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The role of mycorrhizal fungi in the stability and adaptive capacity of forest ecosystems in the Carpathian region

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Abstract. Forest ecosystems of the Carpathian region were characterised by high biodiversity; however, they were increasingly affected by climate change and anthropogenic pressures, leading to a decline in their stability. Under these conditions, understanding the role of mycorrhizal fungi was essential, as they were key drivers of ecosystem functioning. The aim of this study was to evaluate the role of mycorrhizal associations in maintaining the stability and adaptive capacity of forest ecosystems dominated by *Abies alba*. A high diversity of mycorrhiza-forming fungi was identified in the studied forest stands, with ectomycorrhizal symbionts accounting for approximately 80-85% of the total species composition. Mycorrhizal colonisation ranged from 40% to 80% depending on stand type and environmental conditions. The highest colonisation levels were recorded in pure fir stands (72.5%) and in ecologically stable sites with well-developed soils, whereas in disturbed stands this parameter decreased to 47.2%. A close relationship was found between mycorrhizal colonisation intensity and tree vitality: healthy trees exhibited an average colonisation level of 72.3%, while severely weakened trees showed only 37.8%. The obtained results confirmed the important role of mycorrhizal associations in increasing tree resistance to abiotic stress and maintaining the functional stability of forest ecosystems. The practical significance of the results lay in the possibility of using mycorrhizal colonisation intensity as an indicator of stand condition and of considering the role of mycorrhizal associations, when planning forest management measures aimed at increasing forest resilience

Keywords: ectomycorrhiza; fungal diversity; tree vitality; edaphic factors; abiotic stress; soil conditions; symbiotic interactions

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Introduction

Forest ecosystems of the Carpathian region were among the most structurally complex natural systems in Europe, characterised by high biodiversity and a well-developed network of trophic and symbiotic interactions that ensured their ecological stability. During 2000-2025, climate change in the region had intensified, as evidenced by rising average annual temperatures, altered precipitation patterns, and an increasing frequency of droughts and other extreme weather events. S. Karunarathna *et al*. (2025) reported that climate change significantly affected the stability of forest ecosystems by weakening tree physiological processes and increasing their susceptibility to stress factors. M. Gil-Fernández *et al*. (2025) emphasised that changing moisture regimes and anthropogenic disturbances contributed to reduced tree vitality and accelerated the development of pathological processes in forest stands. Under these conditions, internal adaptive mechanisms of woody plants became particularly important, among which symbiotic interactions with mycorrhizal fungi played a central role. Y. Arévalo *et al*. (2025) demonstrated that mycorrhizal associations improved water and mineral nutrient uptake and enhanced plant tolerance to abiotic stress. According to O. Nouwen *et al*. (2025), mycorrhizal fungi also regulated interactions between plants and soil microorganisms, thereby supporting the functional stability of forest ecosystems. Researchers indicated that the diversity of mycorrhizal fungi was a key factor determining ecosystem resilience to climate change and recovery capacity. L. Wang *et al*. (2025) showed that underground mycorrhizal networks facilitated resource redistribution among plants and contributed to ecosystem stability. I. Zegnal *et al*. (2025) confirmed the important ecological role of mycorrhizal fungi in maintaining adaptive potential in forest communities under environmental stress.

Scientists T. Li *et al*. (2025) found that mycorrhizal associations were directly involved in regulating the carbon cycle and maintaining forest biodiversity. This underscored the role of mycorrhizal symbiosis in sustaining the health and resilience of forest stands, particularly in environmentally sensitive mountain ecosystems. Z. Wang *et al*. (2026) noted that fungal diversity significantly influenced ecosystem functioning and resilience under changing climatic conditions. The reported relationship between fungal diversity and ecosystem resilience provided an important theoretical basis for assessing forest adaptive capacity in the Carpathian region. At the same time, M.E. Van Nuland *et al*. (2025) reported that global hotspots of mycorrhizal fungal diversity remained insufficiently protected, which created additional risks for long-term ecosystem stability. Therefore, the conservation of mycorrhizal diversity should be considered a priority for maintaining the long-term stability of forest ecosystems. Despite significant progress in understanding the role of mycorrhizal fungi, several aspects remained insufficiently explored in the Carpathian region, particularly species composition across different forest stand types, the intensity of mycorrhizal colonisation, and its relationship with tree vitality under increasing environmental stress. The lack of integrated studies limited the ability to assess ecosystem adaptive potential and to develop effective conservation and restoration strategies. This study aimed to evaluate the role of mycorrhizal fungi in maintaining the stability and adaptive capacity of forest ecosystems based on their species composition, mycorrhizal colonisation, and relationships with tree vitality. To achieve this aim, the following objectives were defined: to characterise the species composition of mycorrhizal fungi and assess the intensity of root system mycorrhizal colonisation in forest stands; to describe the association between mycorrhizal colonisation intensity and tree vitality status; to analyse the potential role of mycorrhizal associations in supporting stand resistance to abiotic and biotic stress factors.

Materials and Methods

Study was conducted in 2025-2026 in forest ecosystems of the Pokuttya-Bukovyna Carpathians,

within Kolomyia Forestry of the State Specialised Enterprise "Forests of Ukraine". The study sites included forest stands of the Kosiv Forestry (compartments 11, 12, 14, 29, 30, 31, and 35), representing typical forest site conditions of the region and encompassing a wide range of ecological parameters. To ensure representativeness, a network of 22 temporary sample plots was established in uneven-aged stands (58-118 years) dominated by *Abies alba*. These stands exhibited high site productivity classes (I-Ia) (Bonitet class Ia – very high-yielding stands; Bonitet class I – high-yielding stands), stand density ranging from 0.35 to 0.70, and belonged to different forest types. At each sample plot, trees were surveyed and their vitality was assessed using phytosanitary indicators (degree of defoliation, crown condition, and presence of dead branches) following standard forest pathology approaches (Burns, 2009). Trees were classified into three categories: healthy, weakened, and severely weakened. For mycorrhizal analysis, fine root samples were collected within each plot from 3-5 sampling points at a depth of 0-20 cm and transported to the laboratory under moist conditions. Simultaneously, macrofungi were recorded to determine species composition and occurrence of mycorrhizal taxa.

The intensity of mycorrhizal colonisation was determined as the proportion of mycorrhizal root tips relative to the total number of root tips examined, using the method described by M.P. Amaranthus (1998). The analysis included samples from pure fir, fir-beech, fir-spruce, mixed, and disturbed stands. Roots were carefully separated from the soil, washed with distilled water, and analysed under a binocular stereomicroscope Leica EZ4 (Leica Microsystems, Germany). At least 100 root tips were examined for each sample. Root tips with visible ectomycorrhizal structures, including fungal mantle formation, branching pattern, and altered coloration, were classified as mycorrhizal. Primary observations were grouped according to stand composition and ecological conditions, and the obtained values were averaged for each stand type. The results were presented as aggregated descriptive indicators, including mean values and ranges of variation. Since these values summarised grouped stand categories rather than individual observations for each temporary sample plot, statistical comparison between stand types was not performed. This approach was used to provide a comparative ecological characterisation of mycorrhizal colonisation intensity under different environmental and edaphic conditions. Species identification of mycorrhizal fungi was based on macromorphological characteristics of fruiting bodies, including cap shape and colour, hymenophore type, stipe morphology, surface texture, and fruiting body size.

Microscopic identification included the analysis of spore shape, size and ornamentation, basidia structure, hyphal morphology, and the presence of clamp connections, following classical mycological approaches (Stamets, 1993). The ecological roles of fungi and mycorrhizal types were interpreted using the comprehensive synthesis by L.K. Abbott & D.V. Murphy (2007), which described the functional significance of mycorrhizal associations in forest ecosystems. The review by O. Nouwen *et al.* (2025) was used to assess the role of mycorrhizal systems in maintaining ecosystem stability under changing environmental conditions. In addition, the study of T. Li *et al.* (2025) provided important information on the participation of mycorrhizal fungi in carbon cycling and biodiversity conservation within forest ecosystems. Standard deviation was calculated using standard statistical methods according to the formula for sample standard deviation:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}, \quad (1)$$

where SD – standard deviation; x_i – individual observed value; $\bar{x}$ – arithmetic mean of the sample; n – number of observations; Σ – summation of values from $i = 1$ to n. Latin plant nomenclature followed the World Flora Online (n.d.) database, while fungal nomenclature was based on Index Fungorum (n.d.). The study was conducted in accordance with international environmental standards,

including the provisions of the Convention on Biological Diversity (1992). Descriptive calculations were performed using Microsoft Excel.

Results and Discussion

In forest ecosystems dominated by *Abies alba* in the Pokuttya-Bukovyna Carpathians, a high diversity of mycorrhizal fungi was recorded, reflecting the complex structure of belowground symbiotic interactions. More than 40 species belonging to different taxonomic and functional groups were identified in the studied stands. The taxonomic structure of the mycobiota was dominated by genera such as *Russula*, *Lactarius*, *Boletus*, *Xerocomellus*, *Cortinarius*, and *Amanita*. Species of the genera *Russula* and *Lactarius* were the most abundant and form the core of the ectomycorrhizal complex. These taxa largely determined the functional characteristics of the fungal component in mixed coniferous-broadleaf forests. Their dominance indicated the stability of established mycorrhizal associations and their adaptation to regional environmental conditions. The functional structure of the mycobiota was characterised by the dominance of ectomycorrhizal symbionts, among which *Boletus edulis*, *Laccaria laccata*, *Cantharellus cibarius*, and representatives of the genus *Cortinarius* were the most common. These species form close symbiotic associations with tree root systems, enhancing water and mineral nutrient uptake, which was a key factor in maintaining forest stand vitality. In addition, species exhibiting strong host specificity were identified. In particular, *Lactarius salmonicolor* was a characteristic component of fir-dominated stands and can be considered an indicator of well-established ectomycorrhizal associations involving *Abies alba*. The presence of such species reflected the differentiation of mycorrhizal complexes in relation to stand composition.

In addition to dominant ectomycorrhizal symbionts, the mycobiota also included saprotrophic species (*Byssocorticium atrovirens*, *Picipes badius*, *Coprinopsis picacea*, *Pholiota lenta*), which contributed to organic matter decomposition and nutrient cycling. A distinct group was represented by species of the genus *Tomentella*, important components of belowground symbiotic networks. Another group included species with varying degrees of toxicity (*Amanita muscaria*, *Amanita citrina*, *Rubroboletus satanas*), which, despite lacking economic value, were integral components of ectomycorrhizal networks. Their participation in symbiotic interactions expanded the functional potential of mycorrhizal associations and contributed to overall ecosystem stability. Thus, the identified species composition of mycorrhizal fungi was characterised by high taxonomic and functional diversity, creating conditions for the formation of stable symbiotic systems and supporting the adaptive potential of forest ecosystems under changing environmental conditions (Table 1).

Table 1. *Species composition, trophic structure, and occurrence of mycorrhizal fungi*

Species	Trophic group	Frequency of occurrence	Edibility class
1	2	3	4
Byssocorticium atrovirens (Fr.)	Saprotroph	Rare	Inedible
Coprinopsis picacea (Bull.)	Saprotroph	Rare	Inedible
Laccaria laccata (Scop.)	Ectomycorrhizal symbiont	Common	Edible (low culinary value, Category IV)
Lactarius aurantiacus (Pers.)	Ectomycorrhizal symbiont	Common	Conditionally edible (low culinary value, Category IV)
Lactarius camphoratus (Bull.)	Ectomycorrhizal symbiont	Sporadic	Edible (low culinary value, Category IV)
Lactarius rufus (Scop.)	Ectomycorrhizal symbiont	Common	Conditionally edible (low culinary value, Category IV)

Table 1. *Continued*

Species	Trophic group	Frequency of occurrence	Edibility class
Lactarius salmonicolor	Specialized ectomycorrhizal symbiont	Common	Edible (high culinary value, Category I)
Tomentella stuposa (Link)	Ectomycorrhizal symbiont	Sporadic	Inedible
Tomentella terrestris (Berk. & Broome)	Ectomycorrhizal symbiont	Sporadic	Inedible
Xerocomellus chrysenteron (Bull.)	Ectomycorrhizal symbiont	Common	Edible (average culinary value, Category III)
Xerocomellus pruinatus (Fr. & Hök)	Ectomycorrhizal symbiont	Sporadic	Edible (moderate culinary value, Category II)
Xerocomus subtomentosus (L.)	Ectomycorrhizal symbiont	Common	Edible (average culinary value, Category III)
Amanita citrina (Schaeff.)	Ectomycorrhizal symbiont	Sporadic	Toxic
Amanita muscaria (L.)	Ectomycorrhizal symbiont	Common	Toxic
Russula nobilis Velen.	Ectomycorrhizal symbiont	Sporadic	Toxic
Russula fellea (Fr.) Fr.	Ectomycorrhizal symbiont	Common	Conditionally edible (low culinary value, Category IV)
Russula ochroleuca Pers.	Ectomycorrhizal symbiont	Dominant	Edible (average culinary value, Category III)
Russula cyanoxantha (Schaeff.) Fr.	Ectomycorrhizal symbiont	Common	Edible (average culinary value, Category III)
Russula grisea Fr.	Ectomycorrhizal symbiont	Sporadic	Edible (average culinary value, Category III)
Russula emetica (Schaeff.)	Ectomycorrhizal symbiont	Sporadic	Inedible
Russula olivacea (Schaeff.)	Ectomycorrhizal symbiont	Sporadic	Edible (average culinary value, Category III)
Russula viscida Kudrna	Ectomycorrhizal symbiont	Rare	Edible (average culinary value, Category III)
Neoboletus pseudosulphureus (Kallenb.)	Ectomycorrhizal symbiont	Rare	Conditionally edible (moderate culinary value, Category II)
Neoboletus luridiformis (Rostk.)	Ectomycorrhizal symbiont	Common	Conditionally edible (moderate culinary value, Category II)
Caloboletus calopus (Pers.)	Ectomycorrhizal symbiont	Sporadic	Inedible
Boletus edulis Bull.	Ectomycorrhizal symbiont	Common	Edible (high culinary value, Category I)
Picipes badius (Pers.)	Saprotroph	Rare	Inedible
Rubroboletus rhodoxanthus (Krombh.)	Ectomycorrhizal symbiont	Rare	Inedible
Butyriboletus appendiculatus (Schaeffer)	Ectomycorrhizal symbiont	Rare	Edible (high culinary value, Category I)
Strobilomyces strobilaceus (Scop.)	Ectomycorrhizal symbiont	Rare	Inedible
Rubroboletus satanas (Lenz)	Ectomycorrhizal symbiont	Rare	Toxic
Cantharellus cibarius Fr.	Ectomycorrhizal symbiont	Common	Edible (average culinary value, Category III)
Cortinarius delibutus Fr.	Ectomycorrhizal symbiont	Sporadic	Conditionally edible (low culinary value, Category IV)

Table 1. *Continued*

Species	Trophic group	Frequency of occurrence	Edibility class
Cortinarius multiformis (Fr.)	Ectomycorrhizal symbiont	Sporadic	Conditionally edible (low culinary value, Category IV)
Cortinarius caperatus (Pers.)	Ectomycorrhizal symbiont	Common	Edible (moderate culinary value, Category II)
Hebeloma crustuliniforme (Bull.)	Ectomycorrhizal symbiont	Sporadic	Toxic
Lactarius blennius (Fr.)	Ectomycorrhizal symbiont	Common	Conditionally edible (moderate culinary value, Category III)
Lactarius fuliginosus (Krapf)	Ectomycorrhizal symbiont	Sporadic	Edible (moderate culinary value, Category II)
Lactarius subdulcis (Pers.)	Ectomycorrhizal symbiont	Common	Conditionally edible (low culinary value, Category IV)
Lactarius vellereus (Fr.)	Ectomycorrhizal symbiont	Common	Conditionally edible (low culinary value, Category IV)
Pholiota lenta (Pers.)	Saprotroph	Sporadic	Edible (low culinary value, Category IV)
Russula adusta (Pers.) Fr.	Ectomycorrhizal symbiont	Sporadic	Conditionally edible (low culinary value, Category IV)
Tricholoma fulvum (Fr.)	Ectomycorrhizal symbiont	Sporadic	Edible (low culinary value, Category IV)
Tricholoma columbetta (Fr.)	Ectomycorrhizal symbiont	Rare	Edible (low culinary value, Category IV)
Tricholoma saponaceum (Fr.)	Ectomycorrhizal symbiont	Sporadic	Inedible
Paxillus involutus (Batsch)	Ectomycorrhizal symbiont	Common	Toxic

Source: World Flora Online (n.d.), Index Fungorum (n.d.)

The integrated analysis of the species composition of mycorrhiza-forming fungi in the studied stands revealed a highly diverse and functionally balanced fungal assemblage. A clear predominance of ectomycorrhizal symbionts was observed, accounting for approximately 80-85% of the total number of recorded species and highlighting their dominant role in forest ecosystems involving *Abies alba* (Red Book of Ukraine, n.d.). The taxonomic framework of the mycobiota was composed of representatives of the genera *Russula*, *Lactarius*, *Cortinarius*, *Boletus*, and *Tricholoma*, which exhibited different degrees of ecological specialisation. Species of the genera *Russula* and *Lactarius* were the most abundant and constitute the core of the ectomycorrhizal community, whereas the occurrence of specialised taxa, particularly *Lactarius salmonicolor*, indicated a strong association between fungi and stand composition. The distribution pattern showed that the mycobiota had a hierarchical structure: alongside dominant and frequent species such as *Russula ochroleuca*, *Boletus edulis*, and *Cantharellus cibarius*, numerous sporadic and rare taxa were recorded, including *Rubroboletus rhodoxanthus*, *Butyriboletus appendiculatus*, and *Strobilomyces strobilaceus*. This pattern reflected the heterogeneity of ecological conditions and the presence of diverse microhabitats within the studied stands. In addition to ectomycorrhizal fungi, saprotrophic species were also identified. Although their proportion was relatively low (approximately 10-15%), they played a crucial role in organic matter decomposition and nutrient cycling. The coexistence of symbiotic and saprotrophic components indicated the functional balance of the fungal community. Overall, the mycobiota structure was characterised by high diversity, functional differentiation, and the presence of ecologically specialised

species, creating conditions for the formation of stable mycorrhizal associations and supporting the adaptive potential of forest ecosystems. The high taxonomic diversity recorded in the studied stands was consistent with the mycological concepts summarised by P. Stamets (1993), who emphasised that structurally diverse forest ecosystems supported complex fungal communities with multiple ecological functions. Mycorrhizal intensity was assessed based on the proportion of mycorrhizal root tips, a widely accepted indicator of colonisation level in ectomycorrhizal studies. The results showed that mycorrhizal colonisation in stands involving *Abies alba* varies widely, ranging from 40% to 80%, with average values of 50-80%. This indicated a well-established system of ectomycorrhizal associations with pronounced spatial variability (Table 2).

Table 2. *Intensity of root system mycorrhizal colonisation in different types of forest stands*

Stand type	Number of trees, n	Proportion of mycorrhizal roots, % (min-max)	Mean value, %	Environmental conditions
Pure fir stands	10	65-80	72.5	High moisture, well-developed humus horizon
Fir-beech stands	12	60-75	68.3	Stable soil conditions, moderate moisture
Fir-spruce stands	10	55-70	62.4	Acidic soils, moderate moisture
Mixed stands	12	50-65	57.8	Variable conditions, heterogeneous soils
Disturbed stands	8	40-55	47.2	Soil compaction, disturbed forest floor (litter layer)

Note: the values are aggregated descriptive indicators for stand categories grouped by stand composition and ecological conditions. Mean values and ranges summarise the general variation in mycorrhizal colonisation intensity within each stand type and do not represent individual observations for each temporary sample plot
Source: developed by the author

Temporary sample plots were grouped according to stand composition and ecological condition into five categories: pure fir, fir-beech, fir-spruce, mixed, and disturbed stands. This grouping made it possible to compare mycorrhizal colonisation intensity under different forest site conditions without separating each plot individually. Mycorrhizal colonisation was strongly dependent on stand type and environmental conditions. The highest values (>70%) were observed in pure fir and fir-beech stands, characterised by stable edaphic conditions and sufficient moisture availability. These results were consistent with the observations of M.P. Amaranthus (1998), who reported that ectomycorrhizal colonisation tended to increase under favourable soil moisture conditions and in undisturbed forest ecosystems. The higher colonisation levels observed in stable fir-dominated stands therefore reflected the importance of suitable edaphic conditions for the development of ectomycorrhizal symbiosis. In fir-spruce stands, colonisation levels were lower, likely due to more acidic soil conditions. The lowest values occurred in mixed and disturbed stands, where soil compaction, reduced organic matter content, and disruption of the forest floor (litter layer) were observed. This suggested a high sensitivity of mycorrhizal associations to changes in edaphic conditions and anthropogenic impact. The observed differences in mycorrhizal colonisation among stand types were closely associated with variations in soil environmental conditions. Higher mycorrhizal colonisation intensity in pure fir and fir-beech stands were recorded under conditions of sufficient soil moisture and well-developed humus horizons, which created favourable conditions for the development of ectomycorrhizal fungi and root growth. In contrast, reduced colonisation in fir-spruce and disturbed stands may be related to increased soil acidity, soil compaction, disruption of the forest floor, and a decrease in the organic matter content of the upper soil horizons. Disturbance of the litter

layer and reduction of the humus horizon limit nutrient availability and negatively affected the formation of mycorrhizal networks. These results indicated that the structure and functioning of mycorrhizal associations were highly dependent on the preservation of soil properties and forest floor integrity. A clear trend was observed: as the ecological stability of stands increased, mycorrhizal colonisation also increased, indicating that this parameter can be considered an integral indicator of forest ecosystem functional status. The data analysis showed that the results indicated a relationship between mycorrhizal colonisation and tree vitality (Table 3).

Table 3. *Relationship between mycorrhizal colonisation intensity and tree vitality status*

Tree vitality status	Number of trees, n	Mycorrhizal colonisation intensity, % (min-max)	Mean value, %	Standard deviation (±)
Healthy	15	65-80	72.3	4.8
Weakened	12	45-60	52.6	4.2
Severely weakened	10	30-45	37.8	3.9

Source: developed by the author

Tree vitality categories were determined on the basis of an integrated phytosanitary assessment, including visual crown condition, degree of defoliation, and the presence of dead branches. The observed differences among vitality classes were consistent with the forest pathology framework described by R. Burns (2009), where crown thinning, defoliation, and branch dieback were considered key indicators of tree weakening and declining physiological stability. Healthy trees were characterised by well-developed crowns and minimal signs of crown thinning; weakened trees showed moderate defoliation and partial crown degradation; severely weakened trees had pronounced crown thinning, visible dieback, and a higher proportion of dead branches. In healthy trees, mycorrhizal colonisation was highest (on average 72.3%), indicating active ectomycorrhizal functioning and efficient resource exchange between symbiotic partners. In weakened trees, colonisation decreased to 52.6%, accompanied by impaired water balance and reduced growth rates. The lowest values occurred in severely weakened trees (37.8%), indicating degradation of the mycorrhizal system and a decline in its functional efficiency. The results showed a clear negative relationship between the degree of tree weakening and mycorrhizal colonisation. The predominance of ectomycorrhizal fungi (80-85% of the recorded mycobiota) and the higher colonisation intensity observed in healthy trees corresponded to the ecological framework proposed by L.K. Abbott & D.V. Murphy (2007), according to which mycorrhizal symbioses played a fundamental role in nutrient cycling, plant nutrition, and ecosystem stability. The observed decline in mycorrhizal colonisation from healthy to severely weakened trees may also reflect a reduced capacity of trees to withstand biotic stress factors. Trees characterised by lower levels of mycorrhizal colonisation exhibited more pronounced crown thinning, defoliation, and branch dieback, indicating a deterioration of their physiological condition. Ectomycorrhizal fungi enhanced nutrient acquisition, improved water balance, and contributed to the formation of protective rhizosphere microbial communities that may suppress the development of soil-borne pathogens. Therefore, a reduction in mycorrhizal activity may increase tree susceptibility to pathogenic microorganisms and secondary insect pests, which commonly colonised physiologically weakened hosts. These findings suggested that mycorrhizal associations played an important role in supporting tree health and mitigating the effects of biotic stress factors in forest ecosystems. Overall, mycorrhizal colonisation can be considered a reliable indicator of tree vitality and the overall stability of forest ecosystems. To integrate the obtained results and illustrate the relationships between

environmental conditions, mycorrhizal colonisation, and ecosystem responses, a conceptual model was developed (Fig. 1). The model summarised the key pathways linking stand conditions and edaphic factors with the structure and functioning of mycorrhizal associations, their influence on nutrient and water dynamics, and the resulting effects on tree vitality and overall ecosystem stability. It also highlighted the negative impact of anthropogenic pressures, leading to reduced mycorrhizal diversity, decreased colonisation intensity, and subsequent decline in ecosystem resilience.

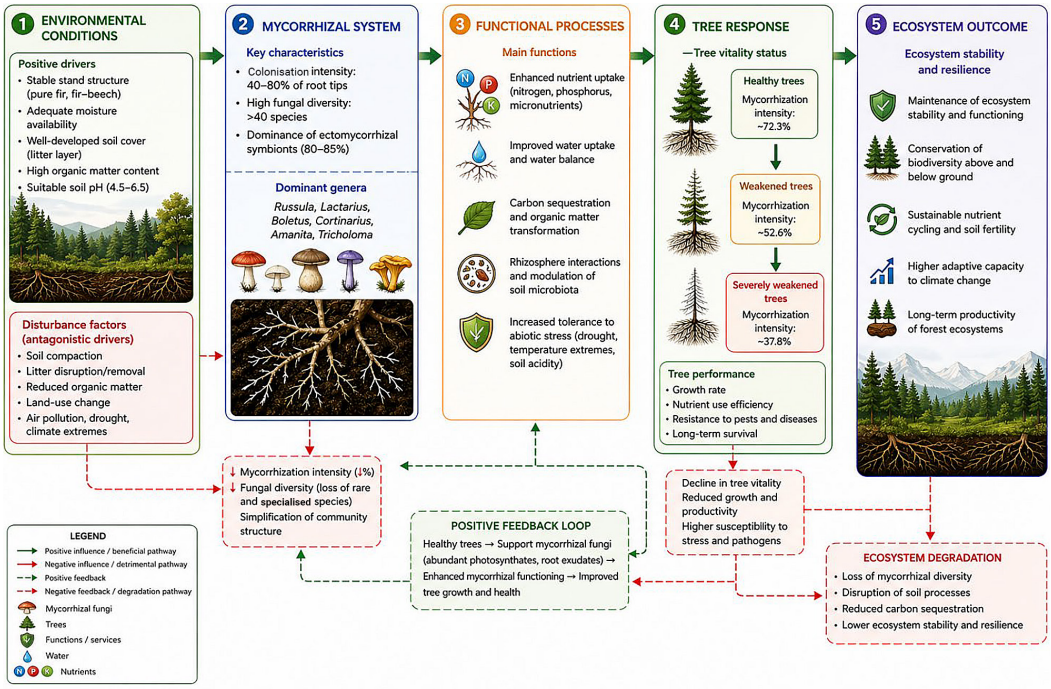

Figure 1. *Role of mycorrhizal associations in forest ecosystem stability and tree adaptation*

Note: the model integrates the effects of edaphic factors and anthropogenic pressures on mycorrhizal colonisation, functional processes, and tree vitality

Source: developed by the author

So, Figure 1 presented a conceptual model describing the relationships among environmental conditions, mycorrhizal functioning, tree vitality, and forest ecosystem stability. The model demonstrated that favourable edaphic conditions promote mycorrhizal colonisation and fungal diversity, whereas anthropogenic and abiotic stress factors negatively affect the structure and functioning of mycorrhizal systems. The framework highlighted the key ecological functions of mycorrhizal fungi, including enhanced nutrient and water uptake, regulation of soil microbiota, carbon cycling, and increased tolerance of trees to environmental stress. The model also illustrated the positive relationship between mycorrhizal colonisation intensity and tree vitality, where higher colonisation levels were associated with improved growth, resistance, and ecosystem resilience. Conversely, disruption of mycorrhizal associations contributes to ecosystem degradation and reduced adaptive capacity of forest stands. The results indicated the decisive role of mycorrhiza-forming fungi in maintaining the stability of forest ecosystems involving *Abies alba*, which

was consistent with concepts of forest ecosystem functioning. Similar conclusions were reported by A. Genre *et al.* (2020), who demonstrated that mycorrhizal symbioses represented highly integrated functional systems regulating nutrient exchange and plant adaptation to environmental conditions. In the studied stands, ectomycorrhizal symbionts accounted for 80-85% of the total fungal assemblage, confirming their dominant functional role within the mycobiota.

The dominant role of the genera *Russula* and *Lactarius* was consistent with the findings of S.W. Simard *et al.* (2012), who identified ectomycorrhizal networks as key structural components ensuring resource transfer and functional connectivity in forest ecosystems. In the investigated stands, the predominance of these taxa indicated the formation of stable and well-developed mycorrhizal systems. Dependence of mycorrhizal colonisation on environmental conditions was also consistent with the results of B.S. Steidinger *et al.* (2019), who demonstrated that climatic and edaphic factors strongly influenced the distribution and functioning of forest-tree symbioses. In the studied stands, the highest colonisation levels were observed under stable and well-moistened conditions, confirming the determining role of edaphic factors. Similar patterns were described by M. Usman *et al.* (2021), who emphasised the importance of mycorrhizal symbiosis in improving tree adaptation to abiotic stress caused by climate change. A higher colonisation intensity detected in ecologically stable stands confirmed the important role of mycorrhizal associations in maintaining forest ecosystem resilience. National studies also indicated that the adaptive capacity of forest ecosystems under changing climatic conditions largely depended on the efficiency of biotic interactions. O. Tkachuk & N. Viter (2022) emphasised the stabilising significance of symbiotic relationships in forest ecosystems, which was consistent with the results obtained in this study.

At the same time, A. Parfenyuk *et al.* (2022) highlighted the importance of root exometabolites in shaping rhizosphere microbial communities. This may explain the relationship observed between soil conditions and mycorrhizal colonisation, as mycorrhizal symbiosis was largely formed through rhizosphere processes. Furthermore, V. Oliferchuk & D. Fedorovych (2021) demonstrated that mycorrhizal fungi can modify rhizosphere microbiota structure and influence plant productivity. In this study, colonisation intensity increased in stable stands and decreased under disturbed conditions. The reduction in mycorrhizal colonisation from 72.3 % in healthy trees to 37.8 % in severely weakened individuals indicated degradation of symbiotic interactions. Comparable conclusions were reported by F.P. Teste *et al.* (2009), who highlighted the importance of mycorrhizal networks for plant survival, resource transfer, and ecosystem functioning. Overall, the results were consistent with contemporary international and national studies and confirmed that mycorrhiza-forming fungi represented a key factor determining the stability, productivity, and adaptive potential of forest ecosystems.

Conclusions

In forest ecosystems of the Pokuttya-Bukovyna Carpathians dominated by *Abies alba*, a high diversity of mycorrhizal fungi was recorded (over 40 species), with a clear dominance of ectomycorrhizal symbionts belonging to the genera *Russula*, *Lactarius*, *Boletus*, and *Cortinarius*, consistent with the structure of stable coniferous-broadleaf forests. The study demonstrated that mycorrhizal colonisation (50-80%) depended on stand conditions and soil characteristics. The highest colonisation levels were characteristic of ecologically stable stands and healthy trees, whereas weakened individuals showed a substantial decline in colonisation intensity, confirming the diagnostic value of this parameter. Ectomycorrhizal fungi accounted for approximately 80-85% of the recorded mycobiota, indicating their dominant functional role in the studied forest ecosystems. The intensity of mycorrhizal colonisation decreased from an average of 72.3% in healthy trees to 37.8% in severely weakened individuals,

demonstrating a strong relationship between symbiotic activity and tree vitality. Mycorrhizal associations enhanced the adaptive potential of trees by improving water and mineral nutrient uptake and contributing to resistance against both abiotic and biotic stress factors. Anthropogenic pressures led to reduced diversity of mycorrhizal fungi and simplification of community structure, resulting in decreased functional efficiency and reduced ecosystem stability. The structure and intensity of mycorrhizal associations played a key role in determining the stability and adaptive capacity of forest ecosystems in the Carpathian region. Future research should focus on the molecular identification of mycorrhizal fungi and the assessment of mycorrhizal network functioning under climate change. The results highlight the potential for using mycorrhizal colonisation as a diagnostic indicator of stand condition and for its application in forest management strategies aimed at enhancing ecosystem stability and productivity.

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Conflict of Interest

None.

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Роль мікоризоутворюючих грибів у стабільності та здатності до адаптації лісових екосистем Карпатського регіону

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Анотація. Лісові екосистеми Карпатського регіону характеризувалися високою біорізноманітністю, однак у сучасних умовах зазнали суттєвого впливу кліматичних змін та антропічного навантаження, що призвело до зниження їх стійкості. У цих умовах особливого значення набуло вивчення ролі мікоризоутворюючих грибів як одного з ключових чинників підтримання функціональної стабільності деревостанів. Метою роботи стало встановлення ролі мікоризних асоціацій у забезпеченні стабільності та адаптаційної здатності лісових екосистем за участі *Abies alba*. У досліджуваних деревостанах було встановлено високий рівень різноманіття мікоризоутворюючих грибів із домінуванням ектомікоризних симбіонтів, частка яких становила близько 80-85 % від загального видового складу. Інтенсивність мікоризації варіювала в межах 40-80 % залежно від типу насаджень та екологічних умов. Найвищі показники мікоризації було зафіксовано у чистих ялицевих деревостанах (72,5 %) та на екологічно стабільних ділянках із добре розвиненим ґрунтовим покривом, тоді як у порушених насадженнях цей показник знижувався до 47,2 %. Виявлено тісний зв'язок між інтенсивністю мікоризації та життєвим станом дерев: у здорових дерев середній рівень мікоризації становив 72,3 %, а у сильно ослаблених – лише 37,8 %. Отримані результати підтвердили важливу роль мікоризних асоціацій у підвищенні стійкості дерев до абіотичних стресів та підтриманні функціональної стабільності лісових екосистем. Практичне значення результатів полягало у можливості використання інтенсивності мікоризації як індикатора стану деревостанів та врахування ролі мікоризних асоціацій при плануванні лісогосподарських заходів, спрямованих на підвищення стійкості лісів

Ключові слова: ектомікориза; біорізноманіття грибів; життєвий стан дерев; едафічні чинники; абіотичний стрес; ґрунтові умови; симбіотичні взаємодії