

Global trait patterns and the economics spectrum of wood-inhabiting fungi

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Abstract

Wood-inhabiting fungi drive woody debris decomposition and forest carbon cycling, with their functional trait trade-offs and environmental adaptation strategies substantially shaping forest carbon sink dynamics. However, global-scale functional trait trade-offs and the adaptive responses to environmental gradients remain poorly understood. Here, we synthesized 26 key traits across 7,454 wood-inhabiting fungal species, integrating with approximately 4.58 million georeferenced occurrence records, to investigate the multidimensional trade-offs, environmental driving mechanisms, and future shifts of fungal functional traits. Our results reveal that fungal traits exhibit intramodule synergy and intermodule trade-offs. Three-dimensional functional axes cumulatively explain 72.1% of the total trait variation, with the microscopic reproductive–dispersal investment axis contributing 42.4%, as the primary driver of functional evolution. Climate and topography hierarchically govern trait axes: temperature and precipitation suppress microscopic reproductive–dispersal traits, whereas elevation positively regulates basidial and spore dimensions. Along the resource acquisition axis, temperature and elevation reduced generative hyphae, precipitation suppresses skeletal hyphae, and temperature, precipitation, and LAI synergistically promote binding hyphal thickening, with slope and aspect exerting secondary modulation. Environmental gradients elicited non-linear responses, low latitudes moderately expand reproductive–dispersal structures, whereas high latitudes exhibit compensatory decrease–increase patterns and trait decoupling, shifting toward brown-rot, gymnosperm-associated, monomitic, and thick-walled spore strategies. Under future climate change, fungal traits are projected to reorganize through macroscopic expansion, microscopic contraction, and hyphal reinforcement. This study establishes the first global wood-inhabiting fungal economics spectrum, elucidating adaptive mechanisms including stress compensation and macro-micro trait decoupling, and identifying key environmental dimensions underlying functional differentiation. This framework may improve the parameterization of fungal functional traits in Earth system models and improve mechanistic predictions of forest carbon-cycle feedbacks.

Introduction

Wood-inhabiting fungi as the principal decomposers of lignocellulosic material in forest ecosystems, drive the turnover and release of the global forest carbon stock ^{1–3}. Some species are important edible and medicinal fungi (e.g., *Auricularia* Bull. and *Ganoderma* P. Karst.) ^{4–5}, forest pathogens (e.g., *Armillaria* (Fr.) Staude and *Heterobasidion* Bref.) ⁶, and toxigenic fungi (e.g., *Amanita* Pers. and *Galerina* Earle) ^{4,7}. Additionally, certain species exhibit application potential in environmental remediation, and dye decolorization (e.g., *Lentinus* Fr. and *Trametes* Fr.) ^{8–9}. Variations in species composition and decomposing capacity of wood-inhabiting fungi constitutes a key determinant regulating lignocellulose degradation and carbon release ^{10–14}. Although fungal functional traits are intrinsically linked to decay capacity ¹⁵, current Earth system models oversimplify fungi into homogeneous functional pools or discrete categories, neglecting mechanistic linkages between fungal traits and ecosystem functions, thereby severely constraining the predictive accuracy of forest carbon sink dynamics ^{16–17}.

Consequently, elucidating trait trade-offs and identifying core functional axes in wood-inhabiting fungi is of urgent practical significance for parameterizing fungal modules in biogeochemical models^{15, 18–19}.

Research on fungal traits has lagged, constrained by exceptionally high species diversity, microscopic individual size, technical difficulties inherent to in-situ trait measurement^{11, 20–24}, and more fundamentally by the fact that the concept of “fungal functional traits” has yet to be widely embraced in ecology^{25–28}. In plant ecology, trait-based trade-offs are formalized into the plant economic spectrum, a continuous axis from rapid resource acquisition to conservative resource utilization that encapsulates the fundamental mechanisms underlying plant responses to environmental change^{29–30}. Although fungal trait trade-off framework and the fungal economic spectrum concept have been proposed^{21, 23}, and preliminary progress have been made in documenting trade-offs between microbial growth and physiological traits³¹ and constructing theoretical frameworks for soil saprotrophic fungal economics³², current studies remain largely conceptual or restricted to local spatial scales and narrow taxonomic groups^{27, 33}. Wood-inhabiting fungi possess distinctive morphological features, observable structures, pronounced phenotypic differentiation, and well-defined ecological functions, constitute an ideal model group for constructing a fungal economic spectrum^{15, 27}. While these traits are widely deployed in taxonomic studies, systematic dissection of the underlying trait trade-off mechanisms remains limited^{21, 34–35}. Functional traits of wood-inhabiting fungi are generally classified into three major categories related to dispersal, reproduction, and resource acquisition and utilization³⁶. Existing studies have demonstrated potential trade-offs among fruiting body size, lifespan, hyphal system type, spore traits, life strategy, host and decay type^{37–40}, which theoretically constitute core dimensions of the fungal economics spectrum¹¹. However, global empirical analyses integrating multiple traits across broad taxonomic coverage remain scarce, and a systematic theoretical framework describing trait trade-offs and the economic spectrum of wood-inhabiting fungi has not been established.

Beyond intrinsic biological trade-offs, environmental filtering constitutes a major driver shaping fungal traits^{11, 16}. Temperature as a key environmental factor, drives fungal migration to higher elevations⁴¹, promotes the coexistence of closely related species through extreme temperature filtering^{42–43}, leads to darker basidiomata pigmentation in cold habitats⁴⁴, shapes the latitudinal unimodal distribution of basidiomata size⁴⁵, and drives phenological differentiation in spore reproduction⁴⁶. Precipitation and humidity regulate spore release and dispersal: high-humidity promotes active discharge, whereas arid environments preferentially select for thick-walled spores or animal-mediated dispersal strategies^{47–48}, with large and ornamented spores concentrated in warm, humid climates⁴⁹. Latitudinal gradients integrate environmental filtering effects, reflecting fungal adaptive strategies^{45, 49–50}. Elucidating trait–environment associations would enable the inference and prediction of trait composition and functional strategies in unsampled regions^{11, 26, 51–52}. Although wood-inhabiting fungal traits are jointly modulated by multiple environmental factors^{45, 49}, current studies remain largely confined to single factors or single traits at regional scales^{11, 23, 36}, leaving substantial gaps in global-scale, multi-trait integrated

assessments and in the systematic elucidation of underlying environmental driving mechanisms. Moreover, distinct functional guilds, such as white-rot and brown-rot fungi, may exhibit divergent or decoupled responses along the same environmental gradient due to differences in physiological and metabolic mechanisms^{21, 36, 52}, a pattern that currently lacks systematic explanation.

Here, we assemble a globally integrated dataset of 26 key functional traits (12 continuous and 14 categorical traits) related to reproduction, dispersal, and resource acquisition and utilization for 7,454 wood-inhabiting fungal species, coupled with georeferenced occurrence records, alongside multi-panel summaries of decay type distributions across geography and climate (Fig. 1). This study aims to comprehensively investigate trade-offs among fungal traits, assess whether they align with the core axes of the plant economics spectrum, and elucidate systematic variations in traits along latitudinal and environmental gradients, thereby predicting future shifts in trait distributions under climate warming scenarios. This work strengthens the empirical foundation of the fungal economics spectrum, provides a standardized trait database and analytical framework for global fungal ecology, and reveals trait–environment relationships that can improve predictions of forest carbon sinks under global change, optimize strategies for deadwood retention, and inform the management of pathogenic fungi.

Results

Within-module integration and cross-module trade-offs

Wood-inhabiting fungal traits exhibited multidimensional associations, characterized by intramodular integration and intermodule trade-offs (Fig. 2). Within the reproductive module, basidial traits (length, width, volume, and shape) were strongly positively correlated ($P < 0.001$), indicating shared developmental regulation. Fruiting body size was strongly negatively correlated with basidial volume ($P < 0.001$), such that annual fungi favored a microscopic construction strategy (small fruiting bodies with large basidia), whereas perennial fungi favored a macroscopic strategy (large fruiting bodies with small basidia). Within the dispersal module, spore length, width, and volume were positively correlated, whereas spore volume was strongly negatively correlated with spore shape ($P < 0.001$). Traits of the resource acquisition module showed strong independence: generative and skeletal hyphal diameters were positively correlated, but their associations with binding hyphae diverged (Fig. 2), reflecting functional differentiation among hyphal types. Brown-rot fungi possessed larger fruiting bodies, hyphae, basidial length and shape, and spore shape than white-rot fungi, but smaller basidial width, spore width, and spore volume, with no differences in basidial size or spore length (Figs. S1–S12).

At the cross-module level, basidial and spore traits were significantly coordinated across the entire matrix ($P < 0.001$; Fig. 2), indicating tight developmental coupling between reproductive and dispersal units. Fruiting body size was strongly negatively correlated with spore volume ($P < 0.001$; Fig. 2), reflecting resource competition between these structures. Between the reproductive and resource modules, fruiting body size covaried with skeletal and binding hyphal diameters but was negatively correlated with most basidial traits (Fig. 2), suggesting that macroscopic reproductive structures depend

on robust hyphae for structural support while competing with microscopic reproductive units for resources; increased generative hyphal diameter enhanced nutrient supply and covaried with basidial traits. Between the dispersal and resource modules, generative and skeletal hyphal diameters were positively associated with spore volume but negatively correlated with spore shape, whereas binding hyphal diameter was strongly negatively correlated with spore volume ($P < 0.001$; Fig. 2), indicating functional differentiation among hyphal types in resource allocation for dispersal.

Functional trait associated economics spectrum

Principal component analysis (PCA) including 26 traits revealed that the first three principal components cumulatively explained 48.6% of the total variance (PC1: 21.7%; PC2: 13.6%; PC3: 13.3%; Fig. S13), indicating a complex multidimensional trait structure. PC1 was primarily driven by spore and basidial size traits; PC2 by hyphal diameter, fruiting body type, and hymenium type; and PC3 by hyphal system type, fruiting body longevity, basidial shape, and spore wall characteristics. To eliminate bias from categorical variable coding, PCA was repeated using only the 12 continuous traits, yielding a cumulative variance of 72.1% for the first three components (PC1: 42.4%; PC2: 16.0%; PC3: 13.7%; Fig. 3, Fig. S14). PC1 integrated basidial and spore volume, width, and length, representing a synergistic axis of microscopic reproductive–dispersal investment; PC2 was jointly driven by basidial shape, spore shape, and fruiting body size, corresponding to a dispersal efficiency versus macroscopic investment axis; and PC3 was independently constituted by skeletal, generative, and binding hyphal diameters, representing a resource acquisition axis. The continuous-trait PCA was highly consistent with the full-trait analysis, highlighting the dominant role of reproductive and dispersal traits (PC1 + PC2: 58.4% variance) in the functional differentiation of wood-inhabiting fungi.

Environmental drivers of trait variation

This study resolved three major axes of the functional economic spectrum of wood-inhabiting fungi and their trait responses to environmental factors (Fig. 4; Figs. S15, S16; Tables S1–S4). Along PC1, precipitation and temperature exerted strong negative effects on all associated traits except basidial width (Fig. 4). Elevation positively affected basidial volume, length, and width, as well as spore volume and length. Leaf area index (LAI) significantly suppressed microscopic reproductive–dispersal unit size; slope positively regulated basidial length and negatively regulated basidial width; eastness suppressed basidial width and spore size; and northness primarily regulated basidial width and shape. Along PC2, precipitation drove fruiting body shrinkage, basidial elongation, and spore slenderness (Fig. 4); temperature had strong negative effects on basidial and spore shape (Fig. 4), with both tending toward spherical forms under warm conditions. Elevation and slope reduced fruiting body size but positively regulated basidial and spore shape; LAI promoted fruiting body enlargement and basidial elongation; northness negatively affected spore and basidial shape, whereas eastness suppressed only spore shape (Fig. 4). Along PC3, temperature and elevation exerted strong negative effects on generative hyphal diameter ($P < 0.001$), eastness and LAI had positive effects, and precipitation showed no significant

effect (Fig. 4). Precipitation exerted a strong negative effect on skeletal hyphal diameter, temperature had a positive effect, and slope had a strong negative effect (Fig. 4). Precipitation, temperature, and LAI all strongly promoted binding hyphal thickening (Fig. 4). Slope and eastness strongly inhibited binding hyphae, whereas northness had a positive effect.

Latitudinal patterns of traits

Along the latitudinal gradient, PC1-associated basidial and spore sizes generally increased at low latitudes, fluctuated at mid-latitudes, and exhibited a compensatory decrease–increase pattern at high latitudes, declining at 60–65° under low-temperature suppression, then rising sharply driven by effective accumulated temperature (Fig. 5). Along PC2, at low latitudes basidial shape first decreased then increased, spore shape first increased then decreased, and fruiting body size continuously declined; mid-latitudes showed the most pronounced fluctuations, with basidial shape plummeting at 55–60°, spore shape decreasing then increasing, and fruiting body size remaining high without a stable trend; at high latitudes, trait decoupling occurred, with fruiting body size reaching its minimum, basidial shape rebounding to a peak, and spore shape surging then plummeting (Fig. 5). Along PC3, generative and skeletal hyphal diameters continuously increased at low latitudes, increased then decreased at mid-latitudes, and generally declined at high latitudes (generative hyphae showed a slight rebound after 65°), whereas binding hyphal diameter continuously thickened from mid-low to high latitudes (Fig. 5). With increasing latitude, the proportions of white-rot fungi and broadleaf hosts declined continuously, while those of brown-rot fungi and gymnosperm hosts increased; at high latitudes, the proportions of symbiotic strategies, monomitic hyphal systems, and thick-walled spores all increased significantly (Fig. S17).

Trait predictions under future climate scenarios

Under the SSP1–RCP2.6 and SSP5–RCP8.5 scenarios, wood-inhabiting fungi underwent systematic trait reorganization (Figs. S18–S24; Tables S5–S8). Along PC1, basidial and spore volume, width, and length all declined significantly (Table S8). Along PC2, fruiting body volume increased substantially, basidial and spore shapes tended toward short, rounded forms, and basidial length decreased (Table S8). Along PC3, all three hyphal diameters consistently increased, with generative hyphae showing the greatest increase. Trait change directions were consistent between scenarios, but magnitudes differed. Along PC1, trait declines were smaller under the high-emission scenario (SSP5–RCP8.5) than under the low-emission scenario (SSP1–RCP2.6) (spore volume Δ : –4.32 vs. –4.59; basidial volume Δ : –68.40 vs. –71.29; Table S8), and PC1 standard deviation was higher (0.036 vs. 0.034; Tables S6, S8). The macro–micro trade-off within PC2 changed synchronously under both scenarios (Tables S5–S8). Along PC3, generative hyphal increase was greater under the high-emission scenario (+0.143 vs. +0.141; Table S8), and the proportion of negative changes in skeletal hyphae increased significantly (23% vs. 14%). Environmental novelty was slightly higher under the high-emission scenario (mean: 11.74 vs. 11.68).

Discussion

Functional traits of wood-inhabiting fungi form a multidimensional adaptive network through intramodule coupling and intermodule trade-offs. Within the reproductive module, basidium traits are tightly co-regulated developmentally ($P < 0.001$)²⁷. However, the significant negative correlation between macroscopic (fruiting body) and microscopic (basidium) reproductive units reflects a trade-off in reproductive resource allocation: annual fungi favor high reproductive investment (small fruiting bodies, large basidia) to maximize colonization, whereas perennial fungi prioritize structural maintenance (large fruiting bodies, small basidia)²⁸. Within the dispersal module, spore length, width, and volume are positively correlated but strongly negatively correlated with spore shape, indicating divergent dispersal strategies: thin-walled, smooth, elongated spores facilitate long-distance wind dispersal, whereas thick-walled, ornamented, near-spherical spores enhance attachment and stress resistance^{26, 44, 54}. Within the resource acquisition module, the positive correlation between generative and skeletal hyphal diameters reflects functional coupling between nutrient transport and structural support, whereas their differentiated relationships with binding hyphae indicate clear functional specialization within the hyphal system^{55–56}. Brown-rot fungi compensate for enzymatic deficiencies through increased hyphal diameter, white-rot fungi exhibit intermediate trait values, and non-saprotrophic fungi maintain high investment across all dimensions to cope with nutrient-limited environments^{15, 57}. At the cross-module level, full-matrix positive correlations between basidium and spore traits ($P < 0.001$) indicate strong developmental coupling between microscopic reproductive and dispersal units^{37, 58}, whereas the negative correlation between fruiting body size and spore volume reflects resource competition^{59–60}. In the reproductive–resource trade-off, large fruiting bodies require robust hyphal support but compete with basidia for resources; conversely, increased generative hyphal diameter enhances nutrient supply and promotes basidium development^{48, 61–62}. In the dispersal–resource module, generative and skeletal hyphae promote spore volume but inhibit elongation, whereas binding hyphae are negatively correlated with spore volume, demonstrating that hyphal functional differentiation differentially shapes dispersal strategies^{52, 56, 59}. Notably, parasitic fungi exploit living hosts and adopt macroscopic explosive investment (enlarged fruiting bodies), whereas symbiotic and non-saprotrophic fungi optimize microscopic traits (thicker hyphae, larger basidia)⁶³. Angiosperm-specialized fungi produce larger, rounder spores, whereas gymnosperm-specialized fungi produce smaller, elongated spores, consistent with adaptations to distinct dispersal vectors and host tissues^{36, 39–40}.

Although trade-off analysis reveals pairwise trait associations, it cannot integrate discrete multidimensional trade-offs into a continuous low-dimensional space^{64–65}. Drawing on plant functional economic spectrum theory and the soil fungal economic spectrum framework^{29, 32, 66}, we constructed a functional economic spectrum for 7,454 wood-inhabiting fungal species across 26 traits using principal component analysis (PCA). Initial PCA including all 26 traits (with categorical variables numerically encoded) identified three core axes cumulatively explaining 48.6% of variance (PC1: 21.7%; PC2: 13.6%; PC3: 13.3%), indicating a complex multidimensional trait structure. To minimize potential bias from

categorical variable encoding, we further analyzed 12 continuous traits following established plant ecology protocols^{29, 67}. The first three principal components cumulatively explained 72.1% of variance (PC1: 42.4%; PC2: 16.0%; PC3: 13.7%), highly consistent with the full-trait analysis and confirming the robustness of this three-dimensional framework. PC1 represents a microscopic reproductive–dispersal investment synergy axis^{68–69}, jointly driven by basidium and spore volume, width, and length. This indicates that wood-inhabiting fungi simultaneously increase investment in microscopic reproduction (basidia) and dispersal (spores), consistent with developmental coupling within reproductive structures⁴⁷. PC2 corresponds to a dispersal efficiency–macroscopic investment differentiation axis, driven by basidium shape, spore shape, and fruiting body size²⁷. This axis distinguishes a “small and refined” strategy optimized for long-distance wind dispersal (elongated spores, small fruiting bodies) from a “large and stable” strategy oriented toward local colonization, reflecting trade-offs between dispersal range and structural maintenance⁷⁰. Together, PC1 and PC2 explain 58.4% of variance, underscoring the dominant role of reproductive–dispersal traits in functional differentiation. PC3 represents a resource acquisition axis, constituted by skeletal, generative, and binding hyphal diameters, reflecting functional differentiation in substrate colonization and nutrient uptake^{29, 67}. Excluding categorical variables did not reduce dimensionality but substantially increased explained variance, confirming that continuous traits more robustly characterize the functional economic spectrum of wood-inhabiting fungi^{32, 65}. This three-dimensional economic spectrum demonstrates that, despite the complexity of trait trade-offs, functional variation in wood-inhabiting fungi can be effectively reduced along conserved strategy axes, providing a theoretical foundation for elucidating functional diversity maintenance, species coexistence, and environmental response patterns in wood-inhabiting fungal communities.

Climate, vegetation, and microtopography are core environmental determinants of spatial differentiation in fungal functional traits^{15, 36, 53, 71}, yet the multidimensional, hierarchical regulatory mechanisms underlying these effects remain insufficiently resolved in wood-inhabiting fungi. This study reveals differential responses of the three major axes of the functional economic spectrum to environmental factors. The PC1 axis (microscopic reproductive–dispersal investment synergy) shows hierarchical coupling between macroclimatic stress compensation and local modification by canopy and topography. Precipitation and temperature significantly reduce basidium and spore size, indicating that warm, humid conditions suppress investment in microscopic reproductive–dispersal structures, whereas cold and arid stress favors larger reproductive units that enhance nutrient storage and offspring colonization success^{37, 47, 49, 54, 72–73}. This pattern parallels climatic associations in arbuscular mycorrhizal fungi, where spores enlarge in cold, arid environments to improve germination success^{49, 74}. The positive effect of elevation further supports this interpretation, as low-temperature, high-radiation conditions at high elevations select for larger reproductive–dispersal structures^{75–76}. Leaf area index, slope, and aspect further fine-tune microscopic structural investment through canopy shading, radiation redistribution, and water stress^{77–78}, reflecting hierarchical coupling between macroclimatic and microtopographic regulation. PC2 reflects environmental decoupling between dispersal efficiency and macroscopic reproductive investment. Precipitation reduces fruiting body volume while promoting

basidium elongation and spore slenderness (Fig. 4)^{72, 79–80}. Temperature significantly constrains basidium and spore shape (Fig. 4), with warmer conditions favoring more spherical forms that enhance dehydration resistance and aerodynamic performance, consistent with latitudinal patterns of increased spore roundness at higher latitudes^{49, 80–81}. Topographic factors (elevation, slope) negatively constrain fruiting body volume but positively drive morphological optimization, indicating that under stressful conditions fungi reduce macroscopic size investment^{76, 82} and maintain dispersal efficacy through fine-scale adjustment of propagule morphology. Increased leaf area index promotes fruiting body enlargement and basidium elongation, suggesting that dense vegetation creates stable microhabitats that permit greater reproductive investment^{77, 83–84}. PC3 (resource acquisition axis) reveals environmentally differentiated trade-offs among hyphal functional components⁸⁵. Generative hyphal diameter is significantly constrained by low temperature, high elevation, and aridity, reflecting streamlining of vegetative reproductive structures under energy limitation⁸⁶. Skeletal hyphae are favored in warm, arid environments, whereas their development is constrained by low temperature, precipitation, and steep slopes. Binding hyphae thicken under warm, humid, high-vegetation-cover conditions, reinforcing the supportive network, but are strongly inhibited on steep and sunny slopes. The asynchronous responses of conductive hyphal simplification and supportive hyphal reinforcement indicate adaptive reorganization within the resource acquisition module under environmental stress. This pattern aligns with Camenzind et al.³², who showed that resource acquisition traits in soil saprotrophic fungi are largely independent of environmental stress gradients and exhibit strong functional conservatism.

Along the latitudinal gradient, the three functional axes exhibit distinct differentiation patterns (Fig. 3, Fig. S16). PC1 and associated basidium and spore volumes peak at low latitudes, indicating that warm tropical environments favor enlarged microscopic reproductive and dispersal units adapted to intense competition and stable forest niches^{45, 49, 76}. Mid-latitudes show complex trait fluctuations, reflecting non-monotonic environmental regulation^{87–88}. High latitudes display a compensatory pattern: low temperature initially suppresses basidium and spore volume, followed by a sharp rebound driven by effective accumulated temperature^{87, 89}. Although PC1 increases at both low and high latitudes, the underlying mechanisms differ—low-latitude peaks reflect optimal trait configuration under resource sufficiency, whereas high-latitude peaks represent stress-driven compensatory adaptation. This contrasts with the hump-shaped latitudinal pattern of fruiting body size, indicating that macroscopic and microscopic reproductive units are governed by independent filtering mechanisms. The PC2 axis shows pronounced latitudinal differentiation. Warm low-latitude environments drive reproductive structures toward elongation and fruiting bodies toward miniaturization, consistent with adaptation to complex interspecific competition⁹⁰. Mid-latitudes, with greater hydrothermal availability and habitat heterogeneity, disrupt trait trade-offs and produce erratic fluctuations in reproductive and dispersal traits, highlighting adaptive uncertainty in transitional zones^{42, 91–92}. At high latitudes, fruiting body volume contracts to a minimum, basidium shape shifts abruptly from near-spherical to elongated, and spore shape shifts in the opposite direction (elongated to near-spherical)⁵². This breakdown of original trait

synergies produces high-latitude-specific adaptive strategies reflecting dynamic trade-offs between dispersal efficiency and resource investment under extreme conditions⁹³. The PC3 axis reveals latitudinal differentiation in resource acquisition strategies. In warm low-latitude environments, fungi increase generative and skeletal hyphal diameters to enhance nutrient transport and structural support, enabling efficient decomposition of diverse substrates^{94–95}. With increasing latitude, energy limitation drives conductive hyphal simplification to reduce maintenance costs, while binding hyphae thicken to reinforce penetration into hard, freeze–thaw-affected wood^{15, 96–97}. This shift coincides with increasing proportions of brown-rot fungi and gymnosperm hosts, reflecting the physiological constraint that low temperature inhibits lignin degradation and favors cellulose utilization^{10, 40, 53, 98}. Increased symbiotic strategies, monomitic hyphal systems, and thick-walled structures at high latitudes further reflect adaptation toward stable carbon acquisition and stress-resistant survival^{99–100}. Although narrow confidence intervals at high latitudes warrant cautious interpretation of ecological generality, the observed extreme specialization trends align with functional mechanisms and reveal distinctive adaptive patterns of wood-inhabiting fungi in polar and cold-temperate forests.

Under future climate scenarios, the three major functional axes exhibit directionally consistent but quantitatively divergent trajectories. The microscopic reproductive–dispersal investment synergy axis (PC1) undergoes comprehensive contraction, with significant reductions in basidium and spore sizes, indicating a generalized decline in fungal resource allocation to reproductive structures under warming^{49, 101}. PC2 displays a decoupled pattern of macroscopic enlargement and microscopic contraction: fruiting body volume increases substantially, whereas basidia and spores shift toward smaller, more rounded morphologies, reflecting asymmetric climatic forcing on macro- versus microscopic reproductive traits^{49, 78, 102}. Along PC3, diameters of all three hyphal types increase uniformly, with generative hyphae showing the greatest expansion, suggesting that fungi reinforce hyphal networks to enhance nutrient acquisition and environmental resilience under climatic stress^{11, 56}. Although change directions are concordant across emission scenarios, their magnitudes differ. Contrary to expectation, the decline in PC1 traits is slightly attenuated under the high-emission scenario relative to the low-emission scenario. This counterintuitive pattern may arise from climate-induced disruption of individual developmental homeostasis, whereby some populations adopt delayed attenuation strategies that dampen population-level average responses, consistent with the observed increase in PC1 standard deviation. The macro–micro trade-off represented by PC2 shifts synchronously under both scenarios, underscoring its robustness to climate warming. Under the high-emission scenario, PC3 exhibits a greater increase in generative hyphae alongside a significant rise in the proportion of negative changes in skeletal hyphae, indicating a further reallocation of resources toward reproductive structures. Notably, as these projections derive from statistical model extrapolation, they should be regarded as preliminary and interpreted with caution^{103–104}.

Conclusion

This study establishes the first global functional trait database for wood-inhabiting fungi, revealing that traits form a multidimensional adaptive network through intramodule synergy and intermodule trade-offs. We propose a functional trait economics spectrum framework for wood-inhabiting fungi, comprising three functional dimensions, viz., microscopic reproductive–dispersal investment axis, dispersal efficiency versus macroscopic investment axis and resource acquisition axis, among which the microscopic reproductive–dispersal investment axis plays a central role in functional trait evolution. Temperature and precipitation as macroclimatic drivers, significantly suppress microscopic reproductive–dispersal traits, whereas elevation positively regulates basidial and spore dimensions, and microtopographic factors such as aspect and slope position impose fine-scale regulation by modulating local radiation budgets and moisture redistribution. Latitudinal gradients drive nonlinear responses, reproductive propagules moderately increase under resource-rich low-latitude conditions, reflecting optimal energy allocation, whereas high-latitude fungi exhibit macro–micro trait decoupling, characterized by enlarged spores and basidia, near-spherical spore morphology, minimized fruiting body size, declining abundances of white-rot fungi and angiosperm hosts, and increasing abundances of brown-rot fungi and gymnosperm hosts, consistent with the physiological constraint that low temperature inhibits lignin-degrading enzyme activity. Under future climate scenarios, traits are predicted to reorganize robustly, exhibiting a coordinated pattern of macroscopic expansion, microscopic contraction, and hyphal reinforcement, with amplified shifts and environmental novelty under high-emission scenarios. This study establishes the first global fungal economics spectrum for wood-inhabiting fungi, elucidates adaptive mechanisms including stress compensation and macro–micro decoupling, identifies key environmental dimensions driving functional differentiation, and provides a theoretical basis for trait parameterization in Earth system models and mechanistic prediction of forest carbon–climate feedbacks.

Declarations

Reporting summary

Further information on research design will be publicly released upon publication.

Data availability

The literature-derived dataset, associated metadata, and all derived data required to reproduce the analyses and figures presented in this study will be made available to editors and reviewers upon request during peer review, and will be publicly released upon publication.

Code availability

The analysis code used to reproduce the results and generate the figures in this study will be shared with editors and reviewers upon request during peer review, and will be made publicly accessible upon publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

S.L. and B.Z. designed this study; S.L. collected the fungal trait data; S.L. and C.R.N. collected the fungal distribution data; S.L., S.M.Z, and M.G.H. analyzed the trait and distribution data; S.L. and B.K.C provided distribution data for some wood-inhabiting fungi collected during field surveys; S.L. wrote the first manuscript draft with considerable inputs from B.Z. and finalized the manuscript. All authors reviewed and approved the final manuscript.

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Figures

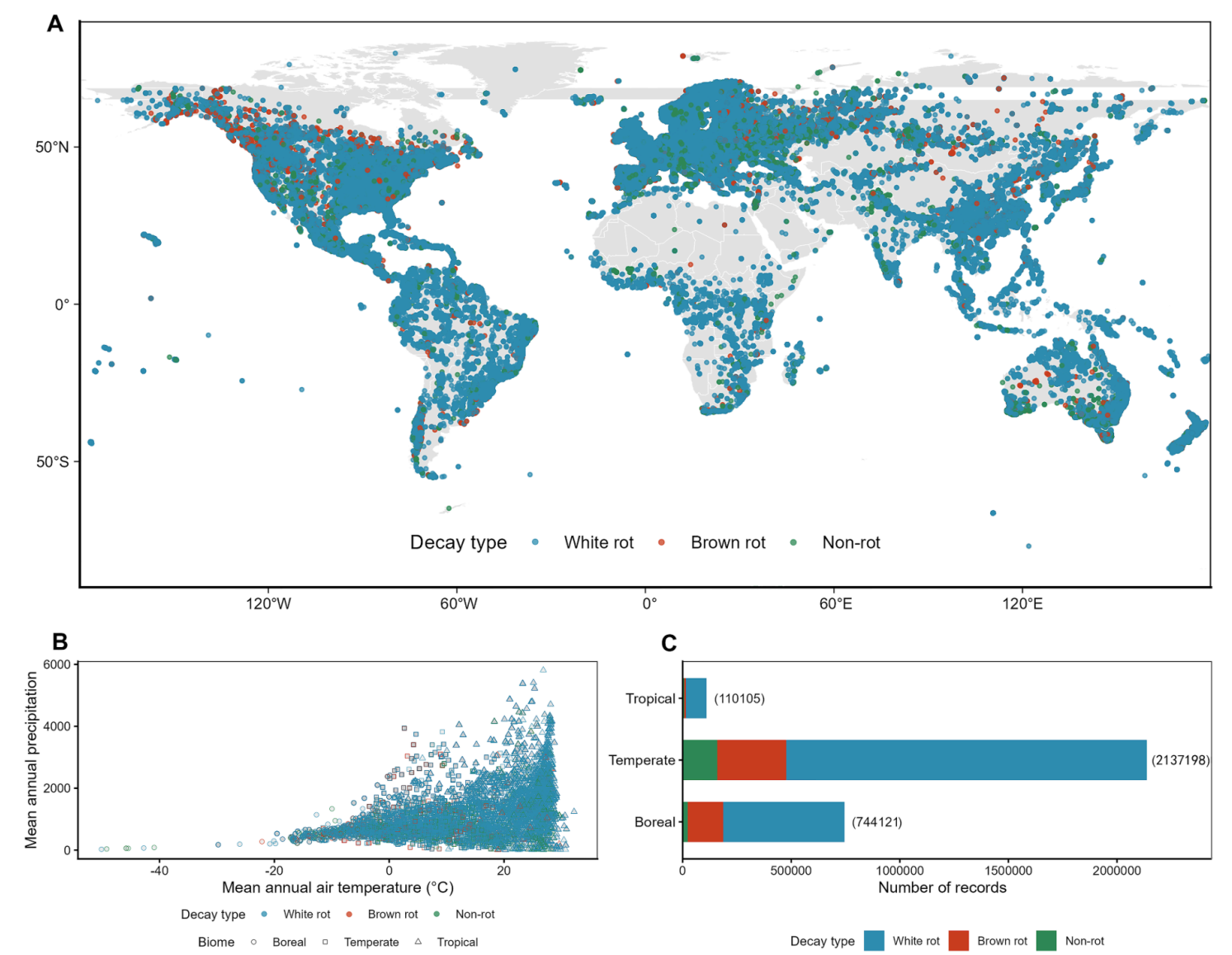


Figure 1

Global distribution patterns of wood-inhabiting fungi and their relationships with climate and biomes. **A.** Global geographical distribution patterns of three wood-inhabiting fungi decay types (white rot, brown rot, and non-rot). **B.** Scatter plot of mean annual air temperature versus mean annual precipitation for wood-inhabiting fungi, categorized by decay type and biome. **C.** Stacked bar chart showing occurrence record counts of three wood-inhabiting fungi decay types across tropical, temperate, and boreal biomes.

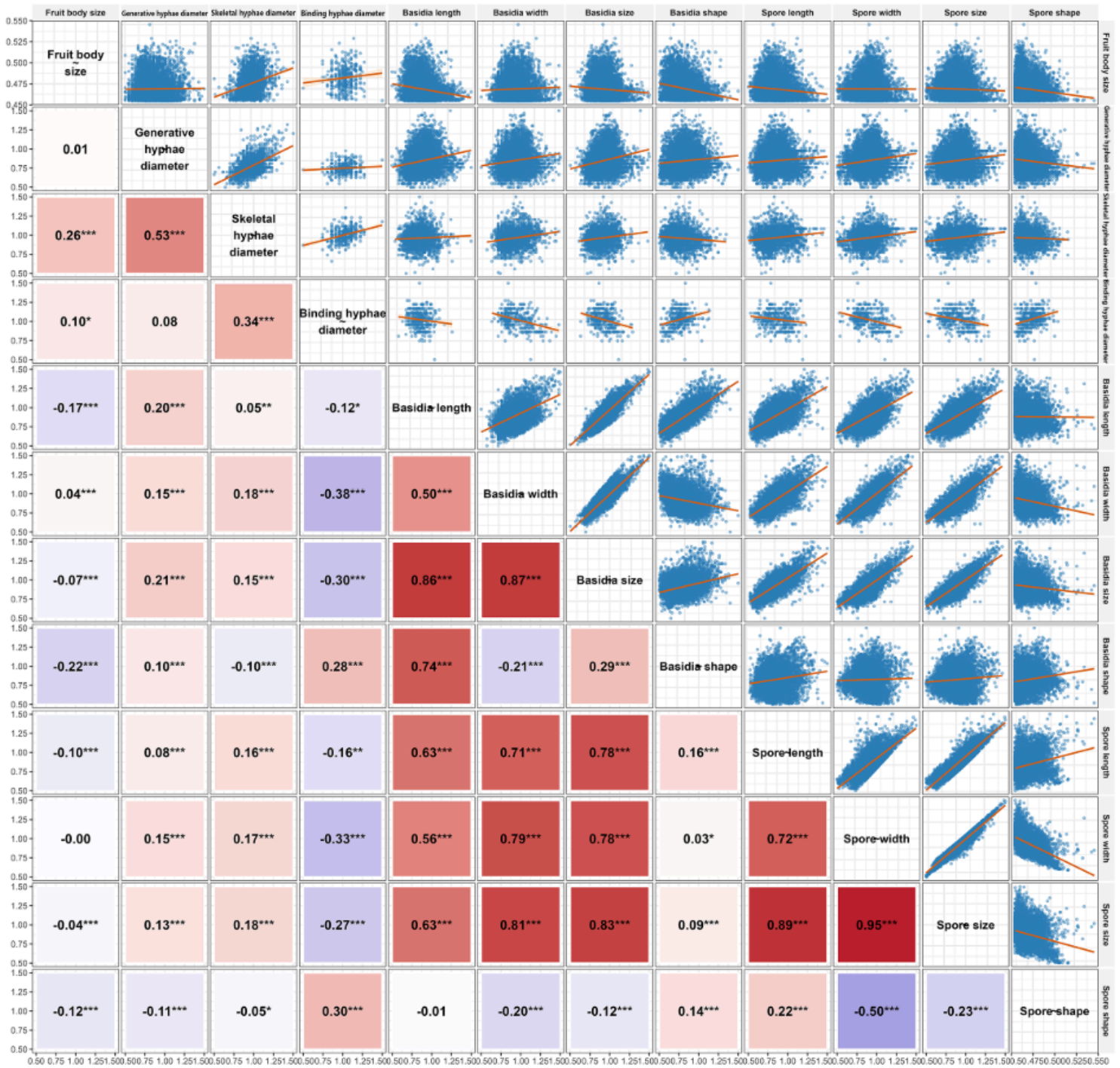


Figure 2

Trade-offs among representative traits in wood-inhabiting fungi. Pairwise correlation matrix of log-transformed and Z-standardized continuous functional traits of wood-inhabiting fungi. The upper triangle shows scatter plots with linear fitting curves, and the lower triangle displays Pearson correlation coefficients.

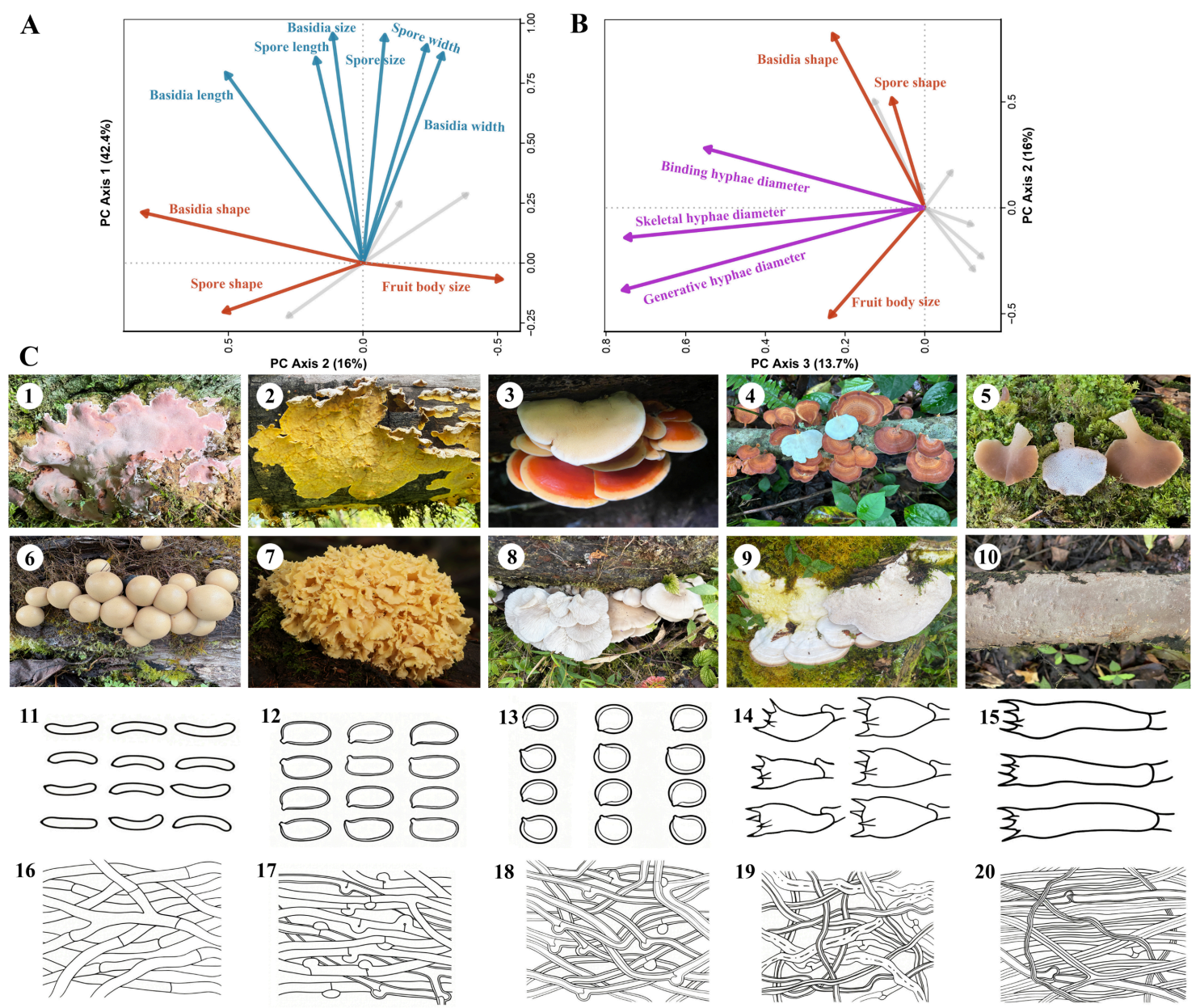


Figure 3

Principal component axes of core functional traits and their representative trait characteristics in wood-inhabiting fungi. **A.** PC1 (42.4% variance explained) and PC2 (16.0% variance explained), showing trait loadings of basidia/spore size traits (blue vectors), basidia/spore shape traits and fruit body size traits (red vectors). **B.** PC2 (16.0% variance explained) and PC3 (13.7% variance explained), showing trait loadings of basidia/spore shape traits (red vectors) and hyphal traits (green vectors). **C.** Representative trait diagram, including Fruit body types (1. Resupinate, *Physisporinus roseus* Liu 519; 2. Effused-reflexed,

Stereum hirsutum Liu 1293; 3. Pileate, *Bondarcevomyces taxi* Liu 1094; 4. Stipitate, *Microporus affinis* Liu 3112); Hymenium types (5. Denticulate, *Pseudohydnum motuoense* Liu 577; 6. Gasteroid, *Apioperdon pyriforme* Liu 1692; 7. Labyrinthine, *Sparassis latifolia* Liu 1395; 8. Lamellate, *Pleurotus ostreatus* Liu 2133; 9. Poroid, *Trametes gibbosa* Liu 973; 10. Smooth, *Hymenochaete murina* Liu 612); Basidiospore-related traits (11. Thin-walled, allantoid; 12. Slightly thick-walled, cylindrical; 13. Thick-walled, subglobose); Basidia-related traits (14. Short-clavate; 15. Long-clavate); and Hypha-related traits (16. Monomitic, simple septa, thin-walled; 17. Monomitic, clamp connections, slightly thick-walled; 18. Dimitic, clamp connections, slightly thick-walled; 19. Dimitic, clamp connections, thick-walled; 20. Trimitic, clamp connections, thick-walled).

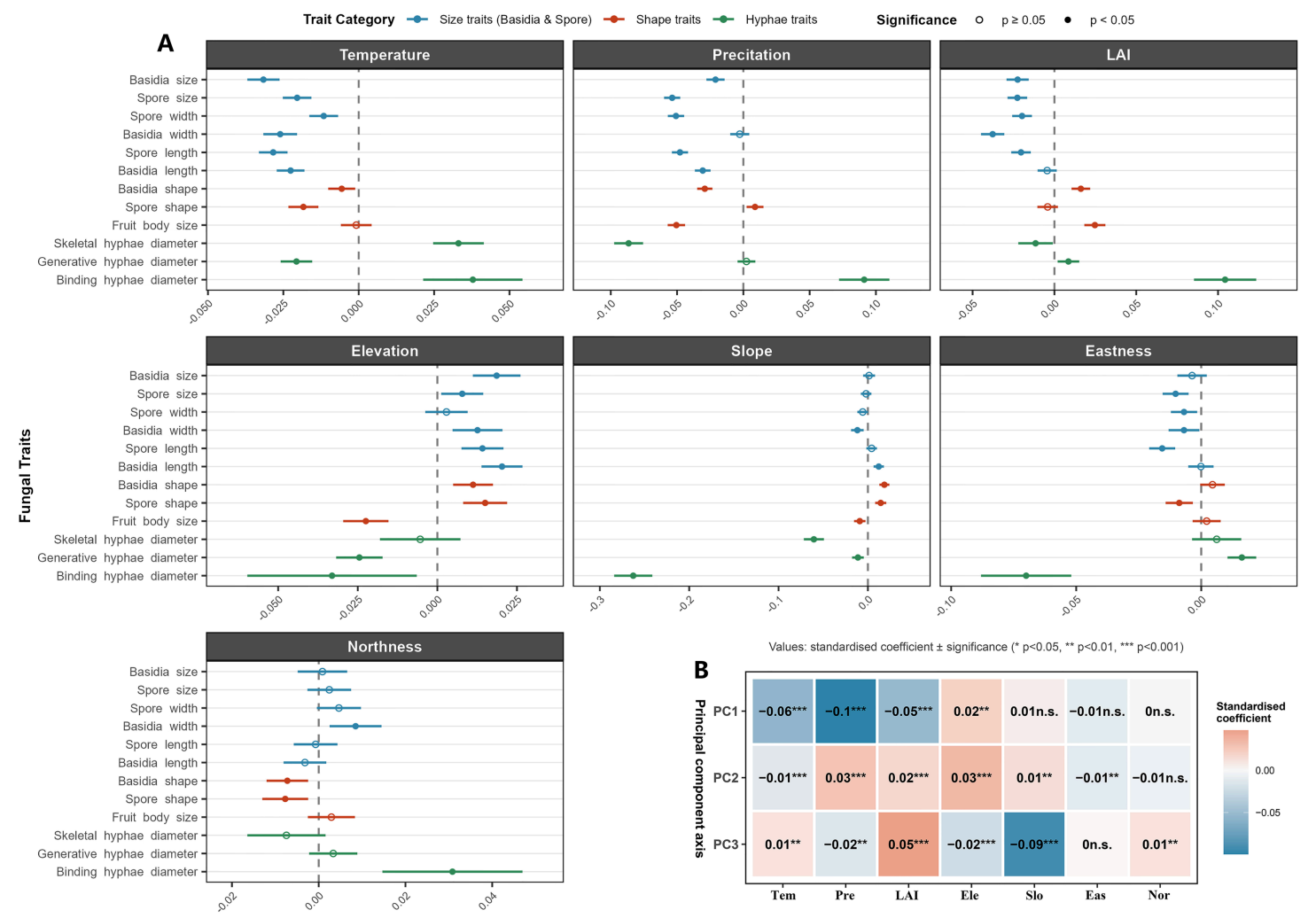


Figure 4

Effects of environmental factors on core functional trait principal component axes (PC1–PC3) in wood-inhabiting fungi. **A.**Influence strength of seven environmental factors (mean annual temperature, mean annual precipitation, leaf area index, elevation, slope, eastness, and northness components of aspect) on PC1 (basidia/spore size), PC2 (basidia/spore shape and fruit body size), and PC3 (hyphal diameter), respectively. **B.** Combined effects of the seven environmental factors on the three principal component axes.

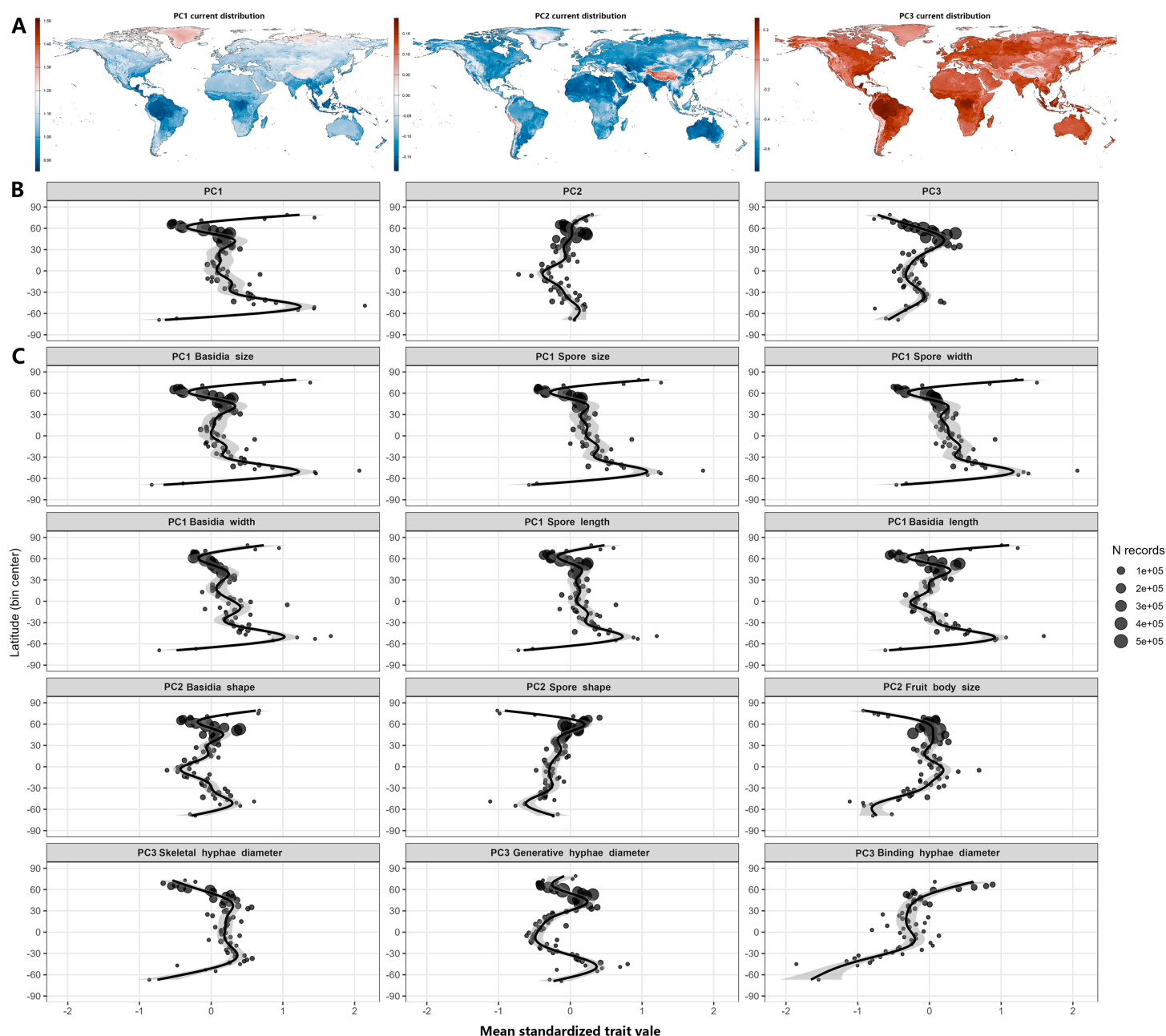


Figure 5

Global distribution and latitudinal patterns of core functional trait principal component axes (PC1–PC3) in wood-inhabiting fungi. **A.** Current global distribution patterns of the three principal component axes, with color gradients indicating PC axis scores. **B.** Latitudinal distribution patterns of the three principal component axes, with solid lines representing smoothed fitted curves and shaded areas denoting 95% confidence intervals. **C.** Latitudinal variation patterns of representative traits loading on each principal component axis, with each subpanel corresponding to the trait group associated with a given PC axis.

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