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'Slow-Fast' Plant Trait Spectra Are Associated With Ecological Niches Across Global Climatic Gradients

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ABSTRACT

Aim: Global climate change is compressing species' realised niches and further threatening their distributions. Species traits, especially the trait spectra synthesised from traits, are one way in which species can match changes in their environment. Hence, integrating trait spectra and niches will help us understand how species adapt to their environment under global change.

Location: Global.

Time Period: Present.

Major Taxa Studied: Angiosperms.

Method: We collected root traits from 158 angiosperm species and leaf traits from 512 angiosperm species from a global trait database to construct the leaf and root trait 'slow-fast' spectrum based on resource acquisition strategy, as well as the collaboration spectrum related to root mycorrhizal colonisation. After rebuilding their phylogenetic relationships and defining species' environmental niches based on 213,979 occurrences of these species, we examined the relationship between these trait spectra and environmental niches along global climatic patterns.

Result: Plants with 'slow' leaf traits were generally associated with narrow niche breadths and marginal niche positions, especially in high precipitation areas. The relationship between the 'slow-fast' spectrum in root traits and 'marginal-central' niche position reversed with decreasing precipitation. However, the relationships between leaf traits and niche variables were significant for woody species but not for herbaceous species.

Main Conclusion: Our research expands the plant trait spectra in macroecology applications. The root and leaf 'slow-fast' trait spectra of angiosperms are driven by both macroclimate and long-term evolutionary pressure. Understanding how these traits relate to the niche of species helps to predict how that species is likely to adapt to environmental change, which can enhance the predictive ability of niche theory for plant environmental adaptability.

1 | Introduction

Global change is threatening the distribution and diversity patterns of plants (Isbell et al. 2023). Future warming of 3.2°C above preindustrial levels is projected to lead to the loss of more than half of the historical geographic range of half of the plants (Wudu et al. 2023). Distributions of native species shrink, or the species go extinct, due to difficulty in adapting to climate change in their habitats (Habel et al. 2019). Concurrently, alien species may further expand and exacerbate spatial homogenisation of plant communities (Bellard et al. 2014; Xu et al. 2023). Species distribution changes have further reshaped global biodiversity patterns (Rubenstein et al. 2023). Biodiversity is both being lost and shifting along altitude and latitude with changes in plant composition under climate change (Loewen et al. 2023). These changes will likely reduce biodiversity of 31% of the world's biodiversity hotspots to an extent that they will no longer be considered biodiversity hotspots (Bellard et al. 2014).

Niche theory can help us predict species' responses to global changes by integrating their interactions with the environment (Sax et al. 2013). A species' niche quantifies the environment they occupy and the resources they use (Davison et al. 2024). This measure has two components: niche breadth and niche position (Brown 1984; Devictor et al. 2010). First, niche breadth is the range of environmental conditions where species occur (Vela Díaz et al. 2020). It indicates the species' tolerance to a range of conditions (Carscadden et al. 2020). Second, niche position is defined as the marginality of a species' environmental distribution relative to the mean environmental conditions of a region (Vela Díaz et al. 2020). It indicates the degree to which a species specialises in a specific set of environmental conditions (Lu and Jetz 2023). Species with wider niche breadth are considered generalists and have stronger tolerance to climate change, making them less likely to go extinct (Saupe et al. 2015). This wider niche breadth also brings more adaptability and allows for species coexistence and biodiversity maintenance (Xu et al. 2023). Meanwhile, specialised ecological niche positions allow species to adapt to more extreme environments, but these species are often unable to adapt to a changing environment because of their narrow requirements (Meza-Joya et al. 2023).

Plants interact with and adapt to the environment that forms their niche through their functional traits both above and below ground. Functional traits are linked to species performance, adaptability and functioning (Kermavnar et al. 2023) and they therefore represent a way that species can match to their environment (Díaz et al. 2016; Violle and Jiang 2009). The combination of multiple correlated traits not only shows plants' ecological strategy (Bergmann et al. 2020; Wright et al. 2004), but also predicts their dispersion and distribution (Midolo 2024). The 'slow-fast' spectrum (also called the plant economic spectrum) based on leaf and root traits is widely used to distinguish plant resource-use strategies (Figure 1, Wright et al. 2004; Weigelt et al. 2021). 'Fast' species with high leaf nitrogen per unit leaf mass (N_{mass}), photosynthesis per unit leaf mass (A_{mass}) and higher root nitrogen (RN) have faster growth and resource-use rates. Alternatively, 'slow' species with longer leaf lifespan, higher leaf mass per unit area (LMA) and root tissue density (RTD) grow slower but are more robust to stress from, for example, herbivory or pathogens (Reich 2014; Wright et al. 2004). Below ground, in addition to the 'slow-fast' spectrum root traits also align with a so-called collaboration gradient (Bergmann et al. 2020). 'Outsourcing' species with thicker root diameters (RD) usually require mycorrhizal fungi for more nutrient absorption, while species with higher specific root length (SRL) can 'do-it-yourself' through their complex root systems (Bergmann et al. 2020; de Vries et al. 2021). Many studies have revealed the correlation between trait spectra and plant ecological strategies, but the understanding of plant distribution patterns and climate adaptation requires us to further link trait spectra with ecological niches.

Studies of these trait spectra show that alone each of them may be linked to niche breadth and position. First, a species' 'slow-fast' strategy is associated with species niche breadth and position (Figure 1). 'Fast' species may be able to adapt to a more diverse climate and soil conditions. 'Slow' species tend to survive in extreme environments through their marginal niche positions. Species with high LMA have marginal niche positions that better tolerate climate stress through developing sclerophyllous leaves (Visakorpi et al. 2024; Weigelt

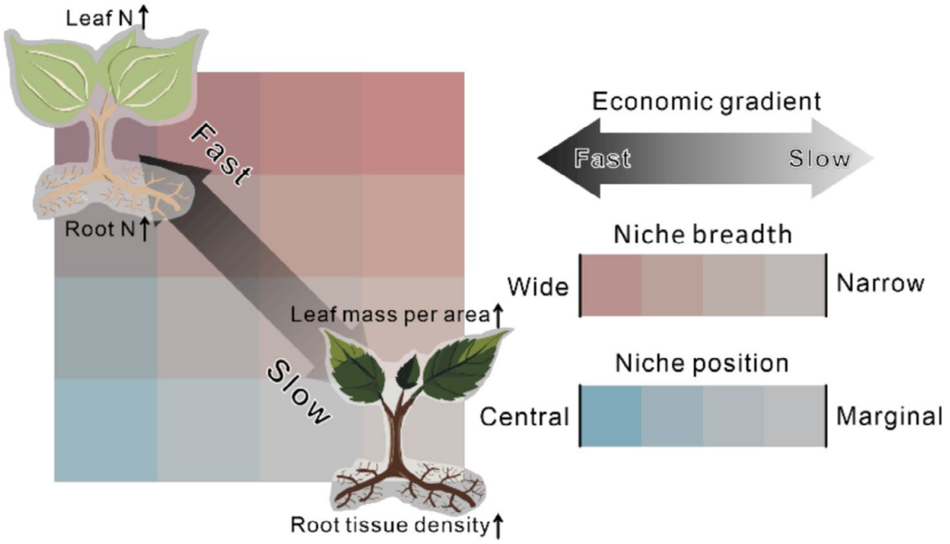

FIGURE 1 | Conceptual figure illustrating how plant niches (position and breadth) are linked to the 'slow-fast' economic spectrum. We decompose plant niche into niche position and niche breadth, representing the position and range of plants in a wide environmental gradient. We also assume that the conservation gradients of leaves and roots are coordinated based on (Weigelt et al. 2021), representing a gradient of species from fast resource return on investment to slow resource return on investment both above and below ground. We hypothesize that species with fast strategies will have central niche positions and wider niche breadths, while species with slow strategies will have marginal niche positions and narrower niche breadths.

et al. 2021). Species with high RTD also develop dense roots to resist resource-poor habitats and environmental stresses (Lerdau et al. 2023). 'Fast' species have more central niche positions and are not adapted to surviving in extreme environments. Species with fast traits (high RN and N_{mass}) typically prefer soils with more nutrients and water (Augusto et al. 2025; Fort and Freschet 2020). Moreover, 'outsourcing' plants usually have a wider climatic niche breadth because they can utilise more soil nutrients with facultative mycorrhizae, and their thicker roots also improve their water uptake ability (Laughlin et al. 2021; Maherali 2020).

In addition, different plant growth forms also affect the relationship between niches and traits. Herbaceous plants typically have faster growth strategies and stronger dispersal abilities (Guo et al. 2018). Herbaceous species have 'faster' leaf traits, explaining their rapid expansion and success early in succession (Matsuo et al. 2024). Moreover, herbaceous plants have a wider niche breadth, which helps them to be distributed in a wide range of areas from tropical to boreal regions (Taylor et al. 2023). Woody plants, which grow more slowly, are more resistant to climate changes (Wang et al. 2025). Woody species also tend to have 'slower' root traits, which explains their stable survival in harsh climates and later successional stages (Illuminati et al. 2025; Matsuo et al. 2024).

Here, we investigate whether species' ecological niches can serve as effective predictors for their functional trait spectra. We integrate leaf and root trait databases to quantify the position of species in these trait spectra and evaluate their climatic and soil niches based on climate and soil data across their distributions. We hypothesise that:

1. The position of species on the leaf and root trait 'slow-fast' spectra is related to their ecological niche, with leaf traits more closely related to climatic niche and root traits related to soil niche.
2. The relationship between species traits and niche is influenced by biogeographical patterns. The traits and ecological niche will change along the temperature and precipitation gradients.
3. The relationship between species traits and niche varies between woody and herbaceous plants. Woody plants may be more conservative than herbaceous plants in their trait spectra and niches.

2 | Methods

2.1 | Data Collection

2.1.1 | Construction of Trait Economic Spectra

2.1.1.1 | Aboveground. The leaf traits used in our study were extracted from the TRY plant trait database (Version 6.0, Kattge et al. 2020). We selected the four most common leaf traits that characterise the worldwide leaf trait 'slow-fast' spectrum (Donovan et al. 2011; Wright et al. 2004): photosynthesis per unit leaf mass (A_{mass}), leaf nitrogen per unit leaf mass (N_{mass}), leaf mass per unit area (LMA) and leaf lifespan. We obtained mean leaf trait values of 512 angiosperms (140 herbaceous species and 372 woody species based on their 'growth form' data in TRY database and shrubs are classified as woody species) from 50,898 records after screening all species with these four traits simultaneously and using the same data cleaning process as for root traits. We did not integrate the trait 'slow-fast' spectrum of belowground and aboveground together because only 36 species have all the leaf and root traits involved in our analysis. Finally, the first axis represents LMA, A_{mass}, N_{mass} and leaf lifespan, which are all linked to the 'slow-fast' spectrum (Figure S1).

2.1.1.2 | Belowground. Fine-root traits used in our study were extracted from the Fine-Root Ecology Database (FRED 3.0, Iversen and McCormack 2021). We chose four fine-root traits in the root economic space from FRED (Freschet et al. 2021): specific root length (SRL), root diameter (RD), root tissue density (RTD) and root nitrogen content (RN). Then we selected the records in 'in situ' and 'outdoor' conditions (natural conditions) in the database to avoid human manipulation affecting root traits (Iversen et al. 2017). SRL and RD are used to build the root trait collaboration spectrum, while RN and RTD are used to build the root trait 'slow-fast' spectrum (Weigelt et al. 2021). The mean root trait values of 158 angiosperms (15 herbaceous species and 143 woody species) were obtained from 553 records after cleaning the data by removing the missing species' scientific names, coordinates and duplicate trait values and selecting all the angiosperms for establishing a complete phylogenetic tree. We used principal component analysis ('*principal*' function in '*psych*' R package, R Version 4.4.2) to reduce all fine root trait dimensions to build the root trait spectra. Since we do not pay attention to the covariance between above-and belowground traits, we applied varimax rotation to align each trait with the main axis to improve interpretability (Carmona et al. 2021; Weigelt et al. 2023). Finally, the root 'slow-fast' spectrum and the collaboration spectrum explained 74.18% of the variation in root traits (Figure S1, Bergmann et al. 2020), which can well represent the variation of root traits.

2.1.1.3 | Occurrence and Biogeographical Data Collection. We extracted the occurrence data of all 634 species from the Global Biodiversity Information Facility in '*rgbif*' R package based on their scientific name (Chamberlain et al. 2022). The occurrence status was 'present' for existing occurrences and we excluded managed species to avoid the impact of artificial environments. We used the '*CoordinateCleaner*' R package to clean all coordinates in the capital, national centroid, sea, zero point and botanical institutions to avoid any bias in the results (Zizka et al. 2019). Finally, we used 213,979 coordinates for all of our species (Figure S2).

We also extracted these species' current climate and soil data based on their occurrences. We calculated the average climate level of the distribution of all species based on the average climate data corresponding to all occurrences. Current climate data was downloaded from the WorldClim 2.1 database at a 30-s (~1 km) resolution grids (Fick and Hijmans 2017). The current climate data consists of 19 (bio1–bio19) average bioclimatic factors from 1970 to 2000, with bio1–bio11 being temperature-related factors and bio12–bio19 being precipitation-related factors (Booth 2022). Soil data was downloaded from the ISRIC global gridded soil database (SoilGrids 2.0) at a 1000-m resolution (Poggio et al. 2021). All the soil data are divided into two categories based on their properties: bulk density, coarse fragments and soil texture fraction (gravimetric contents of sand and clay) belong to soil texture-related factors, while pH, cation exchange capacity, nitrogen and organic carbon concentration belong to soil nutrient-related factors. All soil factors are also divided into six depth intervals: 0–5, 5–15, 15–30, 30–60, 60–100 and 100–200 cm.

2.1.1.4 | Niche Calculation. We used outlying mean index (OMI) analysis based on the 'ade4' R package to calculate species' environmental niche metrics (Dray and Dufour 2007). OMI can calculate niche position and niche breadth in multivariate environments based on ordination techniques (Dolédec et al. 2000). The first step of OMI is to build hyperspace for environmental factors through PCA. The hyperspace is constructed from 50,000 random environmental backgrounds extracted from the global climate and soil dataset we compiled above, and the first three axes of PCA are taken to represent the overall variation of all environmental factors (Table S1). Then we located the environments corresponding to the occurrence data of all species to calculate their niches by using the 'niche' function in the 'ade4' package (Dray and Dufour 2007). This function can divide the environmental data related to the species presence/absence data into niche position and niche breadth. Niche position, also commonly referred to as niche marginality, represents the deviation of a species' mean habitat condition from the global mean habitat conditions (Thuiller et al. 2005). Species with central niche positions grow at the average position of the global environmental gradient, while species with marginal niches are distributed at the edges of the global environmental gradient (Mod et al. 2023). Niche breadth represents the amplitude of the distribution of each species along the global environmental gradients (Thuiller et al. 2005). Wider niche breadth means that species can survive in a larger environmental range, while species with narrower niche breadth can only grow under limited environmental variation (Carscadden et al. 2020). We used the environmental conditions of all 634 species with trait data as a substitute for the global environment in the niche calculation. The distribution range of these species covers the entire vegetation area (Figures S2 and S3) (Thuiller et al. 2005; Wang et al. 2023).

2.2 | Statistical Analysis

To detect and exclude the effect of phylogeny on our trait metrics, we calculated the phylogenetic signal (Winemiller et al. 2015). We measured the phylogenetic signals of traits based on Pagel's Lambda (Pagel 1999). Strong phylogenetic signals (Table S2) indicate that related taxa have similar traits and these traits will respond more conservatively to the environment (Münkemüller et al. 2012). Next, we built a phylogenetic tree for all plants to quantify and control for the influence of phylogenetics in the analysis of traits and niches. The phylogenetic tree for all species was built by the 'V.PhyloMaker2' package (Jin and Qian 2022). We chose a seed plant mega tree (GBOTB database, Smith and Brown 2018) as the basis to build our phylogenetic tree and any other settings were set by default. All species in our analysis have been included in the phylogenetic tree. We excluded the influence of phylogeny in the following statistical analysis.

We evaluated the relationship between species environmental niche and trait spectra using phylogenetic generalised least squares (PGLS) by the 'phylolm' package (Tung Ho and Ané 2014). The PGLS model can incorporate phylogenetic trees into regression to enable us to calculate the independent effects of each variable (Revell 2010). We first used multivariate PGLS to investigate the impact of species niche on trait spectra. Niche breadth and position were set as explanatory variables, while leaf 'slow-fast' spectrum, root 'slow-fast' spectrum and collaboration spectrum were set as dependent variables. We selected the Brownian motion (BM) model as the evolutionary model based on the Akaike information criterion (AIC) to eliminate the interference of phylogenetics on the regression covariance. We further explored the relationship between environmental factors (temperature, precipitation, soil texture and soil nutrients) that make up the ecological niche and trait spectra. To quantify the contributions of different environmental factors to trait spectra, we used the 'phylolm.hp' R package to calculate the individual effects of all different niche factors in predicting trait spectra, as well as the effects of phylogenetic relationships on model goodness of fit (Lai et al. 2023, 2025). 'Phylolm.hp' calculates the individual effects of each variable by decomposing the pairwise shared variance and jointly explained variance by all independent variables based on 'phylolm' (Lai et al. 2025). To evaluate whether the trait spectra-niche relationship is influenced by large-scale climate patterns, we set precipitation and temperature extracted from WorldClim 2.1 (Bio1: annual mean temperature; Bio12: annual precipitation; Fick and Hijmans 2017) in species distribution areas as interaction terms with the niche in PGLS regression to explain the variation of trait spectra. Using the interaction between climate and niche to predict trait spectra will help us better explore whether the relationship between niche and trait spectra follows large-scale climate patterns or flipping (Wiens 2011), although there is a weak correlation (Table S3) between species niche and climate conditions in their distribution areas. We also separately examined whether this relationship is consistent between woody and herbaceous plants due to the significant differences in plant traits and habitat preferences among different growth forms (Chen et al. 2023).

3 | Results

The leaf trait 'slow-fast' spectrum was related to the breadth and position of the ecological niche (Figure 2, Table 1). Species with slow leaf traits, such as larger specific leaf area and leaf lifespan, had broader niches and more specialised niche positions. Species with fast leaf traits, such as higher leaf nitrogen content and photosynthetic rate, had narrower niche widths and common root niche positions. The relationship between leaf traits and ecological niche existed in woody plants, but was not significant in herbaceous plants.

We only found evidence of the correlation between root trait spectra and niches in herbaceous plants (Table 1). Herbaceous plants with 'fast' strategy root traits, such as higher root nitrogen

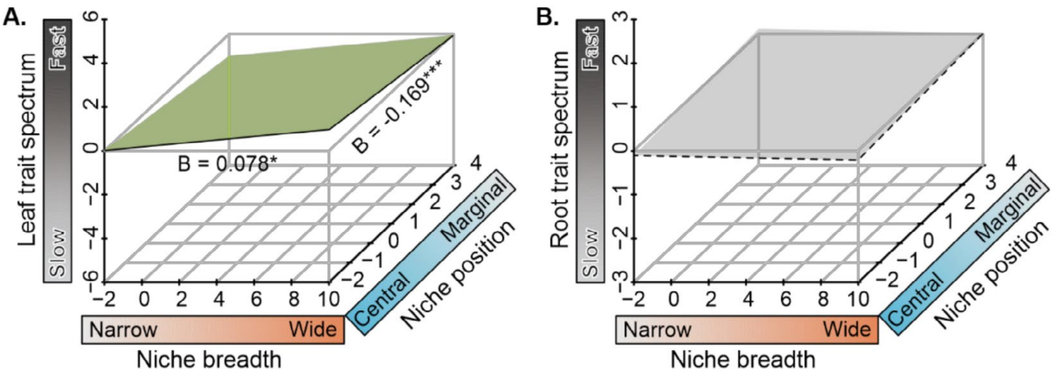

FIGURE 2 | Niche breadth and niche position are linked to the 'slow-fast' spectra only in (A) leaf traits but not in (B) root traits. We mapped standardised regression coefficients (B) between niche and traits spectra by using the multiple phylogenetic least squares regression. Significant regression relationships are marked (*: $0.05 < p < 0.01$; $0.01 < p < 0.001$; $p < 0.001$), while insignificant relationships are marked with dashed lines.

TABLE 1 | The relationship between niche factors and trait economics spectrum.

	Leaf traits			Root traits					
	'Slow-fast' spectrum			'Slow-fast' spectrum			Collaboration spectrum		
	All	Woody	Herb	All	Woody	Herb	All	Woody	Herb
Niche breadth	0.078*	0.075*	0.051	−0.098	−0.007	1.758	−0.029	−0.028	0.483
Niche position	−0.169***	−0.176***	−0.034	0.076	0.041	0.987*	−0.066	−0.065	0.213

Note: We used multiple phylogenetic regression to show the relationship between both leaf and root trait spectra and ecological niche factors.
We presented the standard regression coefficients of the model and annotated the significance level (: $0.05 < p < 0.01$; ***: $p < 0.001$).

content, had more marginal niche positions. Meanwhile, the root trait collaboration spectrum related to mycorrhizal colonisation was not significantly correlated with the niche breadth and position.

The correlation between leaf trait 'slow-fast' spectrum and the niche varied along the precipitation gradient (Figure 3, Table S4). Species with slow strategy leaf traits had more marginal niche positions, and this correlation intensified with increasing precipitation. The relationship between niche position and the root and leaf trait 'slow-fast' spectrum was not significant in semi-arid and arid areas with low precipitation. However, there was a strong negative correlation between niche position and the leaf trait 'slow-fast' spectrum in tropical and subtropical areas with high precipitation. The effect of precipitation on the leaf trait-niche relationship was not significant when the species were separated into woody and herbaceous species (Table S4). Herbaceous plants with 'fast' leaf traits in high-temperature areas had a narrower niche breadth and more marginal niche position, while this pattern was not significant in low-temperature areas.

The correlation between both root trait spectra and ecological niches flipped along the precipitation gradient (Figure 3, Table S4). 'Slow' species had more central niche positions in low precipitation areas and more marginal niche positions in high precipitation areas. In tropical and subtropical areas with high precipitation, species with 'fast' and 'DIY' root traits often had more central niche positions, but this relationship was not significant in low precipitation areas. However, precipitation only affected the relationship between the root trait collaboration spectrum and the niche position of woody plants when species were classified into different growth forms (Table S4). Alternatively, temperature only affected the root trait 'slow-fast' spectrum in herbaceous plants. Herbs with 'fast' leaf traits in high-temperature areas have more marginal niche positions, while this pattern is not significant in low-temperature areas.

The leaf 'slow-fast' spectrum was mainly associated with phylogenetics and temperature niche. While both root trait spectra were mainly controlled by phylogenetics (Figure S4, Table S5). Phylogenetics and temperature explained 31.4% and 8.6% of the total variation in the leaf trait 'slow-fast' spectrum, respectively. Species with 'fast' strategy leaf traits had narrower temperature niche breadths and more marginal temperature niche positions. The root trait spectra, however, were not correlated climate and soil niches. Rather, the phylogenetic relationship explained 27.7% of the total variation in the root trait 'slow-fast' spectrum, and 20.6% of the total variation in the root trait collaboration spectrum.

All of the leaf and root trait spectra of herbaceous plants were strongly related to their environmental niche. Temperature and precipitation niches explained 15% of the variation in the leaf trait slow-fast spectrum of herbaceous plants. Similarly, precipitation and soil nutrient niches explained 67.1% and 25.1% of the variation in the root trait 'slow-fast' spectrum and collaboration spectrum in herbaceous plants, respectively. In woody plants, however, all of the trait spectra were more related to their phylogenetic relationship (Figure 4, Table S5), which explained over 60% of parameter estimates of leaf and root trait spectra in woody plants.

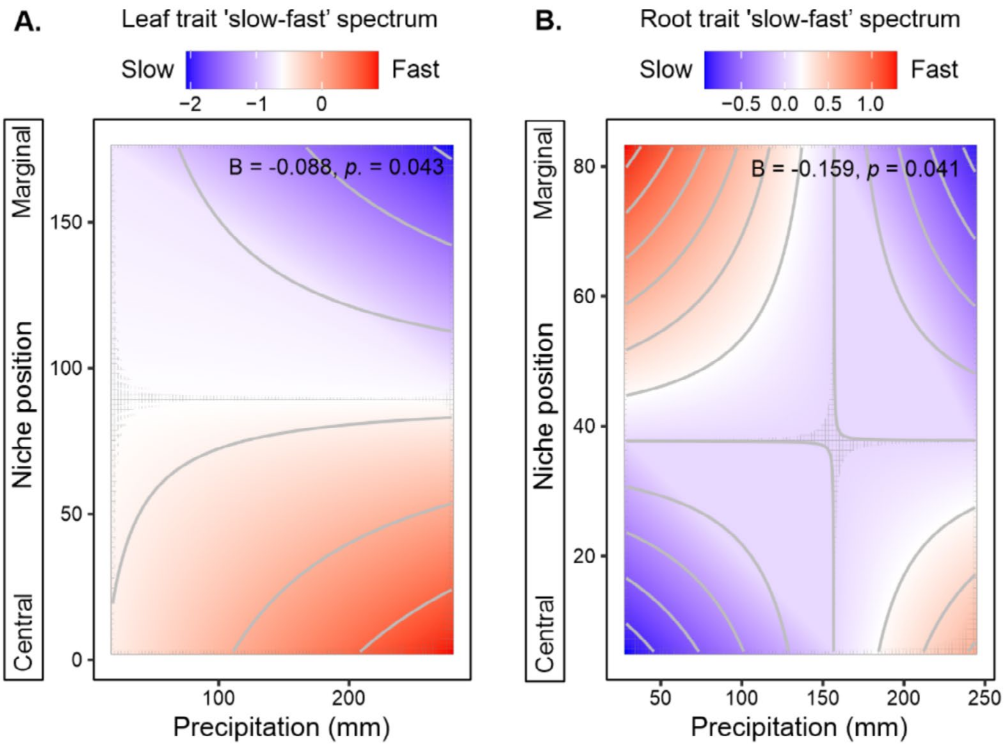

FIGURE 3 | Heat map of interaction effect between niche position and precipitation on trait 'slow-fast' spectrum. The colour band represents the prediction of niche position or precipitation on the leaf (A) and root (B) trait 'slow-fast' spectrum. The deeper the red colour, the larger the expected trait spectra values; the deeper the blue colour, the smaller the expected trait spectra values. B and *p* respectively show the standardised regression coefficients and significance levels when using the interaction between precipitation and niche position (precipitation × niche position) predicting trait spectra based on phylogenetic regression.

4 | Discussion

4.1 | Synchronisation Between Species Traits and Niche

Our results show the synergistic evolution between species' leaf and root trait slow-fast spectra and their environmental niches. Related species tend to share similar traits and niche positions, which follows from the phylogenetic niche conservatism hypothesis (PNC, Wiens et al. 2010). New species originating from the same ancestor may, under certain conditions, share a similar geographical distribution and undergo similar climatic processes during species formation, especially if their divergence occurs in the same region and over a short evolutionary timescale (Qiao et al. 2024). However, geographic isolation, adaptive radiation, or differing climatic histories can lead to substantial variation in these patterns (Anacker and Strauss 2014).

We found that root traits, whether on the 'slow-fast' spectrum or the collaboration spectrum, are more phylogenetically conservative and relatively independent of environmental niches. Considering the consistency between the trait spectra of leaves, stems and roots (Liu, Yang, et al. 2025; Weigelt et al. 2021), the root 'slow-fast' spectrum may play a more important role in the overall plant economics spectrum than the leaf 'slow-fast' spectrum (Da et al. 2025). Compared to leaf traits, root traits are often not only related to climate (Zadworny et al. 2016) but are directly involved in soil biochemical processes (McCormack et al. 2015). However, the highly conservative evolution of the root traits may mask the relationship between the environment and the roots. Root traits are widely recognised as having strong phylogenetic signals (Valverde-Barrantes et al. 2017), and root morphological traits are usually highly conserved (Liu et al. 2019), as are the cellular mechanisms that construct the morphology (Zhang et al. 2024). The variation and distribution patterns of root traits may have been influenced by their ancestors and paleoclimate in the early stages of species evolution (W. Chen et al. 2013; Ma et al. 2018). Moreover, root and leaf traits face different evolutionary pressures because the soil conditions are relatively more stable compared to climatic conditions (Ge et al. 2025; Kembel and Jr 2011). Hence, reconstructing the evolution of the root trait 'slow-fast' spectrum with paleoclimate change in the future may be important for our understanding of the root-environment relationship.

4.2 | Growth Form Matters in the Trait-Niche Relationship

The relationship between trait spectra and the niche varies between herbaceous and woody plants. The leaf trait 'slow-fast' spectrum of woody plants is related to their niche breadth and position. However, the phylogenetic relationship of traits rather than environmental constraints is the main indicator in predicting the trait spectrum-niche relationship of woody plants. The leaves of woody plants have a slower differentiation rate and higher conservation compared to herbaceous plants, so their response to the environmental niche is not strong (Flores

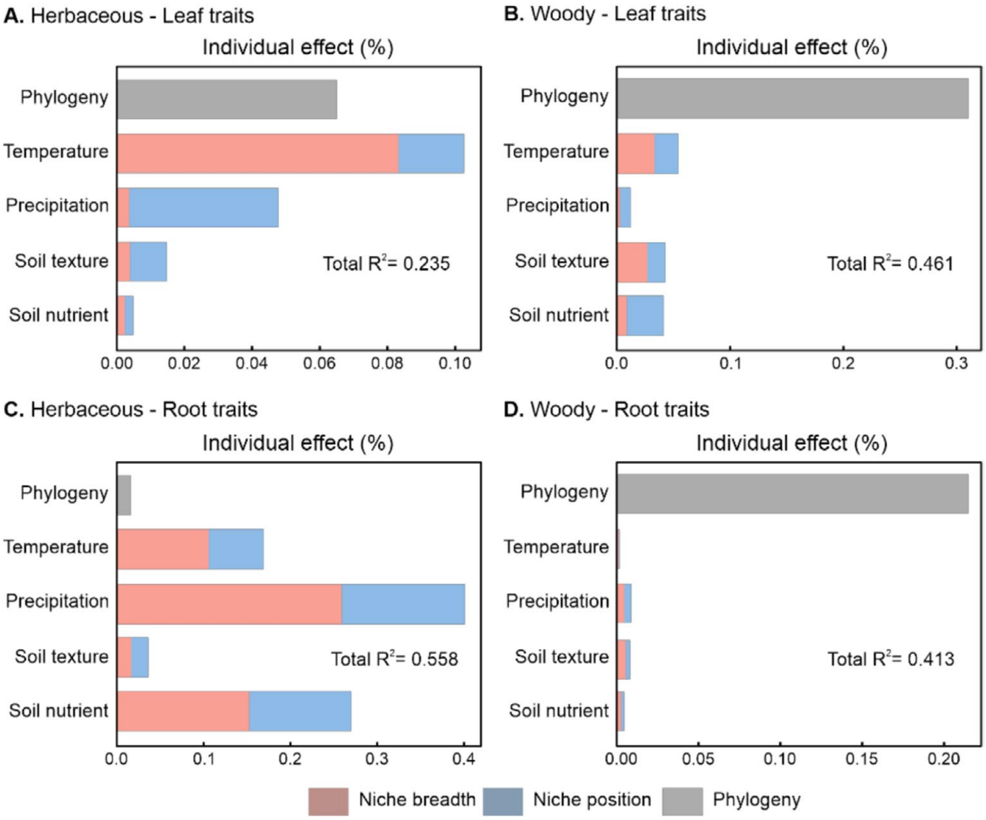

FIGURE 4 | Results of hierarchical partitioning for the effects of environmental niche variables based on phylogenetic generalised least squares (PGLS), including temperature, precipitation, soil texture, and soil nutrient with both niche breadth and position, in explaining the variation of 'slow-fast' traits spectra. PGLS not only incorporates all niche factors to predict trait spectra, but also considers the impact of species phylogenetic relationships in explaining covariance. 'Slow-fast' traits spectra are calculated by (A) herbaceous species' leaf traits, (B) woody species' leaf traits, (C) herbaceous species' root traits, and (D) woody species' root traits. Total R^2 is presented on the right side of each panel. Each bar shows variance explained by the independent effects of each variable based on the 'phylolm.hp' package (Lai et al. 2025).

et al. 2014). On the contrary, leaf and root traits in herbaceous plants are mainly related to the environment. The slow-fast spectrum of root traits in herbaceous plants is related to their niche position. Precipitation and temperature niches are the main factors predicting the 'slow-fast' spectrum of herbaceous leaf traits, while climate and soil nutrients are related to the 'slow-fast' spectrum of herbaceous root traits. Herbaceous plant traits are usually more resilient to respond to environmental variations. For example, the biogeochemical niche of *Artemisia* populations can quickly respond to short-term genotypic variation and/or current environmental conditions (Liu, Yang, et al. 2025), while herbaceous plants rather than woody plants in savanna typically respond faster to changes in precipitation (Belovitch et al. 2023). Hence, the ecological niche of herbaceous plants may be an important direction for explaining the assembly and coexistence mechanisms of grassland communities.

4.3 | Traits-Niche Relationship Predicts the Plants Climate Adaptability

The leaf trait spectrum-niche position relationship is more significant in high precipitation areas. The intensity of the species trait spectrum-niche relationship gradually decreases along the precipitation gradient from wet to dry, showing the environmental filtering effect of precipitation on traits and species (Zuo et al. 2021). The leaf 'slow-fast' spectrum is highly sensitive to precipitation (Lindh and Manzoni 2021). Humid areas usually have stronger environmental heterogeneity and allow for the coexistence of species with both 'slow' and 'fast' strategies (van der Sande et al. 2024). Not only does community biodiversity increase, but intraspecific and interspecific variation in leaf traits also increase accordingly in relatively humid areas (Wang et al. 2022). The functional diversity and dispersion of leaf dry matter content and other traits related to the leaf 'slow-fast' spectrum in shrub communities increase with precipitation (Zuo et al. 2021). The decrease in precipitation may lead to species with specialised drought-tolerant traits driving community production and shifting the trait spectrum at the community level to a 'slow' strategy (Aoyama et al. 2023). Plants in arid areas with low precipitation are usually highly conserved and consistent in leaf traits related to resource acquisition (Liu, Kong, et al. 2025). Plants often specialise their leaf traits through evolution to adapt to arid air and soils to adapt to drought (Cui et al. 2020). For example, grasses in arid areas typically have shorter and smaller leaves (Baird et al. 2021).

The relationship between the root trait 'slow-fast' spectrum and niche position flipped along the precipitation gradient. Species with 'fast' root traits in arid areas may have more marginal niche positions. This result is contrary to our hypothesis that species with 'slow' strategies in arid areas can achieve marginal niche positions to survive. Some studies have found similar results; that is, the 'slow-fast' spectrum of root traits in plants under drought stress may have an 'inverse pattern', which is different from leaf traits (Carvajal et al. 2019). Root traits may shift towards 'fast' strategies to expand belowground water uptake under drought stress (Funk et al. 2024). Numerous experiments have shown that plants will produce higher root tissue density to efficiently uptake water under drought stress, while the opposite is true when water is abundant (Zhang et al. 2019). Meanwhile, the root nitrogen concentration of plants is also related to drought stress (Chandregowda et al. 2023). Roots accumulate more nitrogen to maintain metabolic activity and water uptake under drought stress (Oram et al. 2023). The relationship between the root trait 'slow-fast' spectrum and niche position in high precipitation areas is, however, consistent with our hypothesis. Species with 'fast' root traits gain central niche positions and wider range sizes (Brasil et al. 2025). The different responses of plant leaf and root trait spectrum and niche positions across precipitation gradients show the asynchronous response of aboveground and belowground traits to climate change and challenge the trade-off between traditional 'slow-fast' strategies patterns (Bricca et al. 2023; Laughlin et al. 2021). Incorporating the correlation of root water absorption into the 'slow-fast' strategy in the future will help us better understand the relationship between roots and the environment.

We did not find correlations between the root collaboration spectrum and ecological niche in our dataset. However, the precipitation gradient and niche position of the species can jointly predict their root collaboration spectrum. Mycorrhizal colonisation optimises the belowground resource uptake strategy of plants (Bergmann et al. 2020). Species with ectomycorrhizal (EcM) fungi can adapt to arid environments to establish marginal niche positions (Cosme 2023), while the relatively common distribution of arbuscular mycorrhizal (AM) fungi may reduce the limitations of plant dispersal and help achieve a wider niche breadth (Bennett and Classen 2020). However, the correlation between mycorrhizal colonisation and plant niche is also limited along the biogeographical pattern (Bennett and Classen 2020; Liu et al. 2024). The significant difference in precipitation preferences between AM and EcM plants in humid areas leads to niche differentiation (Liu et al. 2024), while in deglaciated areas, EcM fungi can help plants establish cold resistance and obtain a larger range size (Carteron et al. 2024). This pattern reflects the complex trade-offs of mycorrhizal collaboration as a composite trait under multiple influences such as plants, soil, microbiome and climate.

5 | Conclusions

Our research reveals a general relationship between trait spectra and species' niches. Firstly, the position of species in the leaf and root trait 'slow-fast' spectrum is consistent with their 'marginal-central' niche position, which will help us further understand diversity assembly based on niche and trait complementarity in the future (Wang et al. 2024). Furthermore, the relationship between trait spectra and species' niches was also related to the species growth form and the biomes in which they are located. The traits of herbaceous species were closely related to their ecological niche, while the traits of woody species were mainly constrained by phylogenetics. This difference helps us further understand the differences in species' responses to future climate change. Finally, the leaf trait 'slow-fast' spectrum is negatively correlated with species niche position. This pattern strengthens with increasing precipitation. However, the relationship between the root trait 'slow-fast' spectrum and niche position reverses with increasing precipitation. Different trait spectra may indicate different processes of species environmental adaptation and have different biogeographical patterns (Weigelt et al. 2021).

Author Contributions

Yuheng Chen: conceptualisation; data curation; formal analysis; methodology; visualisation; writing – original draft. **Yann Hautier:** conceptualisation; supervision; writing – review and editing. **George A. Kowalchuk:** resources; supervision; writing – review and editing. **Kathryn E. Barry:** conceptualisation; project administration; supervision; resources; writing – review and editing. All authors read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset and code used in the analyses have been uploaded to an open-source online database (https://doi.org/10.5281/zenodo.15777741).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** geb70115-sup-0001-DataS1.docx.