Modelling the role of mycorrhizal associations in soil carbon cycling: insights from global analyses of mycorrhizal vegetation

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Citation

Huang, W. (2024, April 10). *Modelling the role of mycorrhizal associations in soil carbon cycling: insights from global analyses of mycorrhizal vegetation*. Retrieved from https://hdl.handle.net/1887/3734176

Version: Publisher's Version

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CHAPTER 5

Projected re-distribution of global mycorrhizal vegetation under future environmental change and implications for leaf litter decomposition

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Preparing the submission to Global Change Biology

Abstract

Mycorrhizal associations are highly sensitive to environmental change, including climate change and land-use change. Mycorrhizal vegetation distribution will therefore likely shift in the coming decades with potentially major impacts on ecosystem functioning.

Here, we used existing data about mycorrhizal vegetation distribution and known environmental drivers to model the relationship between environmental factors and mycorrhizal vegetation, and employed this information to project future changes in the global distribution of mycorrhizal vegetation based on future socioeconomic pathways scenarios. Our analysis suggests that changes in temperature and precipitation regimes will lead to the redistribution of mycorrhizal vegetation with some areas becoming unsuitable for particular types of mycorrhizal associations. Globally, the total area covered by mycorrhizal-vegetation is decreasing more than increasing, with the worst decline in the scenario that based on the assumption of CO_2 increase being non-battled (SSP5-RCP8.5). There is a geospatial unevenness in the replacement of vegetation types: AM-vegetation increases in some boreal areas and central Africa, but decreases elsewhere, while EM-vegetation declines in most regions of the Northern Hemisphere, Australia, and central Africa.

Subsequently, we quantitatively assessed the impact of such mycorrhizal vegetation changes on leaf litter decomposition, an important ecosystem process using a process-based model of mycorrhizal impact on plant litter decomposition, Yasso-Myco. We found that the contribution of mycorrhiza on litter decomposition was larger in the scenario based on SSP5-RCP8.5, accelerating the loss in total carbon and changes in global soil chemical composition. Compared to the most stringent mitigation efforts scenario (SSP1-RCP2.6) and the middle of the road scenario (SSP2-RCP4.5), these mycorrhizal impacts could lead to reduced nutrient cycling, and altered plant-mycorrhizal interactions, which could further lead to altered plant distribution and loss of biodiversity. The magnitude of the influence of changes in mycorrhizal vegetation on litter decomposition is comparable to the impacts of climate change. We conclude that changes in mycorrhizal vegetation distribution are a critical aspect to be considered for predicting the responses of terrestrial ecosystems to global environmental change.

5.1 Introduction

Mycorrhizal vegetation refers to plants that form symbiotic relationships with beneficial soil fungi that in exchange for carbon provide plants with nutrients. There are two major types of mycorrhizae present in almost all Earth ecosystems. Ectomycorrhiza (EM) is possessed by only 2% of land plant species, but comprises ca. 25% of terrestrial plant biomass (Soudzilovskaia *et al.*, 2019). EM are primarily associated with trees and woody plants, and are found in temperate and boreal forests, as well as some tropical forests (Smith & Read, 2008). Arbuscular mycorrhiza (AM) is possessed by ca.80% of land plant species (Brundrett & Tedersoo, 2018) which comprise ca 65% of terrestrial plant biomass (Soudzilovskaia *et al.*, 2019). AM are found in a much wider range of plant species and are more abundant in tropical and subtropical regions, especially in grassland ecosystems (Davison *et al.*, 2015).

The global distribution of different mycorrhizal vegetation types is influenced by several environmental factors including soil type, climate, and disturbance history (Barceló *et al.*, 2019; Jo *et al.*, 2019; Sapsford *et al.*, 2021). In nutrient-poor soils, mycorrhizal associations can confer a competitive advantage to plants by enhancing nutrient uptake. Therefore, mycorrhizal vegetation is often more prevalent in ecosystems where nutrient availability is limited (Smith & Read, 2008). Additionally, climate change, including shifts in temperature and precipitation patterns, can also affect mycorrhizal associations and the distribution of mycorrhizal vegetation (Bennett & Classen, 2020). Disturbances of anthropogenic drivers such as land-use change, deforestation and habitat fragmentation will disrupt mycorrhizal networks, altering fungal community composition, potentially causing the variation of mycorrhizal fungi and their associated vegetation distribution (Jo *et al.*, 2019; Sapsford *et al.*, 2021). Thus, mycorrhizae are supposed to be more abundant in natural ecosystems than in agricultural fields or other disturbed environments (Kabir, 2005; Hage-Ahmed *et al.*, 2019).

It has been proposed that distinct mycorrhizal vegetation types are associated with specific ecosystems and soil attributes (Read & Perez-Moreno, 2003; Barceló *et al.*, 2019; Steidinger *et al.*, 2019). As a consequence of their different physiological characteristics, mycorrhizal guilds differ in the pathways of nutrient acquisition from decomposing plant litter. There has been increasing recognition that mycorrhizae are one of the most important factors in the soil-plant rhizosphere and among the microbial interactions that control litter decomposition (Gadgil & Gadgil, 1971; Koide & Wu, 2003; Langley & Hungate, 2003; Bödeker *et al.*, 2016). Plant litter decomposition alone can return ca.50% of net primary production to the soil (Wardle et al., 2004). Hence, it is one of the most important terrestrial C pathways that affect C mineralization and nutrient cycling in soil. Mycorrhizae enable litter decomposition through three potential pathways: (1) mediating litter decomposition by controlling the environment of litter decomposition, including mediation of the microbial community (Fernandez & Kennedy, 2016; Frey, 2019); (2) provisioning substrate for litter decomposition (Leake *et al.*, 2004; Soudzilovskaia *et al.*, 2015b) as mycorrhizal fungi themselves constitute a large pool of biomass in the soil and therewith create an important C source potentially available for decomposition; (3) affecting the amount and quality of plant produced carbon components (Cornelissen *et al.*, 2001; Phillips *et al.*, 2013; Averill *et al.*, 2019). Yet, despite an understanding of the mechanisms involved, the impact of mycorrhizae on the decomposition environment is among the worst-understood aspects of global plant litter decomposition (Lindahl *et al.*, 2007; Osono, 2007; Keller & Phillips, 2019; See *et al.*, 2019).

Environmental changes (i.e. climate change and land use change) can significantly affect the terrestrial carbon cycle in general, and litter decomposition in particular. Global environmental changes are expected to cause variations in the distribution of vegetation worldwide, as the survival and growth potential of different vegetation types are influenced by these changes. The distribution of vegetation can affect carbon uptake rates through photosynthesis (Buyanovsky *et al.*, 1987), the rates of carbon input into the soil by plant litter (Feng *et al.*, 2022), as well as the litter decomposition environment through impacts on the ecophysiological processes associated with living plants and their symbionts (García-Palacios *et al.*, 2013; Xu *et al.*, 2020b; Zhou *et al.*, 2023). For the latter, the mycorrhizal vegetation environment is among the most important, yet poorly understood drivers. Not only are the future changes in mycorrhizal impacts on litter decomposition uncertain, also the future mycorrhizal vegetation redistribution itself is poorly constrained. Consequently, projections of global litter decomposition are uncertain as a whole (Brovkin *et al.*, 2012; Bradford *et al.*, 2016). This poses risks for natural resource management and establishing effective socioeconomic plans (e.g., land use and forestry) for a low-carbon future.

Current models of global litter decomposition and its projections hardly account for these uncertainties. Global litter decomposition models commonly treat climate and litter quality as major factors controlling the litter decomposition process, but do not explicitly account for mycorrhizal impacts. Further research is therefore needed to more reliably predict the impacts of climate and land use change on litter decomposition rates in the future, by taking into account the impact of the mycorrhizal vegetation environment on litter decomposition.

Therefore, in this paper, we aim to i) predict the future mycorrhizal vegetation distribution under different social economic pathways and corresponding climate scenarios in the future (2050) and ii) evaluate the global spatial dynamics of long-term plant litter decomposition as affected by changes in the mycorrhizal vegetation environment. We specifically addressed the following research questions that are key to understanding the role of mycorrhizae in the future global soil carbon cycle:

- Q1: How will the distribution of different mycorrhizal types change in the future?
- Q2: How will changes in the distribution of mycorrhizal vegetation types and biomass affect global patterns and rates of future leaf litter decomposition?
- Q3: What are the impacts and contributions of such changes on future soil carbon stocks?

Our findings emphasize the significance of considering the mechanisms and impacts of changes in the mycorrhizal vegetation environment in mediating global litter decomposition and soil quality across diverse socioeconomic pathways. This is crucial for trimming the uncertainties in soil carbon mineralization and estimating soil C stocks. It appeals to serious consideration of mycorrhizal environmental influences when making land-use and social-economic plans

5.2 Methods

In combination with maps of mycorrhizal vegetation biomass distribution at a global scale (Soudzilovskaia *et al.*, 2019), the recent microbial process model (Yasso-Myco) (Huang *et al.*, 2022b) opens a new perspective to quantify the impact of mycorrhizal vegetation environmental change on ecosystem carbon and nutrient budgets ranging from landscape to global scales.

To evaluate the impacts of changes in the distribution of mycorrhizal vegetation on soil C cycling processes, we focused on effects on plant litter decomposition in top soils, where plant litter is transformed into soil organic matter and carbon compounds are pre-processed for further potential incorporation into particulate organic matter or minerally-associated (i.e. stable) organic matter. For this purpose, we estimated the alterations of the impacts imposed by the predicted re-distribution of mycorrhizal vegetation (hereafter referred to as ‘changes in mycorrhizal environment’) on plant leaf litter decomposition rates over 10 years using the Yasso soil carbon model, at a spatial resolution of 10 arcmin. We used future socioeconomic pathways scenarios of climate and environment information to predict the corresponding global distribution of mycorrhizal vegetation in 2050. We used the relative abundance of given types of mycorrhizal vegetation as parameters in Yasso-Myco to proximate the decomposition environment. This approximation should be treated as the combined effects of including the abundance of different types of mycorrhiza, the microbial community as well as the soil's physical and chemical properties in the environment.

5.2.1 Future environmental scenarios

(1) IPCC-Shared Socioeconomic Pathways (SSP) scenarios

The Intergovernmental Panel on Climate Change (IPCC) predicts that, without significant reductions in greenhouse gas emissions, temperatures could rise by as much as 1.5 to 4.5 Celsius degrees by the end of the 21st century. The IPCC-SSPs (O’Neill *et al.*, 2017) examine scenarios of global society, demographics, and economics that might affect greenhouse gas emissions, which are now being widely used as important inputs for the latest climate modelling efforts – the Coupled Model Intercomparison Project version 6 (CMIP6) (Eyring *et al.*, 2016). The climate projections in CMIP6 were produced based on new pathways of societal development, the Shared Socio-economic Pathways (SSPs), and related to the Representative Concentration Pathways (RCPs). Each scenario represents the potential climate and N-deposition under certain social and economic applications. We selected three out of the five most divergent scenarios, to explore how societal choices will affect global distribution patterns of mycorrhizal vegetation and their impact on global leaf litter decomposition (O’Neill *et al.*, 2016):

SSP1-RCP2.6: The relatively sustainability-focused SSP1 with “very stringent” mitigation efforts of RCP2.6, with 1.8°C temperature increment in 2100. We use RCP126 for simplicity in later text.

SSP2-RCP4.5: The “middle of the road” SSP2 and less stringent mitigation efforts are associated with RCP4.5, with a 2.7°C temperature increment in 2100. We use RCP245 for simplicity in later text.

SSP5-RCP8.5: The high-growth energy-intensive (fossil-fueled development) SSP5 and a high-end no-mitigation RCP8.5, with a 4.4°C temperature increment in 2100. We use RCP585 for simplicity in later text.

(2) Environmental predictions of each scenario

We selected the projected global (excluding the Antarctic) gridded land cover, climate (temperature and precipitation), and nitrogen deposition of 2015 and 2050, under the chosen three SSP-RCP scenarios as driven by the global climate model (GCM)-IPSL (Boucher *et al.*, 2020; Lurton *et al.*, 2020). Out of the approximately 30 global climate models available, GCM-IPSL predicts future climate changes around the average range of predictions (Frank, 2019). Spatial resolution was resampled to 10-arcmin.

5.2.2 Mycorrhizal environment data

We prepared the global AM and EM- mycorrhizal vegetation distribution maps of 2015 based on biomass fractions of four types of mycorrhizal vegetation including AM, EM, ErM (ericoid-mycorrhiza), and NM (non-mycorrhiza) vegetation. These four types of mycorrhizal vegetation proportions add up to 1. The baseline year of mycorrhizal vegetation distribution (2015) is available from Soudzilovskaia *et al.* (2019). To predict future mycorrhizal vegetation distribution for 2050, firstly, we trained a deep-learning model with 2015 environmental data including temperature, precipitation, land cover, and nitrogen deposition as factors controlling mycorrhizal vegetation distribution of AM, EM, ErM, and NM. For that purpose, we applied the Python DF21 package with default parameters. DF21 uses a new regression-based deep-learning model, called Deep Forest (Zhou & Feng, 2019). It is a combination of multiple decision tree models, that aggregates results from random forest sub-models based on internal cross-validation performance within the dataset, leading to an improved predictive performance and insensitivity to hyperparameters compared to traditional decision tree-based models, which is particularly advantageous for future scenario predictions (Zhou & Feng, 2019). To predict mycorrhizal vegetation in 2050, we fed the trained model with temperature, precipitation, land cover, and nitrogen deposition of 2050. The predicted mycorrhizal vegetation maps, including four types of mycorrhizal vegetation of AM, EM, ErM, and NM in 2050 according to three SSP-RCP scenarios as presented in Appendix Figure A5.1

We assessed the accuracy of the model prediction on mycorrhizal distribution using a 5-fold cross-validation. The resampling procedure first split the whole dataset of 2015 mycorrhizal vegetation distribution into 5 groups. For each group, the performance of the prediction was tested with 80% data for training and the rest of the 20% for validation. The outcome of the validation result is presented with the R^2 score. The importance factors of global mycorrhizal vegetation distribution were derived according to the layer feature importance according to the function in DF21 (see Appendix Table A5.2). All the predictions and assessments for mycorrhizal vegetation distribution were processed using Python3.

5.2.3 Litter decomposition model

We used the Yasso-Myco model to estimate the importance of the future mycorrhizal environment on litter decomposition worldwide. Yasso-Myco is a mechanistic model of plant litter decomposition, developed based on the soil C cycle model Yasso (Tuomi *et al.*, 2009; Huang *et al.*, 2022b). Yasso-Myco predicts litter decomposition processes at a given location based on litter quality, quantity, climate, and types of mycorrhizal vegetation present in the location (Huang *et al.*, 2022b). The model represents the decomposing plant litter as five pools of carbon compounds with different chemical qualities (Liski *et al.*, 2005): compounds soluble in water (denoted with W), compounds hydrolysable in acid (A), components soluble in ethanol or dichloromethane (E), compounds neither soluble nor hydrolysable (N), and humus (H) (Berg & Agren, 1984; Palosuo *et al.*, 2005). These components with different decomposability are key to determining the dynamics of litter decomposition and soil C cycling in soil C modelling (Liski *et al.*, 2005; Tuomi *et al.*, 2009; Viskari *et al.*, 2020a). According to plant litter decomposition experiments and the Yasso soil C model, the decomposability of water-soluble, acid-hydrolysable, and ethanol-soluble (WAE) fractions in the litter are relatively labile, while the non-hydrolysable (N) fraction is relatively recalcitrant. Thus, in this study, we defined WAE-fraction as the labile pool and the N-fraction as the recalcitrant pool. Carbon fluxes related to the dynamics of compartment H were not specified in this study, as we consider a decade of litter decomposition to be not long enough for substantial humus formation.

Yasso-Myco inherited litter decomposition representation from the Yasso model. Litter decomposition is represented as a system of linear differential equations, and the total amount of carbon released from each pool is the result of carbon fluxes between the pools and carbon released to the atmosphere as carbon dioxide (Tuomi *et al.*, 2011b; Viskari *et al.*, 2021). The model determines plant litter decomposability at a given site based on plant litter quality, air temperature and moisture, and “mycorrhizal environment” (estimated as the product of the proportion of AM and EM plant biomass in vegetation). Each of the AM and EM fungal impacts depends on the fungal-type-specific ability to affect the litter decomposition process, defined as the mycorrhizal index Mi following the equation *Eq. (5.1)* in Yasso-Myco (Huang *et al.*, 2022b):

$$Mi = m_{iAM} \cdot \lambda_{AM} \cdot G + m_{iEM} \cdot \lambda_{EM} \cdot G, i \in \{A, W, E, N\} \qquad Eq.(5.1)$$

where m_{iAM} and m_{iEM} are the impacts of AM and EM mycorrhizae on C loss from i pool estimated by model parameters; λ_{AM} and λ_{EM} are the fractions of AM and EM vegetation within the total vegetation biomass; G was the gross primary production (GPP) of mycorrhizal vegetation.

5.2.4 Simulations

5.2.4.1 Cumulative litter decomposability over 10 years of incubation

We assessed the effects of vegetation featuring distinct mycorrhizal types on the litter decomposability, while assuming the same input litter quality at all locations. We acknowledge that also litter quality is affected by mycorrhizal vegetation type. However, litter quality is also affected by many other factors and a comprehensive model for litter quality currently does not exist. We may thus underestimate the full extent to which changes in mycorrhizal vegetation types will affect litter decomposability. The relative loss of total mass and of each component (W, A, E and N) in the decomposing litter were estimated globally. Recalcitrant components make up a significant proportion of soil organic matter and can contribute to long-term carbon storage in soils, while labile components are more readily decomposable and can contribute to short-term fluctuations in soil carbon levels. Thus, we majorly focus on the total mass remaining and the recalcitrant components dynamics in this research, labile fractions dynamics will receive less emphasis. For simplicity, we did not include in the assessment the areas where vegetation cover was predicted to appear or disappear in 2050 (present in grey pixels in the results). Instead, we only examined the areas fully vegetated both in 2015 and 2050. To compare the effect of each driver on the global litter decomposition process separately, we additionally performed simulations varying one type of factor per time: (a) Mycorrhizal vegetation fraction; (b) Total mycorrhizal environment, including mycorrhizal vegetation fraction and abundance; (c) Climate, including temperature and precipitation.

5.2.4.2 Global fresh leaf litter decomposition as affected by the decomposing environment

In addition to the analysis described above, we compared the litter mass remaining after 10 years of decomposition, based on global leaf litter production in 2015 and 2050. We used the annual global leaf litter production of each pixel (NPP_{leaf} - net primary production of plant leaf, extracted from the IPSL model estimations) in each 2050 scenario as input data, and simulated the global leaf litter mass remaining in each scenario of 2050 after 10-year decomposition as affected by the decomposition environment changes including climate and mycorrhizal vegetation environment. The global average litter decomposition environment and leaf production in the year 2015 and different scenarios (RCP126, RCP245 and RCP585) of 2050 are provided in Appendix Table A5.1.

5.3 Results

5.3.1 Mycorrhizal vegetation in current and future scenarios

5.3.1.1 Mycorrhizal vegetation distribution

Mycorrhizal vegetation distribution maps of the year 2050 provided us with quantitative estimates of the future distribution of aboveground biomass fractions (*100%) among AM, EM, ErM and NM plants in spatial resolution of 10 arcmins (see Figure A5.1 in the Appendix). The accuracy of predicted mycorrhizal vegetation distribution of each mycorrhizal vegetation type measured as R^2 according to the cross-validation is listed as follows: AM-vegetation 0.834, EM-vegetation 0.787, ErM-vegetation 0.719, and NM-vegetation 0.677. We present the AM and EM-vegetation distribution changes in three future environment scenarios in Figure 5.1.

In general, the sum of areas where mycorrhizal vegetation decreases is larger than the sum of those where it increases. The global mean value of aboveground biomass fractions (*100%) of non-mycorrhizal vegetation was 0.158 in 2015 and showed an increase in all scenarios to 0.184 in RCP126, 0.193 in RCP245, and 0.217 in RCP585 in 2050. Comparing the three future environmental change scenarios, RCP585 has the worst mycorrhizal vegetation decline. In most cases, one mycorrhizal vegetation types is replaced by another and this phenomenon is geospatially un-even: AM-vegetation increases in boreal areas in Eurasia, North America, Australia, and some areas located in central Africa. The rest of the regions with AM-vegetation decreases. EM-vegetation decreases in most areas of the Northern Hemisphere, Australia and central Africa.

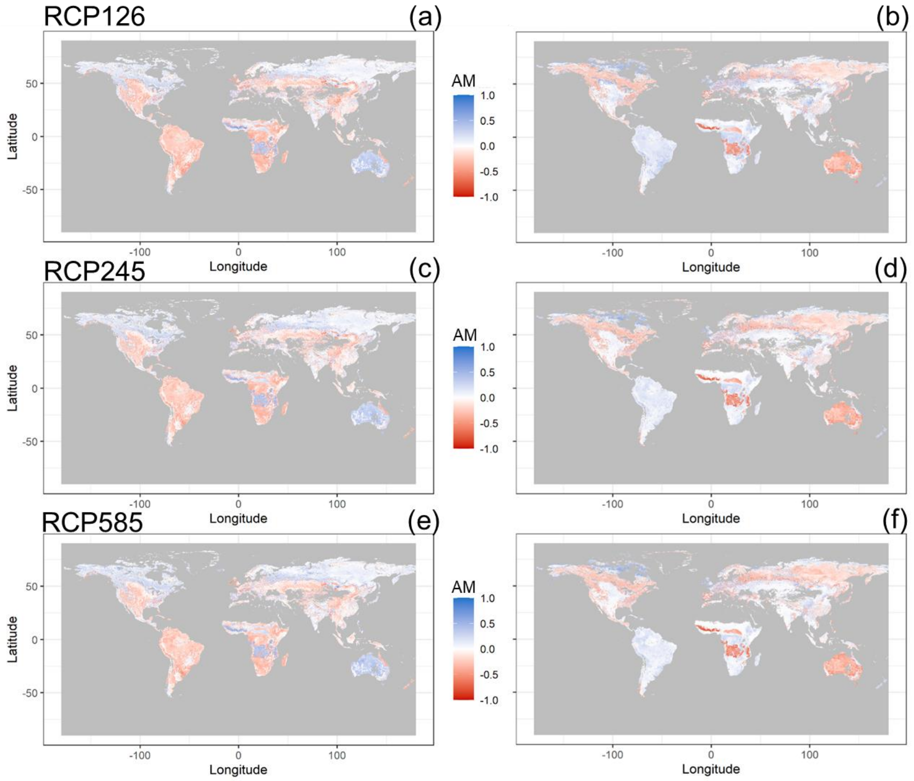

Figure 5.1 Change in distribution of mycorrhizal vegetation in the future scenarios represented by aboveground AM and EM plant biomass proportion (*100%) compared to the year 2015. Pixels in grey represent the area with vegetation loss which were excluded from the analysis. (a) AM plant biomass proportion change in 2050 (RCP126); (b) EM plant biomass proportion change in 2050 (RCP126); (c) AM plant biomass proportion change in 2050 (RCP245); (d) EM plant biomass proportion change in 2050 (RCP245); (e) AM plant biomass proportion change in 2050 (RCP585); (f) EM plant biomass proportion change in 2050 (RCP585).

5.3.2 Analyses of individual chemical compositions

We compared the impact of future vs. current mycorrhizal environments on the decomposability of leaf litter and on the relative loss of recalcitrant carbon components (N-fraction) of decomposing litter. The relative loss of total mass and the loss of the N-fraction in the current year (2015) are shown in Appendix B. Impacts of changes in the global distribution of mycorrhizal vegetation types and of climate on the decomposability of leaf litter are shown in Figure 5.2, and impacts of these drivers on the relative loss of recalcitrant components are shown in Figure 5.3. The values of mycorrhizal index Mi representing the mechanism through which mycorrhizal vegetation affects decomposition are provided in Appendix C, showing the effects of AM vs. EM-vegetation environments on the AWE-fraction and N-fraction in the decomposing litter.

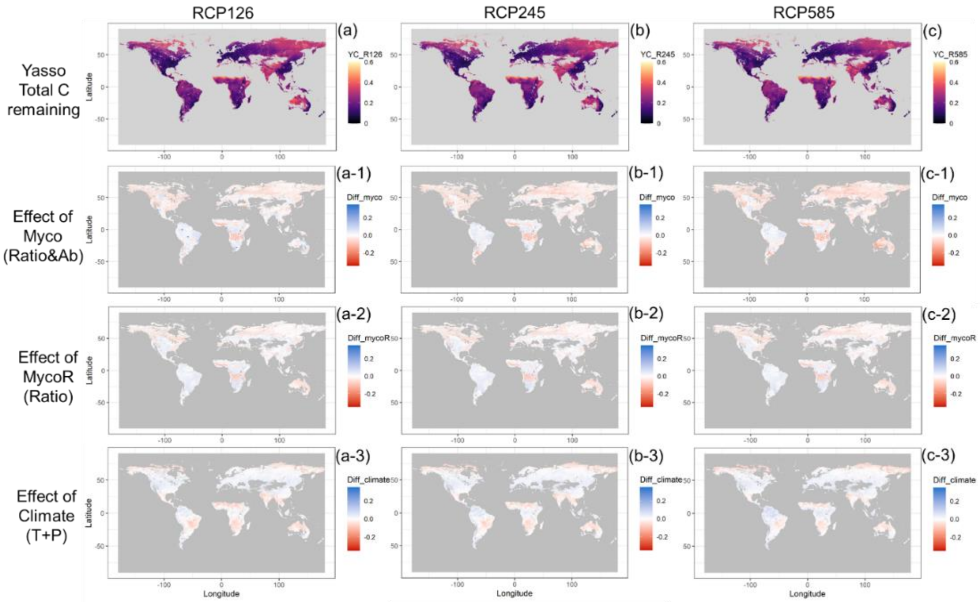

Figure 5.2 Decomposability of leaf litter after 10 years of litter decomposition in future scenarios for (a) 2050 (RCP126) climate scenario, (b) 2050 (RCP245) climate scenario, and (c) 2050 (RCP585) climate scenario. Distinctions are made for: Impact of varying the mycorrhizal environment (including mycorrhizal vegetation fraction and abundance) in each scenario (a-1), (b-1), (c-1); Impact of varying only the mycorrhizal vegetation fraction in each scenario (a-2), (b-2), (c-2); Impact of varying climate (including temperature and precipitation) in each scenario (a-3), (b-3), (c-3).

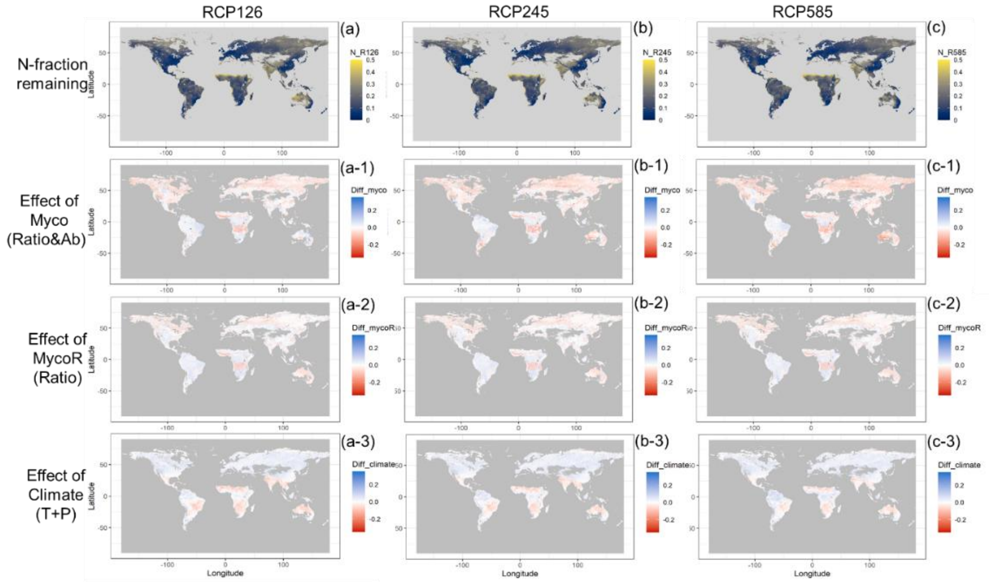

Figure 5.3 Relative fraction of recalcitrant carbon components (N-fraction) in decomposing leaf litter after 10 years of litter decomposition in future decomposing environments for (a) 2050 (RCP126) climate scenario, (b) 2050 (RCP245) climate scenario, and (c) 2050 (RCP585) climate scenario. Distinctions are made for: Impact of varying the mycorrhizal environment (including mycorrhizal vegetation fraction and abundance) in each scenario (a-1), (b-1), (c-1); Impact of varying only the mycorrhizal vegetation fraction in each scenario (a-2), (b-2), (c-2); Impact of varying climate (including temperature and precipitation) in each scenario (a-3), (b-3), (c-3).

5.3.3 Global leaf litter decomposition as mediated by the mycorrhizal-vegetation environment

Figure 5.4 shows the distribution of global leaf litter mass remaining in the total carbon mass and in the N-fraction (recalcitrant carbon) after 10 years of decomposition in both 2015 and 2050. This pattern represents the combined effect of changes in leaf litter production, climate and mycorrhizal vegetation environment. In 2015, global fresh leaf litter production was calculated to be around 10.41 GT (including 2.88GT of recalcitrant components), and after 10 years of decomposition, it contributed to 2.06 GT carbon in the topsoil layer of which 1.59 GT was recalcitrant carbon. In 2050-RCP126, global fresh leaf litter production was around 10.86 GT of which 2.11 GT carbon (including 1.63 GT recalcitrant carbon) was contributed to the topsoil layer after 10 years of decomposition. In 2050-RCP245, global fresh leaf litter production was around 11.31 GT, and after 10 years of decomposition, it contributed 2.18 GT carbon in the topsoil layer (including 1.70 GT recalcitrant carbon); In 2050-RCP585, global fresh leaf litter production was around 12.11 GT, and after 10 years decomposition, it contributed 2.30 GT carbon in topsoil layer (of which 1.80 GT was recalcitrant carbon).

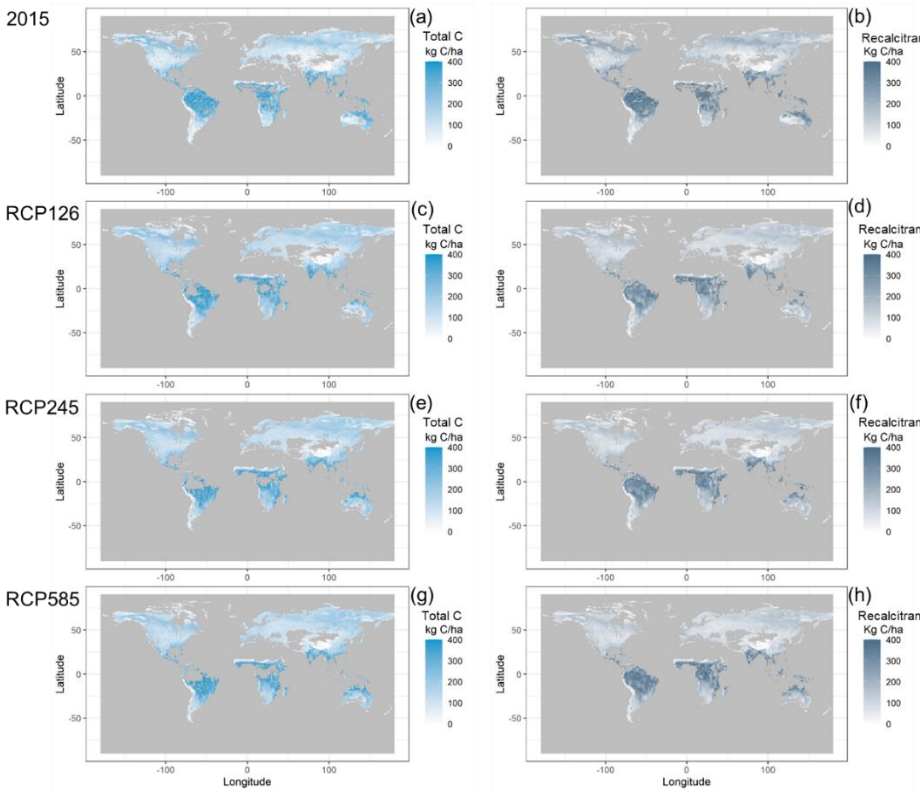

Figure 5.4 Global distribution of current and future leaf litter mass remaining of total carbon and N-fraction litter (recalcitrant carbon) after 10 years of decomposition: (a) Total carbon mass remaining after 10 years of decomposition (2015 baseline); (b) Recalcitrant carbon mass remaining after 10-year leaf litter decomposition (2015 scenario); (c) Total carbon mass remaining after 10 years of decomposition (2050-RCP126 scenario); (d) Recalcitrant carbon mass remaining after 10-year leaf litter decomposition (2050-RCP126 scenario); (e) Total carbon mass remaining after 10 years of decomposition (2050-RCP245 scenario); (f) Recalcitrant carbon mass remaining after 10-year leaf litter decomposition (2050-RCP245 scenario); (g) Total carbon mass remaining after 10 years of decomposition (2050-RCP585 scenario); (h) Recalcitrant carbon mass remaining after 10-year leaf litter decomposition (2050-RCP585 scenario).

Estimations of the total litter mass and the mass of recalcitrant litter remaining after 10 years of decomposition as influenced by each of the drivers of mycorrhizal environment and climate change in each future scenario are shown in Table 5.2. Excluding the areas of new vegetation emergence (i.e. areas changed from being non-vegetated to vegetated) and of vegetation deterioration (i.e. areas changed from vegetated to non-vegetated), we detected that the mycorrhizal vegetation change effects on leaf litter decomposition are comparable to total climate effects including temperature change and precipitation change.

Table 5.2 Total litter mass remaining and recalcitrant litter mass remaining after 10 years of leaf litter decomposition as impacted by different factors in future scenarios.

Impact	Scenarios	Total mass remaining (GT)	Recalcitrant fraction remaining (GT)
2015 baseline		2.01	1.55
Total mycorrhizal environment (accounting for mycorrhizal vegetation abundance and biomass fractionation between distinct mycorrhizal types of vegetation)	RCP126	2.04	1.57
	RCP245	1.97	1.51
	RCP585	1.92	1.44
Biomass fractions vegetation of distinct mycorrhizal types	RCP126	2.06	1.61
	RCP245	2.03	1.60
	RCP585	2.03	1.59
Climate (Precipitation & Temperature)	RCP126	1.99	1.55
	RCP245	2.04	1.60
	RCP585	2.12	1.69

5.4 Discussion

Global patterns of mycorrhizal vegetation distribution are widely recognized to have a strong impact on global plant litter decomposition processes and global soil carbon pool dynamics. The distribution of mycorrhizal vegetation is subject to environmental conditions (Tedersoo *et al.*, 2014; Barceló *et al.*, 2019; Soudzilovskaia *et al.*, 2019), and it is expected that patterns of mycorrhizal vegetation distribution will change in response to changing environmental conditions in the future. However, till now we lacked understanding of the potential effects of global environmental change on mycorrhizal vegetation distribution in view of the potential implications for ecosystem processes, including leaf litter decomposition. The direction and magnitude of mycorrhizal vegetation change impacts will depend on a range of factors, including the specific type of mycorrhizal fungi present, environmental conditions, and the composition of microbial communities in the mycorrhizal vegetation environment involved in the litter decomposition process. Our study is the first attempt to explore future mycorrhizal vegetation distribution change and its implications on future soil carbon dynamics, focusing on the pathway of controlling the environment for plant litter decomposition.

5.4.1 Global mycorrhizal vegetation distribution in future socioeconomic pathways

Our predictions of future mycorrhizal vegetation distribution in 2050 reflected the impacts of different socioeconomic pathways and climate change in the future. One of the most significant socioeconomic pathways affecting mycorrhizal vegetation is the land use and land cover change (Appendix Table A5.2). Our simulations show that, with the expansion of urbanization and agriculture in future, there is an increased likelihood of mycorrhizal vegetation loss, especially in regions where plants of particular mycorrhizal types are already limited in distribution. From RCP126 to RCP 245 and RCP585, the total vegetation cover is decreasing; Moreover, land-use changes can affect the fungal diversity (Tedersoo *et al.*, 2010, 2012), which could also lead to changes in the plant-fungal interactions, leading to altered plant distribution. Our predictions are in accordance with this, as we found in RCP 245 and RCP585 scenarios that the non-mycorrhizal vegetation coverage expands when society is turning into high CO2 emission scenarios.

Climate change is another significant factor affecting mycorrhizal vegetation distribution. As global temperatures rise, the timing of seasonal events such as flowering, plant growth and germination of mycorrhizal fungal spores will change, which in turn can affect the activity of fungal colonization (Kivlin *et al.*, 2013; Soudzilovskaia *et al.*, 2015a; Duarte & Maherali, 2022). Furthermore, changes in rainfall patterns and drought conditions can also affect mycorrhizal vegetation distribution, as the availability of water in the soil is critical for fungal survival and function. Our predictions indicate that the climate change induced by the higher CO_2 emission socioeconomic pathways can cause a reduction in mycorrhizal vegetation distribution.

Increased nitrogen deposition is also considered to be a critical driver for future mycorrhizal vegetation loss since excessive nitrogen deposition can have significant impacts on mycorrhizal fungi. Mycorrhizal fungi are known to improve the water and nutrient uptake of plants, essential for growth in low-nutrient soils. Excessive nitrogen deposition does not only provide additional nitrogen input, it will also reduce the availability of phosphorus in the soil. Both factors are known to negatively impact the eco-physiology of mycorrhizal fungi (Lin *et al.*, 2020; Xia *et al.*, 2020), as well as the levels of plant benefit from the fungi and the amounts of C provided to the fungi. As a result, the fungal biomass and activity in the mycorrhizal vegetation environment are reduced, and all those have cascading effects on plant growth and nutrient acquisition and will contribute to mycorrhizal vegetation loss. However, our analysis of the importance of individual environmental change factors (see Appendix Table A5.2) suggests that N deposition is not a key driver to mycorrhizal distribution in this global analysis compared to land use and climate. N-deposition might thus be mostly important at local scales.

5.4.2 Consequences of changes in mycorrhizal vegetation distribution for future global soil litter decomposition

Mycorrhizal fungi play a vital role in ecosystem functioning, particularly in the decomposition of organic matter in the soil. Different types of mycorrhizal vegetation in the decomposition environment will lead to different amounts of total mass and recalcitrant litter remaining in the decomposing litter. Thus, changes in the mycorrhizal vegetation environment have important implications for ecosystem services such as carbon sequestration, nutrient cycling, and soil conservation (Braghiere *et al.*, 2021).

Our results showed that the impact of mycorrhizal vegetation in different RCPs on the amount of total mass and recalcitrant litter remaining in the decomposing litter can vary. In general, higher RCPs, which represent a more extreme climate change scenario, are associated with an increased decomposability of total litter mass and recalcitrant litter, leading to higher losses of CO_2 and thereby further amplifying climate change. Our estimated amounts of recalcitrant components in the decomposing litter, are assumed to contribute to the soil ‘recalcitrant litter’ pool. This type of litter is particularly important in the context of carbon storage, as it has a longer residence time in the soil. It can contribute significantly to soil carbon stocks, and its loss can reduce the overall carbon storage capacity of soils. Hence, the loss of recalcitrant litter under high RCP scenarios may have long-term implications for carbon storage in the soil. This might have a negative impact on ecosystem functioning, including reduced nutrient cycling, and altered plant-mycorrhizal interactions, which could further lead to altered plant distribution and loss of biodiversity (Tedersoo *et al.*, 2014; van der Heijden *et al.*, 2015).

5.4.3 The magnitude of influence of mycorrhizal vegetation fraction change on litter decomposition is comparable to the change in climate

Our results show that, excluding the effects of vegetation loss, the influence of mycorrhizal vegetation fraction change in the environment to plant litter decomposition is comparable to impacts of climate change, including precipitation and temperature. This indicated that the mycorrhizal vegetation environment may play a critical role in mediating the effects of climate change on ecosystem functioning. Furthermore, the finding of the influence of mycorrhizal vegetation on ecosystem functioning is comparable to that of climate change, suggesting that efforts to conserve and manage ecosystems in the face of climate change should consider the role of mycorrhizal vegetation. For example, conservation efforts aimed at reducing greenhouse gas emissions may not be sufficient to mitigate the effects of climate change on ecosystem functioning if they do not take into account the redistribution of mycorrhizal vegetation.

5.4.4 Future research may be needed to better understand the future global mycorrhizal vegetation and its impact on global litter decomposition

Our study is the first research that looks into global future different types of mycorrhizal vegetation distribution respond to environmental change and how these responses affect litter decomposition. We utilized a widely recognized data source from the GCM-IPSL model, providing valuable insights into the potential impact of climate change and human activities on mycorrhizal vegetation (even though estimates of mycorrhizal vegetation distribution may be uncertain). Moving forward, further research can build on this foundation by exploring additional models and environmental input data to enhance our understanding and reduce uncertainties in predicting future changes in mycorrhizal vegetation distribution. By incorporating a diverse range of models and input data, we can gain a more comprehensive understanding of the potential impacts of environmental change on these vital plant-fungal interactions, leading to more effective conservation efforts and a more sustainable future for our ecosystems.

In this study, we evaluated the decomposition mediation effects of future mycorrhizal vegetation environments. However, mycorrhiza can affect soil C dynamics through two additional pathways: (1) Provisioning of substrate for decomposition. Mycorrhizal fungi themselves constitute a large biomass proportion in soil and therewith create an important soil C pool, potentially available for decomposition (Leake *et al.*, 2004; Soudzilovskaia *et al.*, 2015b); (2) Mediating amount and quality of plant-originated carbon components available for decomposition. Hereto mycorrhizal fungi affect the amount of root exudation of C components (Scott-Denton *et al.*, 2006) and mediate plant litter quality and amounts of plant litter annually shed to the ground. Thus, our estimation is a conservative estimate of the overall effects of mycorrhizal vegetation, as we are not looking at substrate or litter quality impacts. Future evaluation should additionally consider e.g. additional litter inputs due to enhanced vegetation productivity due to increased nutrient uptake facilitated by mycorrhiza; fluxes of labile C from the root and fungal exudates and C fluxes originating from the decomposition of dead mycelium of mycorrhizal fungi (Baskaran *et al.*, 2017; See *et al.*, 2021). The inclusion of these additional processes will contribute to a better understanding of the distribution of global soil C quality and a better estimation of future soil C properties in general and of the impacts thereon by mycorrhiza in particular.

Our work used the relative biomass fractions of different types of mycorrhizal vegetation and Yasso-Myco parameters as proxies representing the abundance of mycorrhizal fungi in the environment. While mycorrhizal fungi are important in litter decomposition, they are not the only microorganisms involved in this process. We assume the mycorrhizal vegetation environment also reflected the complex relationship of mycorrhiza and microbial communities and their impact on the litter decomposition process. Incorporating field measurements for microbial communities in the soil would help us better understand the complex mechanisms in mycorrhizal vegetation environments. Once better methods to measure the composition of soil microbial communities have been developed, future research could investigate how changes in microbial communities, including bacteria and saprotrophic fungi, affect litter decomposition and how these changes interact with mycorrhizal fungi.

Mycorrhizal vegetation plays a significant role in carbon cycling, particularly through its influence on litter decomposition. In this research, we did not incorporate the mycorrhizal impact on the pathway of formation of minerally stabilized carbon in the humus pool. However, our work still provides insights into the important processes preceding global C mineral stabilization from the topsoil since we examined the spatial pattern of long-term development of both labile C pools and recalcitrant plant litter pools. Both pools have the potential to contribute to the formation of mineral-associated organic matter (MAOM) through different mechanisms (Sokol *et al.*, 2019).

5.5 Conclusions

Our study shows that mycorrhizal vegetation distribution is expected to be affected by different socioeconomic pathways and climate change in the future. The larger changes in the mycorrhizal environment in RCP585, compared to RCP126 and RCP245 scenarios, will lead to a faster loss of total carbon. The changes in the mycorrhizal vegetation environment and changes in leaf production in the future will also alter the soil chemical composition by accelerating the decomposition of the most recalcitrant fraction of the leaf litter in the majority of the Northern Hemisphere in the future. The influence of mycorrhizal vegetation fraction changes in the environment is comparable to those due to the change of climate including precipitation and temperature. These findings highlight the need to consider the role of mycorrhizal fungi in addition to the more well-known effects of climate change and have important implications for ecosystem management and conservation that also should take into account the potential impact of changes in mycorrhizal vegetation distribution on the soil carbon cycle. This work is the first necessary step to understanding the role of mycorrhizal vegetation environment in regulating future soil carbon sequestration. It underscores the need for continued research on developing appropriate conservation and management strategies that can maintain or enhance the ecosystem services provided by mycorrhizal vegetation, especially in the face of climate change.

Appendix

A1. Tables

Table A5.1 Global average litter decomposition environment and leaf production in the year 2015 and different scenarios (RCP126, RCP245 and RCP585) of 2050. Climate information includes mean temperature (Tmean), maximum temperature (Tmax), minimum temperature (Tmin) throughout the year in Celsius degrees (°C), and the amount of yearly precipitation (P) in millimetres. Mycorrhizal-vegetation environment-related information including the yearly GPP (g C m^{-2} yr^{-1}) and the proportion of AM and EM mycorrhizal-vegetation types in the environment (*100%). The annual leaf productions are presented in the unit of g C m^{-2}.

	Tmean (°C)	Tmax (°C)	Tmin (°C)	P (mm. yr^{-1})	AM (*100%)	EM (*100%)	GPP (g C m^{-2} yr^{-1})	Leaf production (g C m^{-2} yr^{-1})
2015	9.2	20.6	-2.5	803.4	0.49	0.31	1008.9	91.0
RCP126	11.8	28.6	-5.0	857.4	0.47	0.32	1105.7	96.1
RCP245	12.2	29.0	-4.5	854.9	0.48	0.29	1134.3	99.6
RCP585	13.0	29.7	-3.6	858.3	0.49	0.29	1199.7	103.6

Table A5.2 DF21 derived importance factors of global mycorrhizal vegetation distribution according to the layer feature importance.

	Importance score
Landcover	0.50987
Tmean	0.19959
Tmax	0.08672
N_deposition	0.07629
Tmin	0.07399
Pre	0.05357

A2. Mycorrhizal vegetation distribution represented by relative above-ground biomass of AM, EM, ErM and non-mycorrhizal vegetation biomass in current and future scenarios

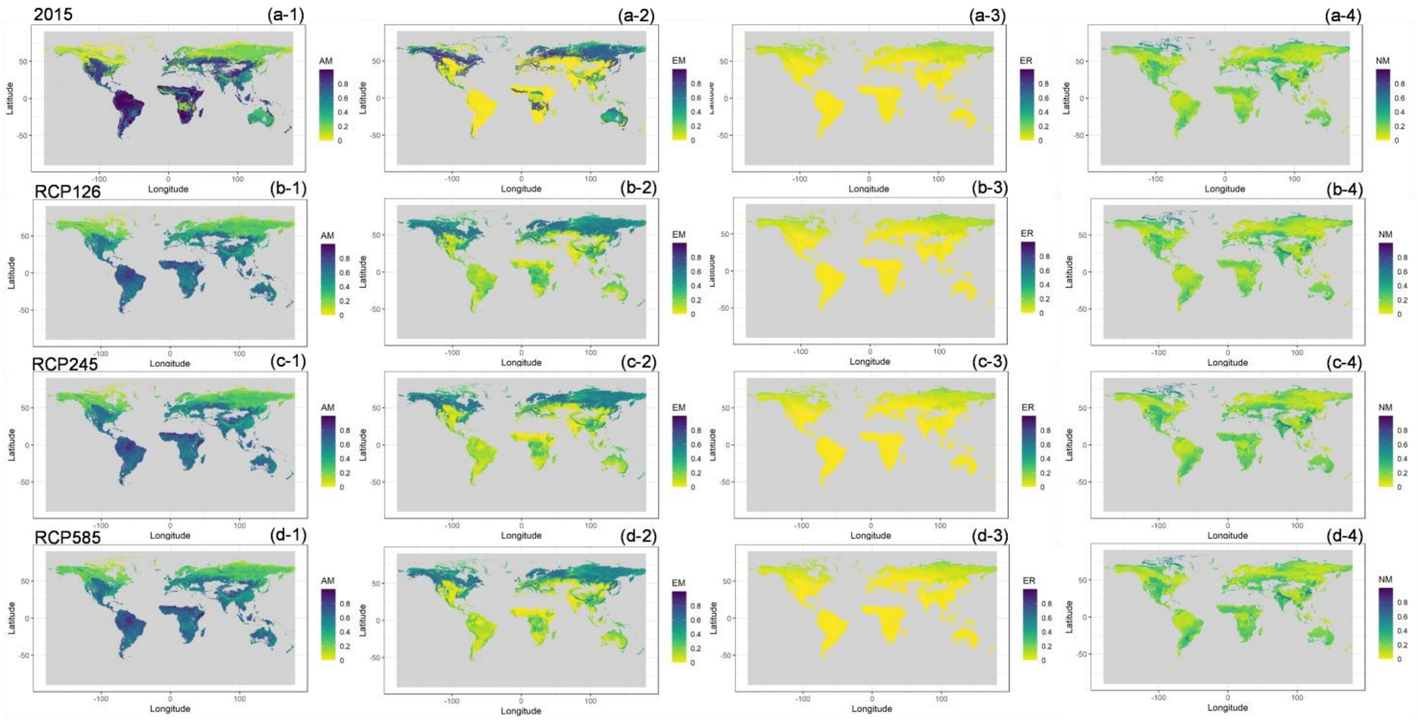

Figure A5.1 Mycorrhizal vegetation distribution represented by relative above-ground biomass of AM, EM, ErM and non-mycorrhizal vegetation biomass in current and future scenarios: (a-1) AM plant biomass proportion in 2015; (a-2) EM plant biomass proportion in 2015; (a-3) ErM plant biomass proportion in 2015; (a-4) Non-mycorrhiza plant biomass proportion in 2015; (b-1) AM plant biomass proportion in 2050_RCP126; (b-2) EM plant biomass proportion in 2050_RCP126; (b-3) ErM plant biomass proportion in 2050_RCP126; (b-4) Non-mycorrhiza plant biomass proportion in 2050_RCP126; (c-1) AM plant biomass proportion in 2050_RCP245; (c-2) EM plant biomass proportion in 2050_RCP245; (c-3) ErM plant biomass proportion in 2050_RCP245; (c-4) Non-mycorrhiza plant biomass proportion in 2050_RCP245; (d-1) AM plant biomass proportion in 2050_RCP585; (d-2) EM plant biomass proportion in 2050_RCP585; (d-3) ErM plant biomass proportion in 2050_RCP585; (d-4) Non-mycorrhiza plant biomass proportion in 2050_RCP585.

A3. Spatial pattern of global litter decomposability following 10 years in a 2015 decomposing environment

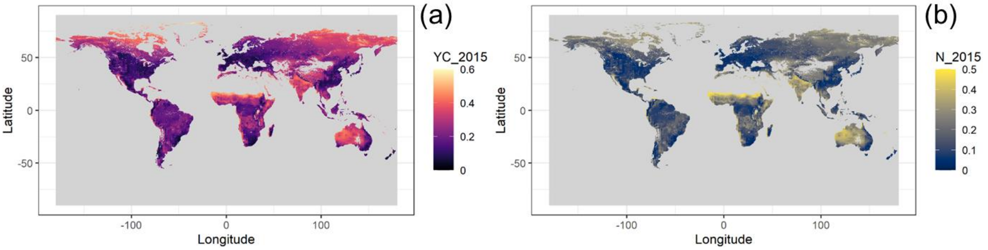

Figure A5.2 Spatial pattern of global litter decomposability following 10 years in a 2015 decomposing environment. (a) Yasso predicted the fraction of carbon remaining in decomposing plant litter mass; (b) N-fraction mass remaining in decomposing plant litter.

A4. Spatial patterns of different types of mycorrhizal vegetation environmental impact on the decomposition of labile (AWE) and recalcitrant (N) chemical components in the litter under current and future scenarios presented using the mycorrhizal index.

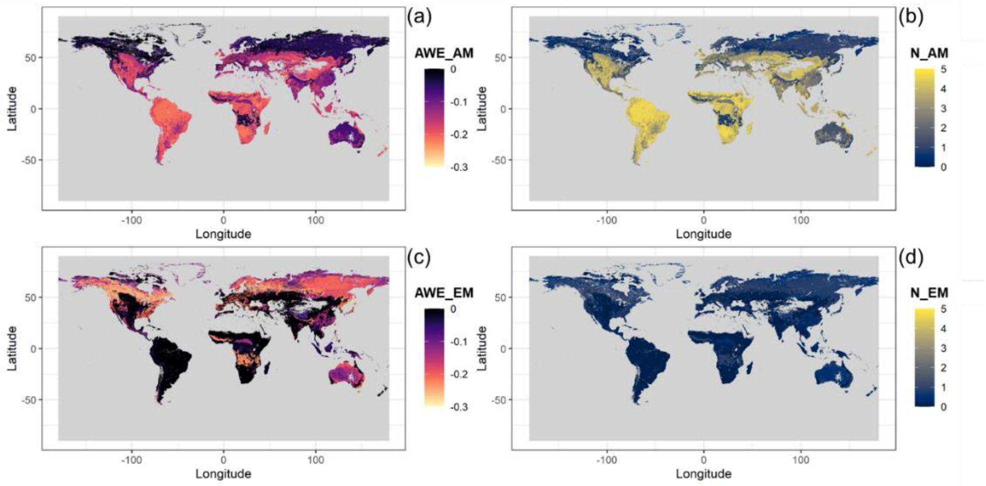

Figure A5.3 AM and EM mycorrhizal environment impacts on the fraction of carbon remaining in the AWE and N litter pools following 10 years of decomposition in the environment of year 2015. (a) AM environment effect on the decomposition of labile components; (b) EM environment effect on the decomposition of labile components; (c) AM environment effect on the decomposition of recalcitrant components; (d) EM environment effect on the decomposition of recalcitrant components.

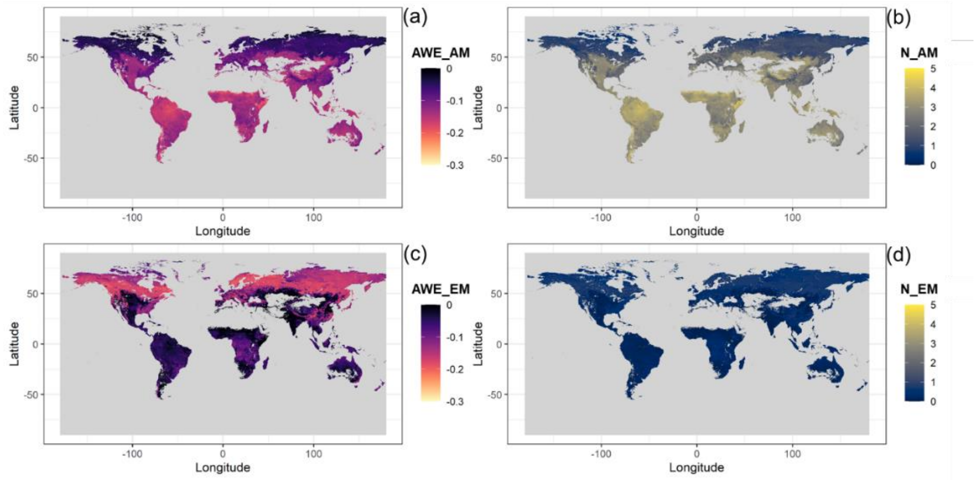

Figure 5.4 AM and EM mycorrhizal environment impacts on the fraction of carbon remaining in the AWE and N litter pools following 10 years of decomposition in the environment of the year 2050 (RCP126). (a) AM environment effect on the decomposition of labile components; (b) EM environment effect on the decomposition of labile components; (c) AM environment effect on the decomposition of recalcitrant components; (d) EM environment effect on the decomposition of recalcitrant components.

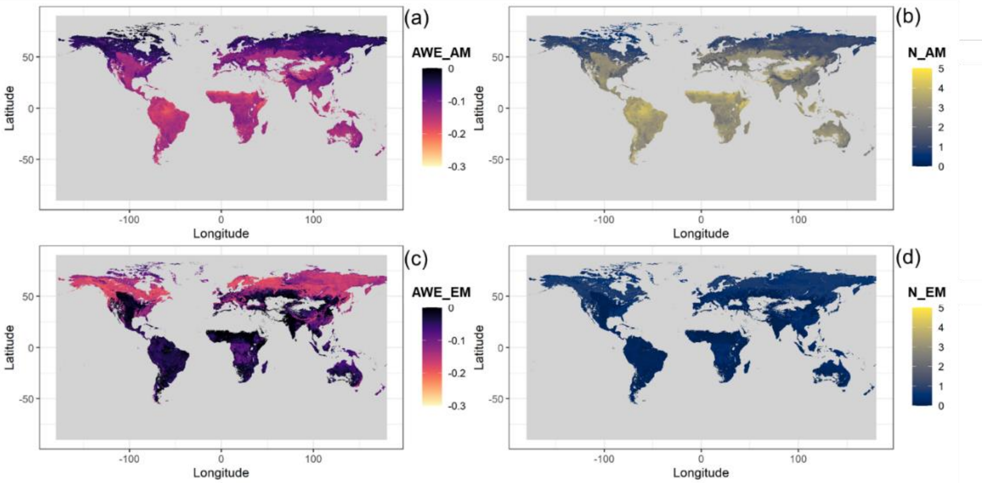

Figure 5.5 AM and EM mycorrhizal environment impacts on the fraction of carbon remaining in the AWE and N litter pools following 10 years of decomposition in the environment of year 2050 (RCP245). (a) AM environment effect on the decomposition of labile components; (b) EM environment effect on the decomposition of labile components; (c) AM environment effect on the decomposition of recalcitrant components; (d) EM environment effect on the decomposition of recalcitrant components.

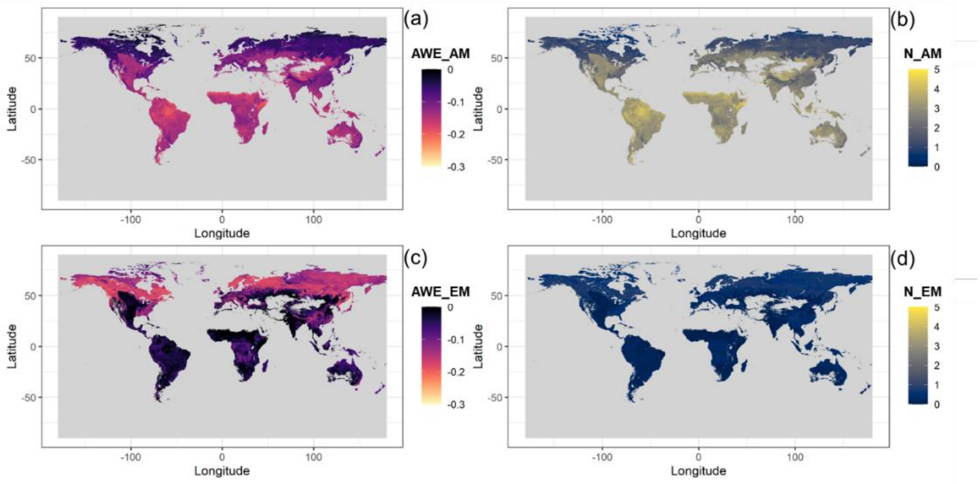

Figure A5.6 AM and EM mycorrhizal environment impacts on the fraction of carbon remaining in the AWE and N litter pools following 10 years of decomposition in the environment of year 2050 (RCP585). (a) AM environment effect on the decomposition of labile components; (b) EM environment effect on the decomposition of labile components; (c) AM environment effect on the decomposition of recalcitrant components; (d) EM environment effect on the decomposition of recalcitrant components.