BIODIVERSITAS
Volume 24, Number 3, March 2023
Pages: 1895-1899

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d240366

Short Communication: The potential of soil microbes in the three *kerangas* forest ecosystems on Belitung Island, Indonesia

DINA OKTAVIA[1,♥], SANTI DWI PRATIWI[2], DESTY PRATIWI[1], NADIA NURANIYA KAMALUDIN[3]

[1]Graduate School, Universitas Padjadjaran. Jl. Dipatiukur 35, Bandung, West Java, Bandung 40132, West Java, Indonesia.
♥email: dina.oktavia@unpad.ac.id

[2]Department of Geosciences, Faculty of Geological Engineering, Universitas Padjadjaran. Jl. Raya Bandung Sumedang Km. 21, Jatinangor, Sumedang 45363, West Java, Indonesia

[3]Department of Soil Science, Faculty of Agriculture, Universitas Padjadjaran. Jl. Raya Bandung Sumedang Km. 21, Jatinangor, Sumedang 45363, West Java, Indonesia

Manuscript received: 4 January 2023. Revision accepted: 29 March 2023.

Abstract. *Oktavia D, Pratiwi SD, Pratiwi D, Kamaludin NN. 2023. Short Communication: The potential of soil microbes in the three kerangas forest ecosystems on Belitung Island, Indonesia. Biodiversitas 24: 1895-1899.* The biogeochemical cycles on Earth are governed by living creatures, therefore the composition and activity of microbial communities are important ecological issues. In this study, we investigated the abundance of soil microbes randomly existing from the three types of *kerangas* forest ecosystems (Bukit Peramun, Cendil *Kerangas* Forest, and Gunung Lumut) in Belitung Island which belongs to the Geosites of Belitong UNESCO Global Geopark. In comparison to the Bukit Peramun and Hutan Cendil habitats, the populations of bacteria and fungus in the Gunung Lumut were greater at 3.11×10^{10} and 1.14×10^{5} cfu g-1, respectively. In Gunung Lumut, there was a comparatively high population of soil bacteria. Gunung Lumut is a site where a variety of mosses have taken over and are overpowered by the terrain due to its high humidity and weathered rocks. Generally, under various conditions, a specific function is more likely to be carried out by soils with higher microbial populations. Understanding soil health and agricultural productivity depends on an understanding of the presence of soil bacteria in various types of *kerangas* forests. Our study aids the Geosites of the Belitong UNESCO World Geopark in ensuring a long-term sustainable ecosystem.

Keywords: Geopark, *kerangas* forest, moss, soil microbes, *Tristaniopsis obovata*

INTRODUCTION

Tin is the primary source of income for the islanders and significantly influences the geography and ecosystem of Belitung Island (Haryadi and Wahyudin 2018). Consequent land degradation mining activities can affect local communities, such as livelihood and health systems, loss of biodiversity, and functions and services forest ecosystem. Last few decades, land use and land cover on Belitung Island have experienced extraordinary changes due to increased anthropogenic activities. The acceleration of urbanization has caused severe ecological damage, such as decreased ecological carrying capacity and loss of water and soil (Kopittke et al. 2019; Fayiah et al. 2020).

The forest ecosystems on Belitung Island typically grow in lowlands and on the quartz sand soil. One of the forest ecosystems on Belitung Island is the heath forest or "*kerangas*" forest. This ecosystem is a fragile forest ecosystem derives from quartz parent material and standing on podzol soil, with poor nutrients and a low pH (Proctor 1999; Moran et al. 2000). The soil texture in the heath forest on Belitung Island is sandy with a pH of less than 5 (Oktavia et al. 2015). The total nitrogen in the soil is low, which may influence the decomposition of organic matter and is strongly influenced by physical environmental conditions such as limited water and high temperatures during summer, particularly in the post-mined land reaching 40°C. Thus, these conditions are less favorable for microorganisms activity, especially bacteria that play a role in the nitrification and ammonification process of soil organic matter (Schmidt et al. 2011).

The biogeochemical cycles on earth are regulated by living organisms, and the structure and function of microbial communities play a crucial ecological role (Hobara et al. 2014; Pennekamp et al. 2017). The stability of an ecosystem is ultimately determined by soil microbes (bacteria and fungi), which also play a critical role in the biotransformation of organic matter and supply the organic compounds that promote plant growth (Khatoon et al. 2017; Prasad et al. 2021). On the other hand, the organic and inorganic substances that plants exude into their environments (in the form of exudate) can be favorable for the survival of soil microbes. The bacteria and fungi, the most well-known microorganisms are responsible for the vast bulk of decomposition, and also make up the largest part of the biomass in soil. Many of the essential transformations in the nitrogen, sulfur, phosphorus, and other element cycles are mediated by microbes (Frey 2019). These roles are important in re-establishing function and biodiversity in ecosystem restoration (Turley et al. 2020; Bullock et al. 2022).

Microbial communities are able to respond more rapidly than plant communities to environmental changes, which in turn affect ecosystem processes, such as carbon and nitrogen cycling, because of the vastness of microbial biomass and diversity (Carney and Matson 2005; Cong et al. 2015; Zechmeister-Boltenstern et al. 2015). Therefore, integrating microbial communities into an ecological succession study can provide much-needed knowledge. Soil health assessment was carried out to see the biodiversity of microorganisms (microbiome) to support environmental conservation (Dubey et al. 2019; Miller et al. 2020). A soil bacterial community consists of many populations (subgroups of one specific type of organisms), each with a characteristic response to certain environmental conditions or human-induced biotic and abiotic stresses. By doing research on soil microbes, we can harness the potential of these microorganisms to support sustainable agriculture. In addition, studying soil microbes can assist us in finding new sources of these essential drugs as the threat posed by antibiotic resistance increases. In this study, we investigated the abundance of soil microbes from the three *kerangas* forest ecosystems belonged to the Belitung Geosites.

MATERIALS AND METHODS

Data collection

This study was conducted on Belitung Island, Indonesia. Data were collected from the three types of *kerangas* forest ecosystems in Belitung Island which belongs to the Geosites of Belitong UNESCO Global Geopark. Soil sampling was carried out randomly on existing research plots, namely Bukit Peramun (2°37'1.68"S, 107°44'22.73", 37 m asl.), Cendil *Kerangas* Forest (2°41'1.09"S, 107°53'1.23", 20 m asl.), and Gunung Lumut (3°1'14.67"S, 108°3'5.01", 159 m asl.) (Figure 1). Bukit Peramun is located in the village of Air Selumar, Sijuk Sub-district, Belitung District. Bukit Peramun eco tourism is a type of special interest tourism managed by community groups. The unique *kerangas* forests and other ecosystems represent a typical relationship between the environment, biodiversity, and culture such as treatment with herbs. Heath forest in Cendil is located in the Cendil Village, Kelapa Kampit Sub-district, East Belitung District. Cendil heath forest is the typical forest in Belitung. Gunung Lumut is located in Limbongan Village, Gantung Sub-district, East Belitung District and is the highest point in the southeastern region of Belitung Island. The forest area on Gunung Lumut is a heath forest with a stretch of moss like a green carpet.

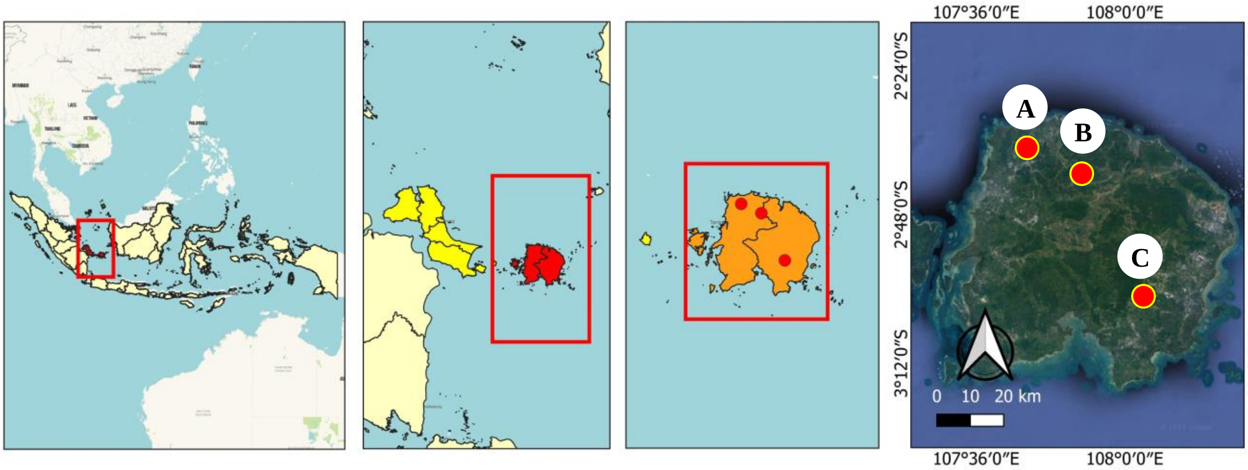

Figure 1A. Study site at kerangas forest ecosystem in the Bukit Peramun (A), Cendil Kerangas Forest (B), Gunung Lumut (C) of Belitung Island, Indonesia

Figure 1B. Forest ecosystem in the Bukit Peramun (A), Cendil Kerangas Forest (B), Gunung Lumut (C) of Belitung Island, Indonesia

The soil was taken from the rhizosphere of the pelawan kiring (*Tristaniopsis obovata*) plants with a depth of 15 cm from the soil surface. The amount of soil taken is as much as 200-300 grams after being composited. This research was conducted in November 2021 and samples of soil were analyzed at the Soil Biology Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Indonesia.

Procedure

Soil samples were collected around the roots of pelawan kiring (*Tristaniopsis obovata*) with four composite rhizosphere points. Collection of soil from the rhizosphere around plant roots was analyzed for total bacteria and fungi, decomposer, NFB, and PSB. One gram of soil was suspended with distilled water to get a 10^{-6} and 10^{-7} dilution. Total 0.5 mL of the last two dilutions were suspend in a petri dish with 15 mL of nutrient media (NA and PDA).

Analysis of decomposer, uncontaminated colonies of microorganisms were isolated on selective cellulose basal medium (CBM) media following the method of Pointing (1999) with slight modification. The modifications included replacing $C_4H_{12}N_2O_6$ with KNO_3 and adjusting the carboxymethyl cellulose (CMC) amount from 4% to 1% and agar from 1.6% to 1%. Microorganisms were grown in complete darkness for 3 to 7 days, and the incubator is set at 25°C. Microorganisms that grow on CBM media with carboxymethyl cellulose as a carbon source can hydrolyze cellulose and be considered decomposer bacteria. For analysis of nitrogen fixation, 1 gram of soil was suspended with distilled water to get a 10^{-7} dilution. The 0.1 mL of the bacterial dilution was mixed with sterile Ashby's and incubate for 3-5 days. Ashby's medium was used to quantify nitrogen-fixing bacteria. After that, it was incubated for 3-5 days. Analysis of phosphate fixation, Okon was medium used to select phosphate-solubilizing bacteria in the soil. One gram of soil was suspended with distilled water to get a 10^{-6} dilution and 0.1 mL of the bacterial suspension was mixed with sterile Okon's medium to quantify phosphate-solubilizing bacteria by clear zone observation method.

RESULTS AND DISCUSSION

High populations of bacteria and fungi indicated the availability of nutrients as a rich source of nutrition for organisms in the ecosystem. Functional bacteria play a great role in the nutrient cycle in the soil through decomposition, fixation, and solubilization of both organic and inorganic materials in soil, hence, aiding nutrient provision for vegetation that grows on the pedosphere. Many bacterial and fungal populations indicated good physical and chemical soil properties. Despite not having any impact on the soil fungal community, soil texture impacted the bacterial population. Bacterial communities prefer soil dominated by clay, followed by medium and fine silt (Seaton et al. 2020). Due to their activity in organic matter decomposition, they are fundamental in soil nutrient turnover and their availability for plants (Shay et al. 2015).

A diverse suite of microfungi associated with bryophytes producing a variety of extracellular enzymes including amylase, cellulases, and polyphenol oxidase, which were capable of degrading the cell wall component of the dead plants (Davey and Currah 2006). This reasons make the total fungi and cellulose decomposer fungi are highest in Gunung Lumut. Plants depend on decomposers organisms that can simplify complex compounds or polymers into simple and absorbable plants (Karyaningsih 2019). Decomposers are responsible for the carbon cycle in the soil (Kravchenko et al. 2019). Fungi are known to form mycorrhizal associated with bryophytes. Through a live interface, mycorrhizal fungi can transfer or assimilate photons to the plant. Mycorrhizal fungi can compete for nutrients from decomposing fungi and dead bryophytes; instead, they actively consume the substrate and enzymatically mobilize both nitrogen and phosphorus (Bending and Read 1995). Furthermore, it appears that mycorrhizal fungi can defend these nutrients source as once a nutrients-rich portion of litter is colonized by a mycorrhizal fungus, further decomposition by bacteria is prevented (Davey and Currah 2006).

The population of NFB in Gunung Lumut was observed as 2.03×10^8 cfu g^{-1}. Meanwhile, the Hutan Cendil has the lowest population density of NFB compared to Bukit Peramun and Gunung Lumut (Table 1). High density can describe the ideal ecosystem conditions for the growth of NFB and other functional bacteria. Nitrogen is one of the essential macronutrients and is required in large quantities (Mastur et al. 2016). Nitrogen can be obtained naturally through the weathering of biomass, soil microorganism, and nitrogen fixation (Pajares and Bohannan 2016). Although, a part of plant essential macronutrients and animal cell-cell-building element, nitrogen is volatile and prone to leaching (Liu et al. 2019). The density of NFB represents the potential supply and availability of nitrogen for the plant (Hindersah et al. 2022). An increase in total soil nitrogen directly affects fertility and soil properties, especially soil chemical and biological properties (Li et al. 2020). Gunung Lumut ecosystems are characterized by low concentrations of inorganic N, low pH, and low temperature, causing N limitation in the system. Fixation of atmospheric N_2 by free-living and symbiotic bacteria is one major source of biologically accessible N (Reed et al. 2013).

In unpolluted habitats, nitrogen-fixing cyanobacteria have been discovered to colonize a variety of moss species (Ininbergs et al. 2011), where the N_2 fixation of moss cyanobacteria associations contribute >2 kg N ha^{-1} yr^{-1} to the total N input in these systems (Sorensen et al. 2012). Mosses can provide a stable and favorable habitat for the cyanobacterial colonizer, promoting N_2 fixation in an N-limited ecosystem (Rousk et al. 2013). By building up N in the moss tissue, which becomes available during disturbances like drying-rewetting and fire events, these moss-cyanobacteria relationships greatly increase the N input in forests (Holland-Moritz et al. 2021). This suggests that cyanobacteria are the ones that fix N_2, and methanotrophs may not have much of an impact (Leppänen et al. 2013).

Table 1. Population of soil microbes in three forest ecosystems on Belitung Island, Indonesia

Population of soil microbes	Bukit Peramun	Hutan Cendil	Gunung Lumut
Population of bacteria (cfu g^{-1})	1.47×10^{10}	1.83×10^{10}	**3.11×10^{10}**
Population of fungi (cfu g^{-1})	2.97×10^{4}	5.14×10^{4}	**1.14×10^{5}**
Population of decomposer (cfu g^{-1})	1.42×10^{10}	1.36×10^{10}	**2.10×10^{10}**
Population of NFB (cfu g^{-1})	1.14×10^{8}	6.17×10^{7}	**2.03×10^{8}**
Population of PSB (cfu g^{-1})	**4.41×10^{7}**	7.07×10^{6}	1.67×10^{7}

Note: NFB: Nitrogen-Fixing Bacteria; PSB: Phosphate Solubilizing Bacteria

The population of PSB in Bukit Peramun was found highest than in Gunung Lumut and Hutan Cendil. The population of PSB in Bukit Peramun was 4.41×10^{7} cfu g^{-1}. The best habitat for PSB is nutrient-rich soil. In Bukit Peramun, dominated by *Tristaniopsis obovata* vegetation, it was easier to find PSB than in Cendil Forest and Gunung Lumut. The surrounding environment in the Hutan Cendil is a *kerangas* forest with a sandy, acidic, high-silica, nutrient-poor soil texture. Meanwhile, the number of PSB bacteria on Gunung Lumut can be less due to mycorrhizal fungi that dominate by absorbing nutrients, so PSB bacteria were less able to survive in this environment (Davey and Currah 2006). Ecosystems with a high population of NFB showed opposite to the presence of PSB.

Studying soil microbes lead to a better understanding of soil ecosystems and can help inform sustainable land management practices. The different types of *kerangas* forest are good representation for microorganism population within the soil. The three areas have different cover plant characteristics that can be used to further highlight the population variation of each functional soil bacteria in the relation to cover plants. The abundance of soil bacteria in different types of *kerangas* forest is crucial for understanding soil health and agricultural productivity. Our research helps Geosites of Belitong UNESCO Global Geopark in order to ensure a sustainable ecosystem in the future. We encourage further study to identify diversity of fungi and bacteria, including the interactions between soil microbes and vegetation and environmental factors.

ACKNOWLEDGEMENTS

This research was funded by Universitas Padjadjaran, Sumedang, Indonesia with grant number 390 4895/UN6.3.1/PT.00/2021.

REFERENCES

Bending G, Read D. 1995. The structure and function of the vegetative mycelium of ectomycorrhizal plants: V. Foraging behaviour and translocation of nutrients from exploited litter. New Phytol 130 (3): 401-409. DOI: 10.1111/j.1469-8137.1995.tb01834.x.

Bullock JM, Fuentes-Montemayor E, McCarthy B, Park K, Hails RS, Woodcock BA, Watts K, Corstanje R, Harris J. 2022. Future restoration should enhance ecological complexity and emergent properties at multiple scales. Ecography 2022 (4). DOI: 10.1111/ecog.05780.

Carney KM, Matson PA. 2005. Plant communities, soil microorganisms, and soil carbon cycling: Does altering the world belowground matter to ecosystem functioning? Ecosystems 8 (8): 928-940. DOI: 10.1007/s10021-005-0047-0.

Cong J, Yang Y, Liu X, Lu H, Liu X, Zhou J, Li D, Yin H, Ding J, Zhang Y. 2015. Analyses of soil microbial community compositions and functional genes reveal potential consequences of natural forest succession. Sci Rep 5 (1): 1-11. DOI: 10.1038/srep10007.

Davey ML, Currah RS. 2006. Interactions between mosses (Bryophyta) and fungi. Can J Bot 84 (10): 1509-1519. DOI: 10.1139/B06-120.

Dubey A, Malla MA, Khan F, Chowdhary K, Yadav S, Kumar A, Sharma S, Khare PK, Khan ML. 2019. Soil microbiome: A key player for conservation of soil health under changing climate. Biodivers Conserv 28 (8): 2405-2429. DOI: 10.1007/s10531-019-01760-5.

Fayiah M, Dong S, Khomera SW, Ur Rehman SA, Yang M, Xiao J. 2020. Status and challenges of qinghai-tibet plateau's grasslands: An analysis of causes, mitigation measures, and way forward. Sustainability 12 (3): 1099. DOI: 10.3390/su12031099.

Frey SD. 2019. Mycorrhizal fungi as mediators of soil organic matter dynamics. Ann Rev Ecol Evol Syst 50 (1): 237-259. DOI: 10.1146/annurev-ecolsys-110617-062331.

Haryadi D, Wahyudin N. 2018. From charm to sorrow: The dark portrait of tin mining in Bangka Belitung, Indonesia. PEOPLE: Intl J Soc Sci 4 (1): 360-382. DOI: 10.20319/pijss.2018.41.360382.

Hindersah R, Kamaluddin NN, Fauzia SR, Setiawati MR, Simarmata T. 2022. Nitrogen-fixing bacteria and organic ameliorant for corn growth and yield increment in Inceptisols. J Degraded Mining Lands Manag 9 (3): 3445-3452. DOI: 10.15243/jdmlm.2022.093.3445.

Hobara S, Osono T, Hirose D, Noro K, Hirota M, Benner R. 2014. The roles of microorganisms in litter decomposition and soil formation. Biogeochemistry 118 (1): 471-486. DOI: 10.1007/s10533-013-9912-7.

Holland-Moritz H, Stuart JEM, Lewis LR, Miller SN, Mack MC, Ponciano JM, McDaniel SF, Fierer N. 2021. The bacterial communities of Alaskan mosses and their contributions to N2-fixation. Microbiome 9 (1): 1-14. DOI: 10.1186/s40168-021-01001-4.

Imu UC, Purnamasari AB, Liana A. 2019. Identifikasi Tumbuhan Lumut di Kawasan Wisata Taman Nasional Bantimurung. Bionature 20 (2): 147. DOI: 10.35580/bionature.v20i2.11288. [Indonesian]

Ininbergs K, Bay G, Rasmussen U, Wardle DA, Nilsson MC. 2011. Composition and diversity of nifH genes of nitrogen-fixing cyanobacteria associated with boreal forest feather mosses. New Phytologist 192 (2): 507-517. DOI: 10.1111/j.1469-8137.2011.03809.x.

Karyaningsih I. 2019. Types of Organisms Decomposers of Soil Pollutants. J For Environ 1 (01): 16-21.

Khatoon H, Solanki P, Narayan M, Tewari L, Rai J, Hina Khatoon C. 2017. Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. Intl J Chem Stud 5 (6): 1648-1656. DOI: 10.20546/ijcmas.2017.605.296.

Kopittke PM, Menzies NW, Wang P, McKenna BA, Lombi E. 2019. Soil and the intensification of agriculture for global food security. Environ Intl 132: 105078. DOI: 10.1016/j.envint.2019.105078.

Kravchenko AN, Guber AK, Razavi BS, Koestel J, Quigley MY, Robertson GP, Kuzyakov Y. 2019. Microbial spatial footprint as a driver of soil carbon stabilization. Nat Commun 10 (1): 1-10. DOI: 10.1038/s41467-019-11057-4.

Leppänen SM, Salemaa M, Smolander A, Mäkipää R, Tiirola M. 2013. Nitrogen fixation and methanotrophy in forest mosses along a N deposition gradient. Environ Exp Bot 90: 62-69. DOI: 10.1016/j.envexpbot.2012.12.006.

Li J, Nie M, Pendall E. 2020. Soil physico-chemical properties are more important than microbial diversity and enzyme activity in controlling carbon and nitrogen stocks near Sydney, Australia. Geoderma 366 (6): 114201. DOI: 114201. 10.1016/j.geoderma.2020.114201.

Liu Q, Liu B, Zhang Y, Hu T, Lin Z, Liu G, Xie Z. 2019. Biochar application as a tool to decrease soil nitrogen losses (NH 3 volatilization, N2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. Glob Change Biol 25 (6): 2077-2093. DOI: 10.1111/gcb.14613.

Mastur, Syafaruddin, Syakir M. 2016. Peran dan pengelolaan hara nitrogen pada tanaman tebu untuk peningkatan produktivitas Tebu. Perspektif 14 (2): 73. DOI: 10.21082/p.v14n2.2015.73-86. [Indonesian]

Miller H, Dias K, Hare H, Borton MA, Blotevogel J, Danforth C, Wrighton KC, Ippolito JA, Borch T. 2020. Reusing oil and gas produced water for agricultural irrigation: Effects on soil health and the soil microbiome. Sci Total Environ 722: 137888. DOI: 10.1016/j.scitotenv.2020.137888.

Moran JA, Barker MG, Moran AJ, Becker P, Ross SM. 2000. A comparison of the soil water, nutrient status, and litterfall characteristics of tropical heath and mixed-dipterocarp forest sites in Brunei 1. Biotropica 32 (1): 2-13. DOI: 10.1111/j.1744-7429.2000.tb00442.x.

Oktavia D, Setiadi Y, Hilwan I. 2015. The comparison of soil properties in heath forest and post-tin mined land: Basic for ecosystem restoration. Procedia Environ Sci 28: 124-131. DOI: 10.1016/j.proenv.2015.07.018.

Pajares S, Bohannan BJM. 2016. Ecology of nitrogen fixing, nitrifying, and denitrifying microorganisms in tropical forest soils. Front Microbiol 7 (7): 1-20. DOI: 10.3389/fmicb.2016.01045.

Pennekamp F, Griffiths JI, Fronhofer EA, Garnier A, Seymour M, Altermatt F, Petchey OL. 2017. Dynamic species classification of microorganisms across time, abiotic and biotic environments-a sliding window approach. PLoS One 12 (5): e0176682. DOI: 10.1371/journal.pone.0176682.

Prasad S, Malav LC, Choudhary J, Kannojiya S, Kundu M, Kumar S, Yadav AN. 2021. Soil microbiomes for healthy nutrient recycling. Current trends in microbial biotechnology for sustainable agriculture. Springer, Berlin, Jerman.

Proctor J. 1999. Heath forests and acid soils. Bot J Scotl 51 (1): 1-14. DOI: 10.1007/978-981-15-6949-4_1.

Reed SC, Cleveland CC, Townsend AR. 2013. Relationships among phosphorus, molybdenum and free-living nitrogen fixation in tropical rain forests: Results from observational and experimental analyses. Biogeochemistry 114 (1-3): 135-147. DOI: 10.1007/s10533-013-9835-3.

Rousk K, Jones DL, DeLuca TH. 2013. Moss-cyanobacteria associations as biogenic sources of nitrogen in boreal forest ecosystems. Front Microbiol 4 (6): 1-10. DOI: 10.3389/fmicb.2013.00150.

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE. 2011. Persistence of soil organic matter as an ecosystem property. Nature 478 (7367): 49-56. DOI: 10.1038/nature10386.

Sorensen PL, Lett S, Michelsen A. 2012. Moss-specific changes in nitrogen fixation following two decades of warming, shading, and fertilizer addition. Plant Ecol 213 (4): 695-706. DOI: 10.1007/s11258-012-0034-4.

Seaton FM, George PB, Lebron I, Jones DL, Creer S, Robinson DA. 2020. Soil textural heterogeneity impacts bacterial but not fungal diversity. Soil Biol Biochem 144: 107766. DOI: 10.1016/j.soilbio.2020.107766.

Shay PE, Winder RS, Trofymow JA. 2015. Nutrient-cycling microbes in coastal Douglas-fir forests: regional-scale correlation between communities, in situ climate, and other factors Front Microbiol 6: 1097. DOI: 10.3389/fmicb.2015.01097.

Turley NE, Bell-Dereske L, Evans SE, Brudvig LA. 2020. Agricultural land-use history and restoration impact soil microbial biodiversity. J App Ecol 57 (5): 852-863. DOI: 10.1111/1365-2664.13591.

Zechmeister-Boltenstern S, Keiblinger KM, Mooshammer M, Peñuelas J, Richter A, Sardans J, Wanek W. 2015. The application of ecological stoichiometry to plant-microbial-soil organic matter transformations. Ecol Monographs 85 (2): 133-155. DOI: 10.1890/14-0777.1.