damage to infected roots, the samples were gently submerged in water, allowing for the careful removal of excess soil and debris before transferring to a clean petri dish containing water. The ECM morphotypes were then identified under a dissecting microscope, based on criteria such as shape, dimensions, surface features, ramification type, colour, size, and the presence of emanating hyphae, rhizomorphs, and cystidia (Agerer & Rambold 2004–2020). Morphotypes exhibiting similar morphological characteristics were pooled and quantified accordingly. Identification and verification of the anatomical and morphological features of ECM structures were conducted using standard ECM descriptions from reference books (Agerer 1987–2006) and the DEEMY online database (Agerer & Rambold 2004–2020).

Soil sampling

A total of 12 soil samples were collected from the bases of three replicates of dipterocarp *(S. lepidota* and *S. leprosula)* saplings at two different plots. Prior to soil sampling, any leaf litter and humus layers were carefully removed. Both *S. lepidota* and *S. leprosula* saplings were chosen as they are commonly found in lowland dipterocarp forests and fast-growing species (Manokaran et al. 1992, Masano et al. 1987, Widiyatno et al. 2014). To avoid the influence of plant size, the selection of plant saplings with a similar range of height (average of 0.32 m) was random among dipterocarp saplings. Topsoil samples from 0–20 cm depth were collected for each species and carefully placed in polybags and air dried. Subsequent analysis of the soil nutrients availability- nitrogen (N), phosphorus (P), potassium (K), carbon (C), and the C:N ratio was done according to Nurul Hidayah et al. (2020).

Analysis of ECM communities and soil properties under different CO_2

The relationship between ECM communities and soil properties was analysed using Canoco 5.0 software (Biometrics, Wageningen, The Netherlands). Detrended Correspondence Analysis (DCA) was first performed to visualise the similarity of ECM species to host species in two plots. The control plot represents normal (0 ppm) while the FACE plot represents elevated CO_2 levels (100–300 ppm). Binary transformation was used to standardise the relative abundance of ECM species. Unconstrained Principal Component Analysis (PCA) was carried out next to identify the variation in soil properties and the distribution of host plants in relation to soil nutrients. The chosen gradient length of DCA was 3.45 indicating that the data were appropriate for conducting Canonical Correspondence Analysis (CCA) (Ter Braak 1986). The CCA allowed for visualisation of sites and species in multidimensional spaces, with the restriction that the ordination axes must be linear combinations of the specified underlying soil nutrients. The significance of each soil variable was determined through a Monte Carlo permutation test based on 499 random trials at a significance level of 0.05 (Ter Braak 1990).

RESULTS AND DISCUSSION

ECM composition

Table 1 presents the occurrence of ectomycorrhizal (ECM) fungi families and genera associated with *S. lepidota* and *S. leprosula* saplings in both control and FACE (Free-Air CO2 Enrichment) plots. The ECM families considered in this study include Theleporaceae, Geastraceae, Gloniaceae and Russulaceae represented by the

Table 1 Ectomycorrhizal (ECM) occurrence on two host plant species (*Shorea lepidota, S. leprosula*) under two different conditions (control and FACE plots)

Condition	Host plant	Theleporaceae	Geastraceae	Gloniaceae	Russulaceae	
		Tomentella	*Geastrum*	*Cenococcum*	*Russula*	*Lactarius*
Control plot	*S. lepidota*	✓	✓	✓	✓	✓
	S. leprosula	✓	✓	✗	✓	✓
FACE plot	*S. lepidota*	✓	✗	✗	✓	✓
	S. leprosula	✓	✗	✓	✗	✓

genera *Tomentella, Geastrum, Cenococcum, Russula* and *Lactarius*. In the control plot, *S. lepidota* exhibited associations with all the ECM genera listed (*Tomentella, Geastrum, Cenococcum, Russula* and *Lactarius*), suggesting a rich and diverse ECM community under normal conditions. In contrast, *S. leprosula* showed associations with most of the genera except *Cenococcum*, indicating slightly reduced ECM diversity compared to *S. lepidota*. Under elevated CO_2 conditions (FACE plot), the ECM diversity associated with *S. lepidota* decreased together with the absence of both *Geastrum* and *Cenococcum*, indicating a potential sensitivity of these genera to elevated CO_2 levels. On the other hand, *Tomentella, Russula* and *Lactarius* persisted, suggesting that these genera are more resilient or adaptable to elevated CO_2 conditions, consistent with studies done by Fransson et al. (2005) and Lindahl et al. (2006). *Shorea leprosula* in the FACE plot showed a similar trend, with the absence of *Geastrum* and *Russula*. However, *Cenococcum* reappeared in the FACE plot for *S. leprosula*, suggesting possible compensatory colonisation by *Cenococcum* under elevated CO_2 conditions while *Russula* remained absent (Pritchard et al. 2008).

The differing responses of *S. lepidota* and *S. leprosula* to elevated CO_2 in terms of ECM associations suggest species-specific interactions between host plants and their mycorrhizal partners. For instance, *S. lepidota* showed a broader ECM diversity under the control conditions but a more pronounced reduction in diversity under elevated CO_2, whereas *S. leprosula* maintained some level of ECM diversity even in the FACE plot, with *Cenococcum* reappearing. This could indicate that *S. leprosula* has a more flexible or resilient ECM association, possibly aiding its adaptability under changing environmental conditions (Van Der Putten et al. 2013, Parrent & Vilgalys 2007).

These findings align with the research of Norby et al. (2010) who reported species-specific responses in ECM diversity under elevated CO_2 in temperate forests, suggesting that different host plants may exhibit varied mycorrhizal associations depending on environmental conditions. Similarly, Parrent and Vilgalys (2007) found that ECM fungal communities are strongly influenced by host plant identity, which is consistent with the observed differences in ECM associations between *S. lepidota* and *S. leprosula* in this study. A previous study recorded increases in ECM abundance under elevated CO_2 (Treseder 2004). However, findings from this study revealed a reduction in ECM diversity, particularly for *S. lepidota*, suggesting that tropical ECM communities may respond differently with some genera potentially more sensitive to elevated CO_2 levels. The observed changes in ECM community structure could have significant implications for nutrient acquisition, as different ECM fungi are known to vary in their efficiency of nutrient uptake, particularly in acquiring P and N from the soil (Agerer 2001, Courty et al. 2010). The persistence of *Tomentella* and *Lactarius* in both conditions suggested that these genera might play a crucial role in maintaining nutrient cycling and supporting plant growth, despite the overall reduction in diversity. Courty et al. (2010) reported that *Lactarius* spp. appear under elevated CO_2, possibly due to its efficient nutrient uptake capabilities. Interestingly, their study also showed that *Geastrum* spp. were observed to have declined under elevated CO2, potentially due to its specific ecological preferences or host requirements (Högberg et al. 2007, Peay et al. 2010).

Table 2 Summary of soil nutrients at Tekam Forest Reserve, Jerantut, Pahang

Nutrient	Control plot	FACE plot	Combination
N (%)	0.37	0.43	0.40
P (mg kg^{-1})	4.20	3.33	3.77
K (mg kg^{-1})	84.93	81.78	83
C (%)	1.49	1.69	1.59
C:N (%)	4.38	4.93	4.66

Soil nutrient availability

Understanding variations in soil nutrient content is crucial for comprehending plant nutrient acquisition strategies and their responses to elevated CO_2 levels. This study assessed primary macronutrients (N, P, K) essential for plant growth, along with carbon (C) content and the C:N ratio, which are important indicators of nutrient availability and decomposition processes (Blanco et al. 2023, Ostrowska & Porębska 2015, Zhang et al. 2019, Zheng et al. 2021) (Table 2).

The results revealed minor variations in soil nutrient content between control and FACE plots. Nitrogen (N) content was slightly higher in the FACE plot (0.43%) compared to the control plot (0.37%). Phosphorus (P) and potassium (K) levels were slightly lower in the FACE plot (3.33 mg kg^{-1} and 81.78 mg kg^{-1}, respectively) compared to the control plot (4.20 mg kg^{-1} and 84.93 mg kg^{-1}). Carbon content was higher in the FACE plot (1.69%) compared to the control plot (1.49%). The C:N ratio was higher in the FACE plot (4.93) compared to the control plot (4.38). The two-sample t-test indicated no significant difference in soil nutrient content between the two plots [t (7) = 0.03, p-value = 0.978].

Our finding suggests that elevated CO_2 levels have minimal impact on soil nutrient dynamics in the short term, consistent with similar studies in tropical forests (Zheng et al. 2021). The minimal variation in soil nutrient content implies that the tropical forest ecosystem may exhibit high resilience to changes in atmospheric CO_2, potentially due to complex interactions among soil microorganisms, plant roots, and broader ecosystem processes (Hungate et al. 1997, Luo et al. 2006). This stability could also reflect the role of unmeasured factors such as microbial activity and root exudates, in maintaining nutrient balance under elevated CO_2 (Schlesinger et al. 2006, Drake et al. 2011).

Moreover, while elevated CO_2 can enhance plant growth and carbon sequestration, its impact on soil nutrient cycling can be limited or negligible in the short term, especially in nutrient-rich tropical ecosystems (Norby et al. 2011). This aligns with the observed minimal changes in nutrient content and supports the notion that tropical forest soils might buffer against atmospheric changes, maintaining nutrient dynamics even under altered environmental conditions (Thompson et al. 2019, Oren et al. 2001).

Relationship of ECM with host species and soil nutrient at different environments

Detrended Correspondence Analysis (DCA)

DCA was employed to examine the relationship between ectomycorrhizal (ECM) fungi and their host plants, specifically *S. lepidota* and *S. leprosula*, in different CO_2 environments. The results of the DCA are summarised in Table 3, which includes eigenvalues and the cumulative explained variation for each axis. Axis 1, with an eigenvalue of 0.59, explained 41.29% of the cumulative variation in shaping the ECM community. The gradient length for Axis 1 was 3.18, reflecting significant separation of ECM species and host plants along this axis.

Under control conditions, DCA revealed a strong association between *S. leprosula* and the ECM fungi *Geastrum* sp. and *Russula* sp. (Figure 1). This suggests that under normal CO_2 levels, *S.*

Table 3 Summary of Detrended Correspondence Analysis (DCA) on ectomycorrhizal (ECM) community in Tekam Forest Reserve

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.5933	0.2735	0.013	0.0018
Explained variation (cumulative)	41.29	60.32	61.23	61.35
Gradient length	3.18	2.27	2.23	2.45

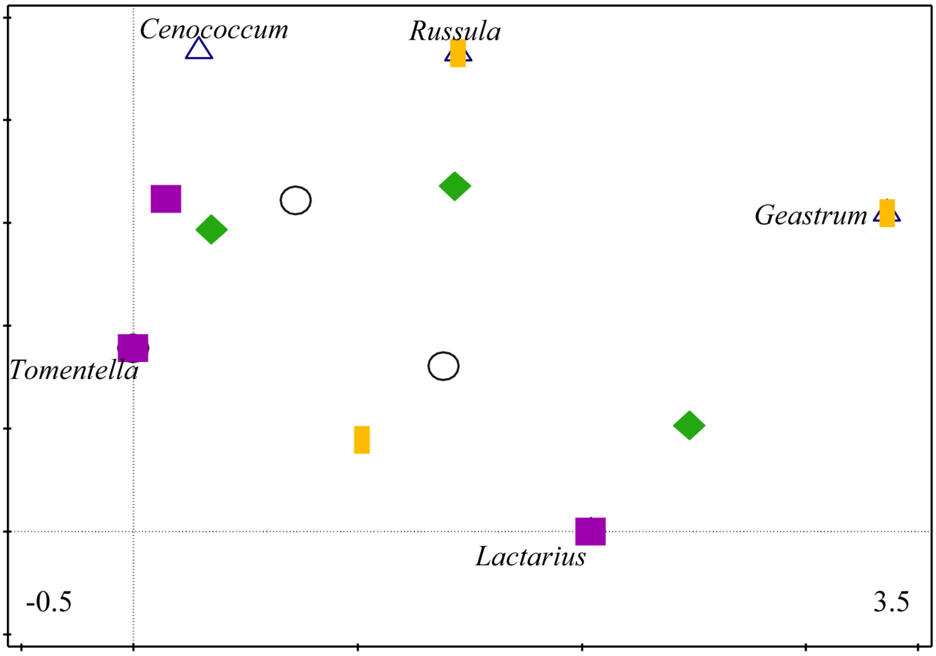

Figure 1 Detrended Correspondence Analysis (DCA) of five ECM with 12 soil samples in Tekam Forest Reserve. For control plot, *Shorea leprosula* is coded in rectangular (yellow) while *S. lepidota* in diamond (green). For FACE plot, *S. leprosula* is coded in square (purple) while *S. lepidota* in empty circle (black)

leprosula establishes good symbiotic relationship with these specific ECM genera, which may optimise nutrient acquisition strategies under current environmental conditions (Courty et al. 2010). In contrast, under elevated CO_2 conditions (FACE plot), *S. leprosula* showed a shift in associations, favouring *Lactarius* sp. and *Tomentella* sp. over *Geastrum* sp. and *Russula* sp. This shift may reflect changes in root exudate composition or physiological responses of *S. leprosula* to elevated CO_2, which in turn altered the ECM community structure (Treseder 2004, Van der Putten et al. 2013).

Shorea lepidota exhibited weaker or minimal associations with ECM fungi in both control and FACE plots, suggesting that it may not rely as heavily on ECM symbiosis as *S. leprosula*, or it may associate with ECM fungi not captured in this analysis. This could indicate that *S. lepidota* has a more stable but less diverse ECM community or is less responsive to CO_2-induced changes (Parrent & Vilgalys 2007). The observed limited associations of *Cenococcum* sp., known for its stress tolerance and ability to thrive in various environments, with both *S. leprosula* and *S. lepidota* may suggest that *Cenococcum* operates more independently or in a generalist role, rather than forming specific associations with these host plants (Agerer 2001, Courty et al. 2010).

The findings indicate that variations in ECM fungal associations are more likely driven by host specificity rather than soil nutrient status. The DCA analysis demonstrated distinct ECM-

Table 4 Summary of Principal Component Analysis (PCA) on the plant host in study plots in the Tekam Forest Reserve Jerantut, Pahang

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.5067	0.2972	0.1583	0.0378
Explained variation (cumulative)	50.67	80.39	96.22	100.00

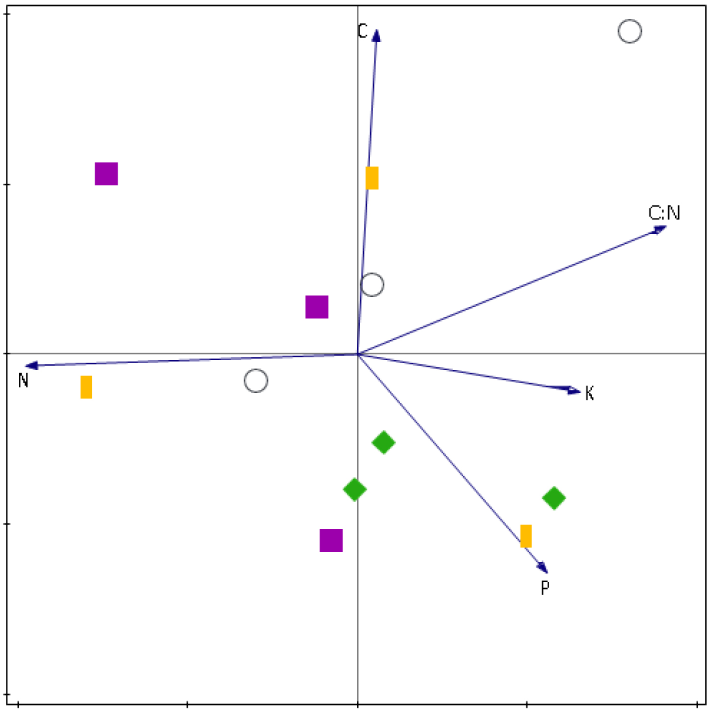

Figure 2 The Principal Correspondence Analysis (PCA) of 12 soil samples in Tekam Forest Reserve (P=available phosphorus; K=available potassium; N= total nitrogen, C= total carbon, C:N=ratio of total carbon and nitrogen). For control plot, *Shorea leprosula* is coded in rectangular (yellow) while *S. lepidota* in diamond (green). For FACE plot, *S. leprosula* is coded in square (purple) while *S. lepidota* in empty circle (black)

host plant associations that change under different environmental conditions (control vs. FACE plots) but remain consistent within each host plant species. This suggests that ECM fungi select their hosts based on specific plant characteristics such as root exudates, rather than soil nutrient availability alone (Parrent & Vilgalys 2007, Smith & Read 2010). The minimal variation in soil nutrient content between control and FACE plots (Table 2) supports this notion, indicating that nutrient status does not solely drive differences in ECM community structure. The stability in nutrient content across conditions suggests that other factors such as host plant-specific interactions with fungi, are more influential (Treseder 2004).

Principal Component Analysis (PCA)

The variations of soil nutrients of these samplings were investigated using PCA and summarised in Table 4. PCA was performed to analyse the relationship between plant host and the soil nutrients availability. The first two PCA eigenvalue axes had values of 0.507 and 0.297, explaining 50.67% and 80.39% of the variance, respectively. These showed significant relationships between soil nutrients with both axes, and that the distribution of the plant hosts is strongly controlled by soil nutrients in general. Figure 2 illustrated that nitrogen (N) and carbon (C) are closely associated with plant hosts in both control and FACE plots. In contrast, phosphorus

Table 5 Summary of Canonical Correspondence Analysis (CCA) on the ECM community in study plots in the Tekam ForestReserve, Jerantut, Pahang

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2949	0.1996	0.0363	0.0012
Explained variation (cumulative)	20.52	34.41	36.93	37.01
Pseudo-canonical correlation	0.8073	0.7393	0.3128	0.0686
Explained fitted variation (cumulative)	55.44	92.96	99.78	100.00

(P) shows a strong association only in the control plot, while potassium (K) and the C:N ratio do not significantly influence plant distribution. The PCA results indicate that soil nutrient levels directly influence host plant distributions. This means that variations in soil nutrients can affect where different host plants are found. However, the analysis does not explicitly address how soil nutrients might influence ECM fungi distribution via plant hosts.

Our findings suggest that soil nutrients play a key role in shaping host plant distributions, which may in turn, affect ECM fungi indirectly. While the PCA results show direct associations between soil nutrients and plant hosts, the indirect effects on ECM fungi distribution should be considered in the context of host plant changes. Previous studies have reported inconsistent results regarding the impact of soil nutrients on ECM colonisation, with some showing positive effects (Terrer et al. 2016, Wang et al. 2015) and others reporting negative effects (Alberton et al. 2007, Hu et al. 2006). In tropical rainforests, elevated CO_2 can affect ECM fungi colonisation by altering plant community dynamics and nutrient availability (Ellsworth et al. 2017, Jiang et al. 2020b). The intermediate-host plant stress hypothesis suggests that ECM communities are typically higher under moderate stress levels but may decrease under severe stress (Swaty et al. 2004). Although our results did not show statistically significant changes in ECM fungi distribution, the lower soil moisture observed in the FACE plot could contribute to reduced ECM colonisation, as adequate water availability supports a higher diversity of ECM fungi by providing increased carbohydrates to the underground community (Gehring et al. 2014).

Canonical Correspondence Analysis (CCA)

The CCA was used to explore relationships between soil nutrients and ECM communities in the Tekam Forest Reserve. As detailed in Table 5, CCA Axis 4 explained 37.0% of the variation in ECM community distribution, with a pseudo-canonical correlation of 0.81. However, the Monte Carlo permutation test showed no significant correlations across the axes (pseudo-F=1.0, p=0.40), indicating that the influence of soil nutrients on ECM community distribution was minimal. The CCA results illustrated the interactions between specific soil elements and ECM communities, as shown in Figure 3. For instance, *Russula* sp. and *Lactarius* sp. were associated with an enriched C:N ratio, suggesting their preference for nutrient conditions prevalent in specific environments. In the control plot, *S. leprosula* exhibited notable associations with certain ECM fungi. Whereas in the FACE plot, *S. lepidota* demonstrated different fungal associations. Notably, *Tomentella* sp., known for its preference for nitrogen-rich soils, was more commonly associated with *S. lepidota* in the control plot. Interestingly, our analysis revealed that neither potassium nor the C:N ratio had a significant impact on plant species distribution in either plot.

This finding contrasts with studies conducted in temperate forests, which found a strong preference for high C:N ratios by ECM fungi (Averill et al. 2014, Lin et al. 2017). In tropical rainforests, the influence of soil nutrients on ECM community distribution appears to be less pronounced, possibly due to the complex nature of nutrient-fungal interactions and the ability of fungi to utilise

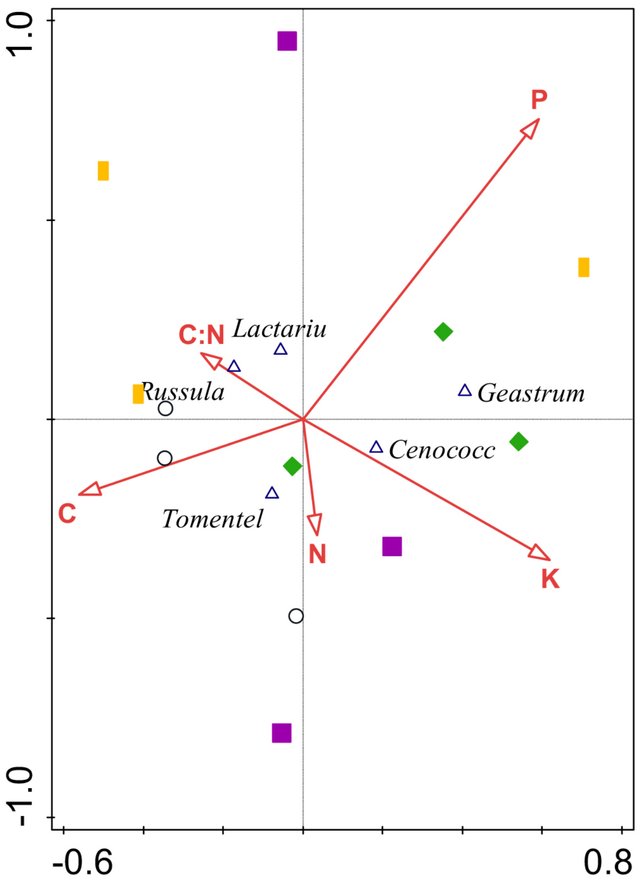

Figure 3 Canonical Correspondence Analysis (CCA) ordination plot showing the relationships among ECM fungi species, host plants, and soil nutrient availability under ambient (control) and elevated CO_2 (FACE) conditions. Length and direction of vectors indicate the strength and direction of the influence of soil nutrients (P = available phosphorus; K = available potassium; N = total nitrogen; C = total carbon; C:N= carbon to nitrogen ratio) on both ECM fungi and host plant species. For control plot, *Shorea leprosula* is represented by yellow rectangles and *S. lepidota* by green diamonds. For FACE plot, *S. leprosula* is represented by purple squares and *S. lepidota* by black empty circles

available nutrients efficiently (Abuzinadah & Read 1986). Soil nutrients play a crucial role in ECM fungi colonisation, as ECM fungi are essential for nitrogen cycling by decomposing organic complexes (Avis et al. 2003, Twieg et al. 2009). For instance, *Tomentella* sp. is known for its role in nitrogen uptake, aligning with its classification as a nitrophile (Hagenbo et al. 2018, Jörgensen et al. 2022, Ning et al. 2018, Sterkenburg et al. 2015). Phosphorus storage and transport are also vital, with ECM fungi facilitating favourable conditions for nutrient cycling (Casieri et al. 2013, Costa et al. 2016, Nehls & Plassard 2018, Van Tichelen & Colpaert 2000). Previous research indicated that Dipterocarpaceae species have strong associations with specific soil nutrients, particularly phosphorus, magnesium, and calcium (Paoli et al. 2005). Other soil characteristics, including exchangeable calcium, magnesium and potassium, influence dipterocarp community composition in Borneo forests (Sukri et al. 2012). These findings underscore the complexity of nutrient-fungal interactions in tropical rainforests and suggest that ECM community structure may be influenced by factors beyond soil nutrient availability alone. In summary, while our CCA results did not reveal statistically significant correlations, they provide valuable insights into the nuanced interactions between soil nutrients and ECM communities. The minimal impact of soil nutrients observed in our study highlights the need for further research to understand the broader ecological factors influencing ECM fungal distribution in tropical ecosystems.

CONCLUSION

This study examined the relationship between soil nutrients and the distribution of ECM fungi under normal (control plot) and elevated CO_2 concentrations (FACE plot). Our findings indicate that elevated CO_2 concentrations lead to specific changes in the associations between Dipterocarpaceae plants and their environment, specifically impacting the connection between host plants and ECM fungi communities. Nitrogen availability had a more pronounced effect on ECM fungi distribution compared to phosphorus. Elevated CO_2 levels significantly influence soil nutrient availability and mycorrhizal community composition, as noted in recent studies (Tarin et al. 2021, Zhang et al. 2016). Additionally, increased atmospheric CO_2 can raise total carbon levels, potentially leading to soil acidification and affecting microbial communities. For instance, Wang et al. (2022) observed decreased basidiomycota abundance due to increased soil acidification from high organic carbon. Therefore, further research is needed on how soil nutrients affect ECM fungi diversity associated with Dipterocarpaceae in tropical forests. Our results support predictions that elevated CO_2 promotes plant growth and carbon sequestration, with subsequent effects on soil carbon levels (Wang et al. 2019, Chen et al. 2020). Understanding these impacts is crucial for forest ecosystem research, highlighting the need for ongoing investigation into how soil nutrients drive ECM fungi assembly under changing atmospheric conditions.

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