



REVIEW ARTICLE

Plant functional traits as indicators of forest management strategies and ecological resilience

Manish Singh^{1*}, Rajesh Joshi², Mithilesh Singh¹, Sumit Rai¹, Hukum Singh³, Bishnu Prasad Sahoo⁴, Gaurav Singh⁵, Prabal Kumar⁶ & Anil Kumar Kewat⁴

¹Center for Environmental Assessment and Climate Change, Govind Ballabh Pant National Institute of Himalayan Environment, Almora 263 643, Uttarakhand, India

²Govind Ballabh Pant National Institute of Himalayan Environment, Sikkim Regional Centre, Pangthang, Gangtok 737 101, Sikkim, India

³Plant Physiology Discipline, Forest Research Institute, P.O. New Forest, Dehradun 248 006, Uttarakhand, India

⁴Forest Ecology and Climate Change, Forest Research Institute, P.O. New Forest, Dehradun 248 006, Uttarakhand, India

⁵ICAR-Indian Institute of Soil and Water Conservation, Research Center, Anand 388 110, Gujarat, India

⁶Mountain Division (CS-1), Ministry of Environment, Forest and Climate Change, Jorbagh 110 016, New Delhi, India

*Correspondence email - manish.s92@gmail.com

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Abstract

Forests are complex socio-ecological systems that deliver key ecosystem services such as biodiversity conservation, water regulation, carbon storage and timber production. Increasingly, traditional timber-focused management is giving way to ecosystem-based approaches that incorporate plant traits into forest management plans. This shift supports biodiversity conservation, improves ecosystem resilience and promotes long-term forest health. Plant functional traits such as wood density, leaf size, root depth and specific leaf area, play a key role in regulating ecosystem processes and elucidating interactions between tree species and their environment. This review summarises current evidence that trait-based frameworks improve forest management, support climate change efforts and enhance ecosystem services. A structured literature search identified studies linking functional diversity to ecosystem stability, carbon sequestration, nutrient cycling and adaptability. By focusing on functional traits, this approach provides insight into how these traits influence ecosystem functions like carbon storage, nutrient recycling and habitat availability. Furthermore, practitioners can predict forest responses to climate change and other biotic and abiotic stresses by incorporating functional traits into forest management strategies, thereby fostering ecosystem services. Overall, integrating functional traits provides a robust framework for improving forest resilience, conserving biodiversity and balancing ecological health with economic goals in changing climate scenarios.

Keywords: ecosystem services; ecosystem sustainability; forest management; functional traits

Introduction

Forests are dynamic, complex ecosystems that deliver diverse goods and services to society (1). The ecosystem-based approach has emerged as a holistic framework that integrates forest functions and associated ecosystem services with traditional timber-focused forest management practices (2). However, plant functional traits not only regulate growth and development but also enhance species performance and contribute to the provision of ecosystem services, including carbon sequestration, biodiversity conservation and water cycling (3). The integration of functional traits into forest management plans is a key component of this transition (4), influencing both the effectiveness and cost-efficiency of specific ecosystem services (5). By understanding how functional traits respond to environmental conditions, forester managers can develop strategies to optimise the provision of desired ecosystem services (6).

Key functional traits are fundamental to biodiversity

conservation, enabling forest managers to enhance ecosystem services and support sustainable forest management practices (Fig. 1). Tree growth rates play a crucial role in climate change mitigation by directly influencing carbon sequestration potential. In contrast, wood density contributes to structural stability in forests and enhances resilience to disturbances (7, 8). Leaf traits influence key processes such as nutrient cycling, photosynthesis and water-use efficiency, thereby regulating ecosystem functioning, while reproductive traits are vital for biodiversity conservation and species persistence (9, 10). Leaf traits such as leaf nitrogen content, specific leaf area (SLA) and leaf longevity are widely used to characterise nutrient cycling, drought resilience and plant photosynthetic capacity (10). Field measurement of SLA typically involves collecting leaves from representative trees and determining leaf area using a leaf area meter or scanning techniques. Leaf nitrogen content is quantified using established laboratory methods, such as Dumas combustion or the Kjeldahl method (3). Careful consideration should be given to the selection of representative leaves to minimise sampling bias, as well as

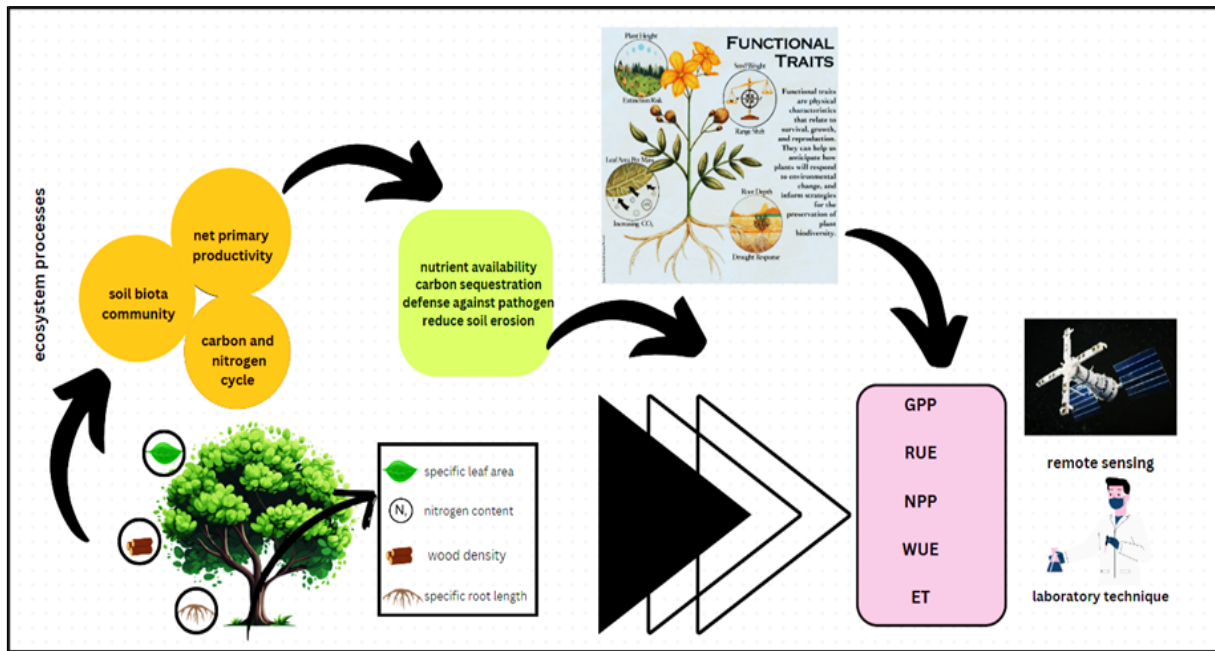


Fig. 1. Conceptual framework illustrating the role of plant functional traits in ecosystem functioning.

to the inclusion of multiple growth stages to capture variability across plant species (8, 10). Wood traits such as wood density, growth and their mechanical properties are important parameters for assessing ecosystem stability, forest biomass and carbon storage (3, 11–13). Furthermore, root traits such as root–shoot ratio, depth and biomass, regulate water and nutrient uptake and help explain plant survival strategies (14). Reproductive traits such as phenology, seed size and dispersal mechanisms, provide important insights into forest regeneration potential and plant reproductive strategies (15, 16). Phenological traits, including flowering, fruiting and leaf fall, are particularly important for understanding plant responses to disturbances across diverse environmental conditions. These traits are typically assessed through periodic monitoring of phenological events in marked trees, such as leaf senescence, flowering, fruiting and bud dormancy, enabling accurate evaluation of climatic variability (13, 16).

Plant functional traits encompassing physiological, morphological and phenological characteristics, provide a basis for

ecosystem-based interventions, guiding forest managers in species selection, biodiversity conservation and overall ecosystem management (Fig. 1). Additionally, plant functional traits constitute a critical component of management plans, as dominant species within a community largely regulate ecosystem processes and functions. Focusing on the functional traits of dominant species provides forest managers with valuable insights into ecosystem dynamics and informs effective management strategies (17), as summarised in Table 1.

Functional diversity, defined as the range of functional traits within a community, is a key determinant of ecosystem functioning. Higher functional diversity is generally associated with greater ecosystem stability and resilience, while specific traits such as leaf area, serve as indicators of plant responses to changing environmental conditions. For example, studies across North and South America have demonstrated considerable variation in functional diversity and distinctiveness among different biomes, reflecting diverse adaptive strategies among plant species. These findings highlight that

Table 1. Methods for assessing plant functional traits and their applications in forest management

Method	Description	Examples of use	Strengths	Limitations	References
<i>In situ</i> measurement technique	Direct measurement of functional traits (e.g., leaf size, wood density, tree height, biomass)	Measuring tree height for species	Accuracy, site-specific data	Labor-intensive, time-consuming	(18)
Remote sensing	Use of drones, satellites or LIDAR to assess canopy structure	Canopy height and NDVI via satellites	high efficiency, covers extensive area	Limited resolution, expensive	(19)
Functional trait databases	Using existing trait data (e.g., TRY database)	Assessing leaf area index	Saves time and effort	May lack local specificity	(20)
Ecophysiological models	Simulations of traits and performance under varying conditions	Modelling water use efficiency	Predicts responses to changes	Requires high-quality input data	(21)
Plant functional traits (PFTs)	Grouping species with similar functional traits (e.g., drought tolerance)	Monitoring drought-tolerant species	Simplifies analysis and planning	It does not give detailed information about loss of individual species.	(22)
Community weighted methods (CWM)	Calculates weighted averages of traits based on species abundance	CWM for leaf nitrogen concentration	Quantifies community-level traits	Rely on specific data	(23)
Functional diversity indices	Metrics like functional richness, divergence or evenness	Assessing trait diversity in forests	Measures ecosystem stability and resilience	Complex calculation, needs trait data	(24)
Tree inventory data	Combines tree species identification and basic measurements	Plot-based tree diameter data	Widely available, standardised	Limited data available	(25)
Soil and environmental surveys	Traits inferred based on environmental factors (e.g., soil type, moisture)	Linking wood traits to soil moisture	Links traits to habitat conditions	Assumption based	(26)

incorporating functional traits into forest management plans can enable managers to design more effective, ecosystem-based interventions (27).

Methodology

A comprehensive literature search was conducted using Google Scholar, Crossref, SpringerLink and PubMed, without bias towards journal impact factor, review policy or indexing status. The search employed the keywords “plant functional traits”, “forest management” and “ecological resilience”, with Boolean operators (AND, OR) applied to refine the results. The search was not restricted by publication year but was limited to articles published in English. The initial search yielded a substantial number of records (Table 2), including 1104 from Crossref, 4 from PubMed and 100 from Google Scholar. In the second stage, studies were screened based on titles and abstracts for relevance to plant functional traits in forest ecosystems and associated climatic factors, as well as for the inclusion of original data or comprehensive reviews. Non-English studies and those focused on aquatic ecosystems were excluded. Of the 1104 records identified, 1064 were excluded after title and abstract screening. After removing duplicates, 40 items from the remaining literature were selected for the qualitative synthesis (Fig. 2). A word cloud was generated based on the frequency of terms identified during the literature search (Fig. 3). The visualisation indicates that terms such as carbon, biomass, sequestration, forest management and functional traits were among the most frequently occurring across the selected literature. This pattern reflects the strong emphasis on ecosystem service demands, particularly those related to carbon dynamics and forest management.

Plant silicon as an adaptation to stress in the ecosystem

Silicon plays a key role in plant physiology, influencing community assembly, species composition and plant–environment interactions (Fig. 4). High grazing intensity has been shown to increase silicon accumulation in grasses; however, herbivores such as locusts preferentially consume low-silicon grasses, reducing their biomass and abundance relative to high-silicon accumulators (41). Silicon availability also promotes the establishment of grass vegetation in estuarine and tidal marsh ecosystems (42).

A theoretical model of pasture succession suggests that calcium-rich conditions initially favour legumes (43). Over time, calcium is leached while silicon accumulates, shifting dominance towards grasses. Silicon uptake varies among taxa, influencing species dominance, environmental adaptation (44) and herbivory responses (45). Herbivores generally prefer low-silicon species (44–46) and show reduced growth in high-silicon environments, thereby favouring species adapted to silicon-rich diets (47, 48).

Applications of functional traits in forest management

Functional traits provide insights into species performance and environmental interactions, enhancing biodiversity, ecosystem resilience, sustainability and resource-use efficiency. The detailed application of functional traits in management plans is discussed in Tables 3 and 4.

Root-level traits

Root-level traits such as root depth, nutrient uptake capacity and belowground biomass, govern a plant's ability to access soil, withstand drought and compete under resource limitation. Deeper and more extensive root systems enhance access to stable water sources and improve resilience under climate variability,

while nutrient uptake traits influence nitrogen and phosphorus acquisition and soil-plant feedbacks. The strategies below directly affect carbon allocation patterns and ecosystem processes, such as soil carbon storage and nutrient cycling. Nutrient uptake traits determine how plants acquire nitrogen and phosphorus and interact with soil systems. These mechanisms influence carbon use and key ecosystem functions, including soil carbon sequestration and nutrient cycling. Root traits define the physiological constraints on leaf and stem characteristics and should therefore be prioritised when classifying plant functional types (52).

Leaf-level traits

Leaf-level traits such as SLA, leaf area, leaf nitrogen content, photosynthetic rate, stomatal density, leaf water potential, leaf toughness and water-use efficiency regulate carbon assimilation, biomass production and short-term physiological processes. Higher SLA and nitrogen content are generally associated with rapid photosynthesis and fast growth but shorter tissue lifespan, whereas low SLA and tougher leaves reflect conservative strategies that enhance stress tolerance and longevity (37). These trade-offs underpin the globally recognised “leaf economics spectrum”, which describes coordinated variation in leaf structure, chemistry and function across species and environments. As leaves mediate energy capture and directly influence productivity and carbon cycling, they represent the second hierarchical level after roots (8, 10).

Wood/stem-level traits

Wood (stem)-level traits such as wood density, diameter at breast height (DBH) and canopy height-reflect mechanical support, hydraulic conductivity and carbon storage capacity. High wood density, typically associated with slower growth, confers greater structural stability and disturbance resistance, whereas lower density supports rapid growth. These traits represent life-history strategies linked to survival, resilience and ecosystem carbon sequestration, while also influencing forest architecture and light interception, thereby scaling individual physiology to stand-level functioning (13).

Conventional conservation approaches often emphasise species richness alone; however, integrating functional traits provides a more robust basis for ensuring ecosystem stability. Functional traits enable forest managers to identify nitrogen-fixing species that enhance soil fertility and to prioritise conservation in ecosystems at risk of degradation, linking biodiversity directly to ecosystem services such as water filtration and pollination (53). These traits regulate key ecosystem processes, including carbon sequestration, water regulation and nutrient cycling, thereby improving the delivery of ecosystem services. For instance, species with larger leaf areas generally exhibit higher carbon assimilation potential, while deeper root systems enhance drought tolerance and soil water retention (54).

Functional trait-based approaches also support the design of resilient plantations by combining fast-growing species with slow-growing, resource-efficient species, thereby balancing productivity with ecological stability. Traits such as SLA, seed size and wood density guide the selection of species suited to local environmental conditions. Species with high SLA are typically fast-growing and suitable for rapid canopy recovery on degraded lands (13), whereas species with higher wood density are better suited to wind- or snow-prone environments (7). Integrating traits such as

Table 2. Studies on plant functional traits in forest management and ecological resilience

Research title	Forest type	Species/family	Location	Functional traits	Data analysis method	Reference
Plant functional traits and environmental conditions shape community assembly and ecosystem functioning during restoration	Tallgrass prairies	Various <i>Prairie</i> species	Michigan	SLA, leaf N, plant height	Structural equation modelling	(28)
Plant functional traits differ in adaptability and are predicted to be differentially affected by climate change	Eucalyptus woodlands	<i>Corymbia calophylla</i>	Australia	Leaf size, SLA, wood density, N	Mixed-effects models	(29)
Plant functional groups and species contribute to ecological resilience a decade after woodland expansion treatments	Sagebrush steppe	<i>Artemisia, Chrysothamnus, Purshia, Festuca</i>	USA	Cover change, resilience metrics	Long-term field experiments	(30)
Simulating forest resilience: a review	Global forest types	Not specified	America and Europe	Not specified	Review of simulation models	(31)
Resilience of Amazon forests emerges from plant trait diversity	Amazon rainforests	Amazonian tree species	Amazon	Trait diversity, ecological sorting	Biogeochemical modelling	(32)
Plant functional traits as measures of ecosystem service provision	Various ecosystems	Multiple species	Canada	Leaf area, wood density, N content	Literature review	(33)
Unleashing the power of plant structural and functional diversity: from common observations to theory and management models	Agroforestry systems	Various tree species	Europe	Structural & functional diversity	Framework/modelling	(34)
Implications of plant functional traits and drought survival strategies for ecological restoration.	Mediterranean ecosystems	Shrubs and trees	California	Leaf area, root depth, WUE	Field-based drought assessment	(35)
The role of topography and plant functional traits in determining tropical reforestation success	Tropical forests	Various tropical species	Australia	Root adaptations, nutrient acquisition traits	Field experiments across topographical gradients	(36)
Coordination of leaf functional traits under climatic warming in an arid ecosystem	Arid ecosystems	Dominant arid plant species	China	Leaf area, SLA, photosynthetic rates	Field warming experiments	(37)
Plant species richness and functional traits affect community stability after a flood event	Temperate grasslands	Various grassland species		Plant height, leaf size, root depth	Post-flood biomass and trait analysis	(38)
Functional diversity enhances tree growth and reduces herbivory damage in secondary broadleaf forests, but does not influence drought resilience	Secondary broadleaf forests	Beech (<i>Fagus sylvatica</i>) and associated species	Spain	Wood density, leaf toughness and growth rates	Comparative analysis	(39)
Low- to moderate-level forest disturbance effects on plant functional traits and associated soil microbial diversity in Western Himalaya	Subtropical forests	Native Himalayan species	India	Leaf area, SLA, plant height	Assessment under disturbance levels	(40)

Table 3. Plant functional traits: ecological significance and methods of field and laboratory assessment

Trait	Category	Definition/Ecological meaning	Measurement method	Field/Lab based
Specific leaf area (SLA)	Leaf	Leaf area per unit dry mass; indicates growth rate and resource-use strategy	Measure fresh leaf area using leaf area meter/scanner → oven dry → weigh → area/dry mass	Field + Lab
Leaf area/leaf size	Leaf	Photosynthetic surface influencing carbon gain and water loss	Leaf area meter or image analysis of scanned leaves	Field + Lab
Leaf nitrogen content	Leaf	Indicator of photosynthetic capacity and nutrient cycling	Dumas's combustion or Kjeldahl digestion for %N	Lab
Leaf water potential	Leaf	Plant water stress indicator	Pressure chamber (Scholander type)	Field/Lab instrument
Stomatal density	Leaf	Regulates gas exchange and transpiration	Leaf impressions/microscopy counting	Lab
Photosynthetic rate	Leaf	Carbon assimilation capacity	Portable photosynthesis system (IRGA)	Field
Leaf toughness	Leaf	Resistance to herbivory/mechanical damage	Penetrometer or force gauge	Lab/Field
Growth rate	Whole plant	Biomass accumulation over time	Repeated diameter at breast height (DBH)/height or biomass measurements	Field
Biomass (aboveground/belowground)	Whole plant	Productivity and carbon storage	Harvest/dry weight or allometric equations	Field + Lab
Wood density	Stem	Mass per unit volume; relates to strength and carbon storage	Core sample → volume displacement → oven dry weight	Lab
Tree diameter (DBH)	Stem	Proxy for growth and biomass	Diameter tape at 1.3 m height	Field
Root depth	Root	Access to water/nutrients; drought tolerance	Soil excavation, coring or trench method	Field
Nutrient uptake traits	Root	Ability to acquire soil nutrients	Soil-plant nutrient assays	Lab
Water use efficiency (WUE)	Physiological	Carbon gain per unit water loss	Gas exchange or carbon isotope analysis ($\delta^{13}\text{C}$)	Field + Lab
Silicon accumulation	Defense	Herbivore/stress defense strategy	Tissue digestion + elemental analysis	Lab
Canopy structure/height	Structural	Stand-level productivity and light interception	LiDAR, drones, satellite or ground surveys	Remote sensing + Field
Phenology (flowering/fruiting/leaf fall)	Reproductive	Timing of life-cycle events; climate response	Periodic visual monitoring/recording	Field
Seed size	Reproductive	Dispersal ability and establishment strategy	Caliper/weight measurement	Lab
Trait diversity metrics (CWM, functional richness, evenness, divergence)	Community	Community-level functional composition	Statistical calculations from species trait data	Analytical

Table 4. Multidisciplinary applications of plant functional traits

Application of functional traits	Example	Uses	References
Identification of functional traits best suited for future climate change adaptation	Phenology and water tolerance	Climate change adaptation studies	(16)
Reintroduction of species having carbon storage and water filtration ability	Structure of the root and water tolerance	Used mainly in wetland restoration	(49)
Management of habitat for ecosystem sustainability	Growth rate and reproductive strategies	Used in fisheries	(50)
Protection of species based on ecological processes	Mechanism of pollination and its dispersal	Used in conservation biology studies	(51)
Forest restoration plans and sustainable harvesting	Seed dispersal and wood density	Forestry	(26)
Selection of different high-yielding crop varieties and their resilience to abiotic stresses	Drought tolerance, salt tolerance	Used in agricultural studies	(18)
Enhancement in ecosystem services	Plant height and nutrient content	Used in grassland management strategies	(23)

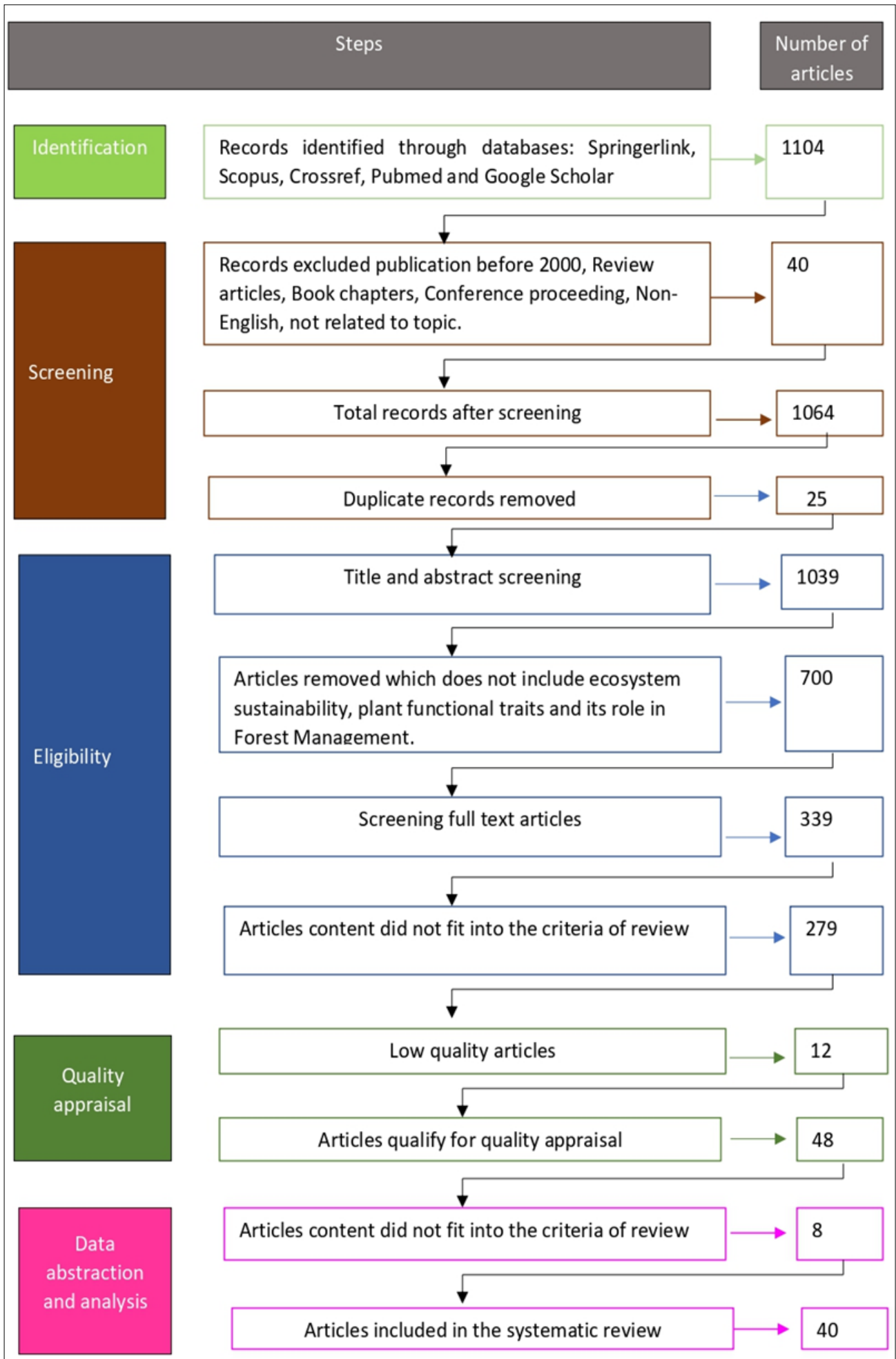


Fig. 2. Flow diagram of the literature search and study selection process for the systematic review.

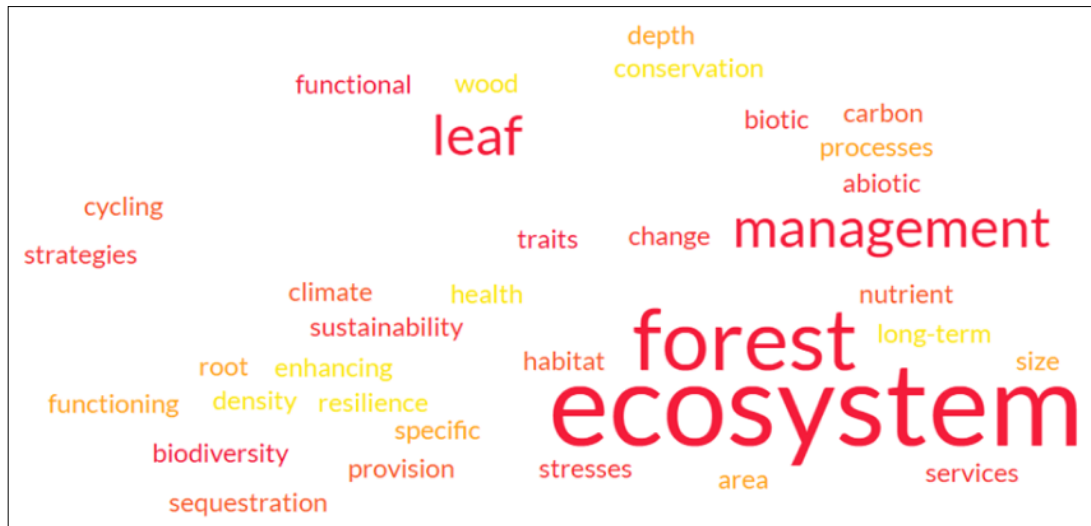


Fig. 3. Word cloud showing the frequency of terms identified during the literature search.

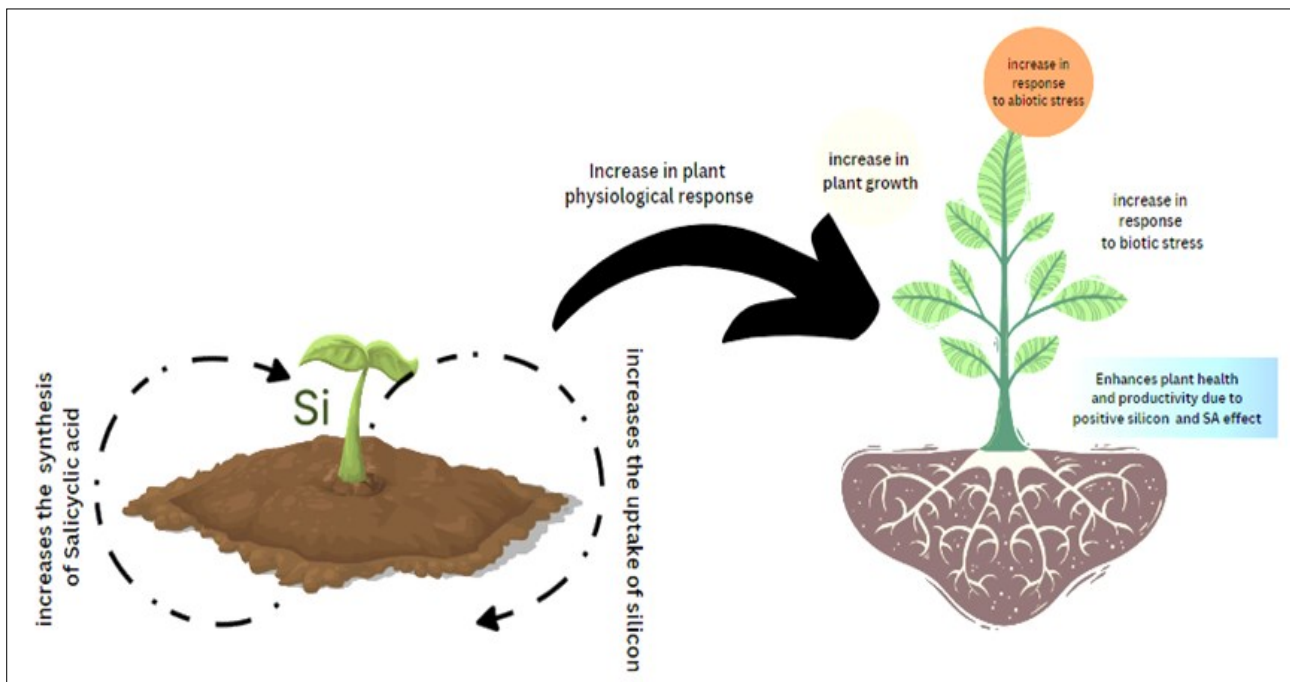


Fig. 4. Role of silicon in plant physiological responses.

leaf water potential and stomatal density further enables the assessment of drought resilience. Collectively, these traits provide a predictive framework for evaluating forest responses to environmental stresses including pests, diseases and climate change allowing managers to anticipate risks and implement effective interventions (55).

In production-oriented forests, balancing timber yield with ecosystem health is essential to sustain multiple ecosystem services, including carbon sequestration, nutrient cycling and habitat provision. Wood density and growth rate are key indicators of timber quality and inform harvesting strategies, while species with strong resprouting capacity support rapid regeneration following selective logging. Overall, integrating plant functional traits offers a mechanistic framework that links species growth, resource-use efficiency and stress tolerance to management outcomes, enabling the selection of species or trait combinations that simultaneously optimise timber production and ecosystem stability (7).

Invasive plants in sub-Saharan Africa: ecosystem disruption, disease risk and functional trait-based management

Several studies have documented the widespread and detrimental impacts of invasive alien plants (IAPs) in sub-Saharan Africa, significantly affecting biodiversity, livelihoods and ecosystem integrity. These species release secondary metabolites or allelopathic compounds that alter soil physicochemical properties, including soil organic matter, microbial communities and nutrient availability. For example, *Acacia melanoxylon* and *Acacia mearnsii* have been shown to modify nutrient cycling and increase soil nitrogen levels.

The rise of IAPs driven by climate change and anthropogenic activities, has made sub-Saharan Africa highly susceptible to invasions. Forest managers use plant functional traits linked to resilience and recovery to predict climate responses, control invasions and maintain ecosystem services. Invasive species proliferation reduces native biomass, disrupts ecosystem functioning and diminishes economic value (17, 27).

Furthermore, IAPs can influence disease transmission in sub-Saharan Africa by providing suitable habitats for disease

vectors and facilitating vector–plant interactions. For example, the malaria vector *Anopheles gambiae* exhibits increased energy reserves and fitness when feeding on plant species such as *Bidens pilosa*, *Ricinus communis* and *Parthenium hysterophorus* (56–64). These interactions may elevate the risk of arbovirus transmission.

Effective management of invasive plants requires integrating appropriate management strategies with knowledge of functional traits and remote sensing technologies. These approaches enable the detection and analysis of high-resolution imagery and plant functional traits, supporting the identification, monitoring and early intervention of invasive species before they spread (65).

Different approaches to improve the effects of plant functional traits in response to ecosystem functioning

Individual-level trait measurement

Accounting for intraspecific variability is essential for improving the prediction of functional traits, as it strongly influences community dynamics and ecosystem functioning (66). At the individual level, tree height and growth rate are closely correlated, and interspecific variation in these traits drives the effects of aboveground biodiversity on specific root length (67). Similarly, variation in individual-level traits of phytoplankton influences biomass production and resource-use efficiency (68). Therefore, incorporating intraspecific variability is critical for accurately predicting ecosystem functioning.

Selection of singular and multiple trait functional diversity

Relationships between plant traits and ecosystem functions are often weak when assessed solely using traditional community-weighted approaches. To address this limitation, trait abundance distribution methods are employed to characterise the frequency distribution of functional traits within a community. These approaches incorporate higher-order moments—such as variance, skewness and kurtosis—alongside the community-weighted mean. By capturing trait variability and distribution shape, these metrics complement the mean and provide deeper insights into community structure and the role of dominant species (69).

These distributions enhance the predictive accuracy of plant traits for ecosystem functioning, as variance and kurtosis show functional divergence and evenness and skewness represent the trait distribution asymmetry (69). Though, skewness and kurtosis account for 38 % of the variation in multifunctionality for SLA and maximum plant height, which exceeds the 15 % explained by mean and variance, respectively (69). These findings highlight the need to incorporate skewness and kurtosis, which have high predictive power of multifunctionality.

Functional diversity has emerged as a key driver of ecosystem functioning, comprising three components: functional divergence, functional richness and functional evenness (24, 70). However, various mathematical-based algorithms, such as distance and hypervolume, have been developed to delineate the trait space occupied by species. Therefore, careful consideration of functional diversity indices is recommended when selecting traits to enhance predictive power for ecosystem functioning (71, 72).

Challenges and limitations

Integration of functional traits into management plans is very challenging as their interactions operate from individual trees to entire landscapes. It is necessary to adopt multi-level and spatial resolutions to integrate these ecosystem services into useful

forest products (5, 73). Another challenge is context-dependent relationships between functional traits and ecosystem services, which can vary across environmental conditions and forest types (4). Therefore, forest managers should carefully adhere to these context-dependent relationship and their management practices. Additionally, public and stakeholder participation is crucial for integrating these practices, which bring together diverse perspectives and engagement and can enable forest managers to plan trade-offs among various ecosystem services effectively (4). Several challenges arise during the analysis of plant functional traits, including measurement error, environmental error and trait plasticity.

Measurement error: Minor errors in estimating traits such as SLA or biomass are common and can substantially affect assessments. Ensuring precision and sufficient replication is therefore critical for reliable results.

Environmental context: Incorporation of variability in environmental conditions is necessary to interpret lab-based data, as plant functional traits may vary with different environmental conditions, such as soil fertility and water availability (8).

Trait plasticity: Plant functional traits can exhibit plasticity in response to environmental factors such as SLA and nitrogen content, which can complicate the interpretation of data (10).

Context dependency is a major challenge as plant functional traits and ecosystem services often vary across forest types, environmental conditions and disturbance regimes. The same trait may confer different or even opposing benefits depending on context. For example, high SLA promotes rapid growth and productivity in moist, nutrient-rich sites but increases water loss and mortality under drought. Similarly, low wood density supports rapid biomass accumulation in plantations but increases vulnerability to hydraulic failure and wind damage in stress-prone environments, whereas deep roots enhance drought tolerance in arid soils but provide limited advantage in waterlogged or shallow soils (4, 8).

Future perspectives and research directions

Integrating functional traits into forest management plans highlights the need to address existing knowledge gaps and strengthen trait-based applications. For underrepresented species across boreal and tropical regions (20), global trait databases such as the TRY database, should incorporate traits relevant to ecosystem functioning and management, including pest resistance, drought tolerance and carbon sequestration potential. This underscores the importance of integrating functional traits and their responses to environmental drivers, including soil variability, climate change and anthropogenic disturbances.

Engaging policymakers and ecological stakeholders in trait-based frameworks can advance ecological sustainability and resource-use efficiency, ensuring forests meet both ecological and societal demands (53). Future research should prioritise integrating these traits into restoration, ecosystem management and climate adaptation strategies to enhance resilience to abiotic and biotic stresses such as drought, pests and fire, while informing species selection for restoration and afforestation programmes (55).

Advances in remote sensing and machine learning further support large-scale trait mapping, enabling efficient monitoring and assessment of forest ecosystems (74).

Conclusion

Integrating plant functional traits such as specific leaf area (SLA), root biomass, wood density and nutrient content into forest management provides a robust, ecosystem-based framework for enhancing resilience, productivity, biodiversity conservation and sustainable forest management. Trait-based approaches enable informed species selection, optimise forest composition and align management strategies with environmental conditions by linking plant characteristics to growth, resource use and disturbance responses. These approaches also improve the prediction and delivery of ecosystem services, including carbon sequestration, water regulation and biodiversity conservation, thereby supporting the balance between ecological integrity and economic objectives.

Despite challenges associated with phenotypic plasticity, variability in trait datasets and the integration of ecological, climatic and socio-economic dimensions, functional trait-based frameworks offer significant potential for advancing adaptive forest management. Their incorporation into restoration, afforestation and climate adaptation strategies will be critical for ensuring forest sustainability under changing environmental conditions.

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Authors' contributions

MS¹ contributed to data curation, investigation, formal analysis, software and writing - original draft. RJ contributed to conceptualisation, supervision, visualisation and writing - review and editing. MS² contributed to conceptualisation, supervision, methodology and writing - review and editing. SR is involved in formal analysis, software and writing - original draft. HS and BPS contributed to visualisation and writing - review and editing. GS and PK contributed to conceptualisation and supervision. AKK participated in data curation, formal analysis and writing - review and editing. All authors read and approved the final manuscript. [MS¹ stands for Manish Singh and MS² stands for Mithilesh Singh].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

- Chamberlain JL. Sustainable forest management beyond the timber-oriented status quo: transitioning to co-production of timber and non-wood forest products-a global perspective. *Curr For Rep.* 2020;6:26–40. <https://doi.org/10.1007/s40725-019-00107-1>
- Nijnik M, Miller D. Targeting sustainable provision of forest ecosystem services with special focus on carbon sequestration. *Dev Environ Sci.* 2013;13:547–68. <https://doi.org/10.1016/B978-0-08-098349-3.00025-6>
- Cornelissen JH, Lavorel S, Garnier E, Díaz S, Buchmann N, Gurvich DE, et al. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Aust J Bot.* 2003;51:335–80. <https://doi.org/10.1071/BT02124>
- Felton A, Nilsson U, Sonesson J, Felton AM, Roberge JM, Ranius T, et al. Replacing monocultures with mixed-species stands: ecosystem service implications of two production forest alternatives in Sweden. *Ambio.* 2016;45:124–39. <https://doi.org/10.1007/s13280-015-0749-2>
- Baskent EZ, Borges JG, Kašpar J, Tahri M. A design for addressing multiple ecosystem services in forest management planning. *Forests.* 2020;11:1108. <https://doi.org/10.3390/f11101108>
- Zhou D, Ni Y, Yu X, Lin K, Du N, Liu L, et al. Trait-based adaptability of *Phragmites australis* to the effects of soil water and salinity in the Yellow River Delta. *Ecol Evol.* 2021;11:11352–61. <https://doi.org/10.1002/ece3.7925>
- Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. Towards a worldwide wood economics spectrum. *Ecol Lett.* 2009;12:351–66. <https://doi.org/10.1111/j.1461-0248.2009.01285.x>
- Sterck FJ, Poorter L, Schieving F. Leaf traits determine the growth-survival trade-off across rain forest tree species. *Am Nat.* 2006;167:758–65. <https://doi.org/10.1086/503056>
- Westoby M, Falster DS, Moles AT, Vesk PA, Wright IJ. Plant ecological strategies: some leading dimensions of variation between species. *Annu Rev Ecol Syst.* 2002;33:125–59. <https://doi.org/10.1146/annurev.ecolsys.33.010802.150452>
- Wright IJ, Reich PB, Westoby M, Ackerly DD, Baruch Z, Bongers F, et al. The worldwide leaf economics spectrum. *Nature.* 2004;428:821–7. <https://doi.org/10.1038/nature02403>
- Grime JP. *Plant strategies, vegetation processes and ecosystem properties.* Chichester: John Wiley & Sons; 2006.
- Shipley B, Vile D, Garnier E. From plant traits to vegetation structure: chances and challenges for functional plant ecology. *Ecology.* 2006;87:183–90. <https://doi.org/10.1890/05-0822>
- Poorter L, McDonald I, Alarcón A, Fichtler E, Licona JC, Peña-Claros M, et al. The importance of wood traits and hydraulic conductance for the performance and life history strategies of 42 rainforest tree species. *New Phytol.* 2010;185:481–92. <https://doi.org/10.1111/j.1469-8137.2009.03092.x>
- Körner C. Concepts in empirical plant ecology. *Plant Ecol Divers.* 2018;11:405–28. <https://doi.org/10.1080/17550874.2018.1540021>
- Aerts R. The advantages of being evergreen. *Trends Ecol Evol.* 1995;10:402–7. [https://doi.org/10.1016/S0169-5347\(00\)89156-9](https://doi.org/10.1016/S0169-5347(00)89156-9)
- Lavorel S, Garnier E. Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Funct Ecol.* 2002;16:545–56. <https://doi.org/10.1046/j.1365-2435.2002.00664.x>
- Gillison AN. Plant functional types and traits at the community, ecosystem and world level. In: van der Maarel E, Franklin J, editors. *Vegetation ecology.* Chichester: Wiley-Blackwell; 2013. p. 347–86. <https://doi.org/10.1002/9781118452592.ch12>
- Perez-Harguindeguy N, Diaz S, Garnier E, Lavorel S, Poorter H, Jaureguiberry P, et al. Corrigendum to: New handbook for standardised measurement of plant functional traits worldwide. *Aust J Bot.* 2016;64:715–6. https://doi.org/10.1071/BT12225_CO
- Asner GP, Martin RE, Anderson CB, Knapp DE. Quantifying forest canopy traits: imaging spectroscopy versus field survey. *Remote Sens Environ.* 2015;158:15–27. <https://doi.org/10.1016/j.rse.2014.11.011>
- Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, et al. TRY plant trait database-enhanced coverage and open access. *Glob Chang Biol.* 2020;26:119–88. <https://doi.org/10.1111/gcb.14904>
- Ruehr NK, Grote R, Mayr S, Arnoeth A. Beyond the extreme: recovery of carbon and water relations in woody plants following heat and

- drought stress. *Tree Physiol.* 2019;39:1285–99. <https://doi.org/10.1093/treephys/tpz032>
22. Lavorel S, Grigulis K, McIntyre S, Williams NS, Garden D, Dorrrough J, et al. Assessing functional diversity in the field—methodology matters. *Funct Ecol.* 2008;22:134–47. <https://doi.org/10.1111/j.1365-2435.2007.01339.x>
 23. Garnier E, Cortez J, Billès G, Navas ML, Roumet C, Debussche M, et al. Plant functional markers capture ecosystem properties during secondary succession. *Ecology.* 2004;85:2630–7. <https://doi.org/10.1890/03-0799>
 24. Villéger S, Mason NW, Mouillot D. New multidimensional functional diversity indices for a multifaceted framework in functional ecology. *Ecology.* 2008;89:2290–301. <https://doi.org/10.1890/07-1206.1>
 25. Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia.* 2005;145:87–99. <https://doi.org/10.1007/s00442-005-0100-x>
 26. Cornwell WK, Cornelissen JHC, Amatangelo K, Dorrepaal E, Eviner VT, Godoy O, et al. Plant functional traits and ecosystem processes: a global synthesis. *Ecol Lett.* 2008;11:1065–74. <https://doi.org/10.1111/j.1461-0248.2008.01219.x>
 27. Echeverría-Londoño S, Enquist BJ, Neves DM, Violle C, Boyle B, Kraft NJ, et al. Plant functional diversity and the biogeography of biomes in North and South America. *Front Ecol Evol.* 2018;6:219. <https://doi.org/10.3389/fevo.2018.00219>
 28. Zirbel CR, Bassett T, Grman E, Brudvig LA. Plant functional traits and environmental conditions shape community assembly and ecosystem functioning during restoration. *J Appl Ecol.* 2017;54:1070–9. <https://doi.org/10.1111/1365-2664.12885>
 29. Ahrens CW, Andrew ME, Mazanec RA, Ruthrof KX, Challis A, Hardy G, et al. Plant functional traits differ in adaptability and are predicted to be differentially affected by climate change. *Ecol Evol.* 2020;10:232–48. <https://doi.org/10.1002/ece3.5890>
 30. Freund SM, Newingham BA, Chambers JC, Urza AK, Roundy BA, Cushman JH. Plant functional groups and species contribute to ecological resilience a decade after woodland expansion treatments. *Ecosphere.* 2021;12:e03325. <https://doi.org/10.1002/ecs2.3325>
 31. Albrich K, Rammer W, Turner MG, Ratajczak Z, Braziunas KH, Hansen WD, et al. Simulating forest resilience: a review. *Glob Ecol Biogeogr.* 2020;29:2082–96. <https://doi.org/10.1111/geb.13197>
 32. Sakschewski B, Von Bloh W, Boit A, Poorter L, Peña-Claros M, Heinke J, et al. Resilience of Amazon forests emerges from plant trait diversity. *Nat Clim Chang.* 2016;6:1032–6. <https://doi.org/10.1038/nclimate3109>
 33. Miedema Brown L, Anand M. Plant functional traits as measures of ecosystem service provision. *Ecosphere.* 2022;13:e3930. <https://doi.org/10.1002/ecs2.3930>
 34. Bravo F, van Der Werf W, Tognetti R, Mazía N, Anten NP, Piazza MV, et al. Unleashing the power of plant structural and functional diversity: from common observations to theory and management models. *Food Energy Secur.* 2024;13:e70005. <https://doi.org/10.1002/fes3.70005>
 35. Balachowski JA, Voltaire FA. Implications of plant functional traits and drought survival strategies for ecological restoration. *J Appl Ecol.* 2018;55:631–40. <https://doi.org/10.1111/1365-2664.12979>
 36. Cheesman AW, Preece ND, van Oosterzee P, Erskine PD, Cernusak LA. The role of topography and plant functional traits in determining tropical reforestation success. *J Appl Ecol.* 2018;55:1029–39. <https://doi.org/10.1111/1365-2664.12980>
 37. Yu H, Chen Y, Zhou G, Xu Z. Coordination of leaf functional traits under climatic warming in an arid ecosystem. *BMC Plant Biol.* 2022;22:439. <https://doi.org/10.1186/s12870-022-03818-z>
 38. Fischer FM, Wright AJ, Eisenhauer N, Ebeling A, Roscher C, Wagg C, et al. Plant species richness and functional traits affect community stability after a flood event. *Philos Trans R Soc B Biol Sci.* 2016;371:20150276. <https://doi.org/10.1098/rstb.2015.0276>
 39. Espelta JM, Cruz-Alonso V, Alfaro-Sánchez R, Hampe A, Messier C, Pino J. Functional diversity enhances tree growth and reduces herbivory damage in secondary broadleaf forests, but does not influence resilience to drought. *J Appl Ecol.* 2020;57:2362–72. <https://doi.org/10.1111/1365-2664.13728>
 40. Singh S. Low to moderate-level forest disturbance effects on plant functional traits and associated soil microbial diversity in Western Himalaya. *Front For Glob Chang.* 2021;4:710658. <https://doi.org/10.3389/ffgc.2021.710658>
 41. Seidler R, Bawa K. Biodiversity in logged and managed forests. In: Levin SA, editor. *Encyclopedia of biodiversity.* Amsterdam: Academic Press; 2013. p. 446–58. <https://doi.org/10.1016/B978-0-12-384719-5.00248-3>
 42. Asner GP, Mascaro J, Muller-Landau HC, Vieilledent G, Vaudry R, Rasamoelina M, et al. A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia.* 2012;168:1147–60. <https://doi.org/10.1007/s00442-011-2165-z>
 43. Munishi LK, Ngondya IB. Realizing UN decade on ecosystem restoration through a nature-based approach: a case review of management of biological invasions in protected areas. *PLOS Sustain Transform.* 2022;1:e0000027. <https://doi.org/10.1371/journal.pstr.0000027>
 44. Cadotte MW, Carscadden K, Mirotchnick N. Functional diversity and ecosystem services. *J Appl Ecol.* 2011;48:1079–87. <https://doi.org/10.1111/j.1365-2664.2011.02048.x>
 45. Díaz S, Fargione J, Chapin FS III, Tilman D. Biodiversity loss threatens human well-being. *PLoS Biol.* 2006;4:e277. <https://doi.org/10.1371/journal.pbio.0040277>
 46. Anderegg WR, Flint A, Huang CY, Flint L, Berry JA, Davis FW, et al. Tree mortality predicted from drought-induced vascular damage. *Nat Geosci.* 2015;8:367–71. <https://doi.org/10.1038/ngeo2400>
 47. Agha SB, Alvarez M, Becker M, Fèvre EM, Junglen S, Borgemeister C. Invasive alien plants in Africa and the potential emergence of mosquito-borne arboviral diseases—a review and research outlook. *Viruses.* 2020;13:32. <https://doi.org/10.1038/ngeo2400>
 48. Junker RR, Kuppler J, Bathke AC, Schreyer ML, Trutschnig W. Dynamic range boxes—a robust nonparametric approach to quantify size and overlap of n-dimensional hypervolumes. *Methods Ecol Evol.* 2016;7:1503–13. <https://doi.org/10.1111/2041-210X.12611>
 49. Lavorel S, Storkey J, Bardgett RD, De Bello F, Berg MP, Le Roux X, et al. Linking functional diversity and ecosystem services. *J Veg Sci.* 2013;24:942–8. <https://doi.org/10.1111/jvs.12083>
 50. Keddy PA. A pragmatic approach to functional ecology. *Funct Ecol.* 1992;6:621–6. <https://doi.org/10.2307/2389954>
 51. Paini DR, Sheppard AW, Cook DC, De Barro PJ, Worner SP, Thomas MB. Global threat to agriculture from invasive species. *Proc Natl Acad Sci USA.* 2016;113:7575–9. <https://doi.org/10.1073/pnas.1602205113>
 52. Hao Q, Yang S, Song Z, Li Z, Ding F, Yu C, et al. Silicon affects plant stoichiometry and accumulation of C, N and P in grasslands. *Front Plant Sci.* 2020;11:1304. <https://doi.org/10.3389/fpls.2020.01304>
 53. Cooke J, Leishman MR. Is plant ecology more siliceous than we realise? *Trends Plant Sci.* 2011;16:61–8. <https://doi.org/10.1016/j.tplants.2010.10.003>
 54. Massey FP, Ennos AR, Hartley SE. Silica in grasses as a defence against insect herbivores: contrasting effects on folivores and a phloem feeder. *Ecology.* 2006;87:595–603. <https://doi.org/10.1111/j.1365-2656.2006.01082.x>
 55. Cooke J, DeGabriel JL, Hartley SE. The functional ecology of plant silicon. *Funct Ecol.* 2016;30:1270–6. <https://doi.org/10.1111/1365-2435.12711>
 56. Massey FP, Hartley SE. Physical defences wear you down: progressive and irreversible impacts of silica on insect herbivores. *J*

- Anim Ecol. 2009;78:281–91. <https://doi.org/10.1111/j.1365-2656.2008.01472.x>
57. Frew A, Weston LA, Reynolds OL, Gurr GM. The role of silicon in plant biology: a paradigm shift in research approach. *Ann Bot.* 2018;121:1265–73. <https://doi.org/10.1093/aob/mcy009>
 58. Violle C, Navas ML, Vile D, Kazakou E, Fortunel C, Hummel I, et al. Let the concept of trait be functional. *Oikos.* 2007;116:882–92. <https://doi.org/10.1111/j.0030-1299.2007.15559.x>
 59. Nyasembe VO, Cheseto X, Kaplan F, Foster WA, Teal PE, Tumlinson JH, et al. The invasive American weed *Parthenium hysterophorus* can negatively impact malaria control in Africa. *PLoS One.* 2015;10:e0137836. <https://doi.org/10.1371/journal.pone.0137836>
 60. Albert CH, Grassein F, Schurr FM, Vieilledent G, Violle C. When and how should intraspecific variability be considered in trait-based plant ecology? *Perspect Plant Ecol Evol Syst.* 2011;13:217–25. <https://doi.org/10.1016/j.ppees.2011.04.003>
 61. Kramer-Walter KR, Bellingham PJ, Millar TR, Smissen RD, Richardson SJ, Laughlin DC. Root traits are multidimensional: specific root length is independent from root tissue density and the plant economic spectrum. *J Ecol.* 2016;104:1299–310. <https://doi.org/10.1111/1365-2745.12562>
 62. Fontana S, Thomas MK, Moldoveanu M, Spaak P, Pomati F. Individual-level trait diversity predicts phytoplankton community properties better than species richness or evenness. *ISME J.* 2018;12:356–66. <https://doi.org/10.1038/ismej.2017.160>
 63. Gross N, Bagousse-Pinguet YL, Liancourt P, Berdugo M, Gotelli NJ, Maestre FT. Functional trait diversity maximises ecosystem multifunctionality. *Nat Ecol Evol.* 2017;1:0132. <https://doi.org/10.1038/s41559-017-0132>
 64. Hanisch M, Schweiger O, Cord AF, Volk M, Knapp S. Plant functional traits shape multiple ecosystem services, their trade-offs and synergies in grasslands. *J Appl Ecol.* 2020;57:1535–50. <https://doi.org/10.1111/1365-2664.13644>
 65. Laliberté E, Legendre P. A distance-based framework for measuring functional diversity from multiple traits. *Ecology.* 2010;91:299–305. <https://doi.org/10.1890/08-2244.1>
 66. Uyi O, Mukweho L, Ejomah AJ, Toews M. Invasive alien plants in Sub-Saharan Africa: a review and synthesis of their insecticidal activities. *Front Agron.* 2021;3:725895. <https://doi.org/10.3389/fagro.2021.725895>
 67. Weidenhamer JD, Callaway RM. Direct and indirect effects of invasive plants on soil chemistry and ecosystem function. *J Chem Ecol.* 2010;36:59–69. <https://doi.org/10.1007/s10886-009-9735-0>
 68. Witt A, Beale T, Van Wilgen BW. An assessment of the distribution and potential ecological impacts of invasive alien plant species in eastern Africa. *Trans R Soc South Africa.* 2018;73:217–36. <https://doi.org/10.1080/0035919X.2018.1529003>
 69. Afzal MR, Naz M, Ashraf W, Du D. The legacy of plant invasion: impacts on soil nitrification and management implications. *Plants.* 2023;12:2980. <https://doi.org/10.3390/plants12162980>
 70. Goncalves E, Herrera I, Duarte M, Bustamante RO, Lampo M, Velasquez G, et al. Global invasion of *Lantana camara*: has the climatic niche been conserved across continents? *PLoS One.* 2014;9:e111468. <https://doi.org/10.1371/journal.pone.0111468>
 71. Kilawe CJ, Baltazary IS, Malila BP, Lyimo PJ, Mwakalukwa EE. Replacement of native trees by the neotropical invasive tree *Cedrela odorata* L. in the Kimboza Forest Reserve, Tanzania. *Biol Invasions.* 2023;25:3697–710. <https://doi.org/10.1007/s10530-023-03136-x>
 72. Garbuzov M, Reidinger S, Hartley SE. Interactive effects of plant-available soil silicon and herbivory on competition between two grass species. *Ann Bot.* 2011;108:1355–63. <https://doi.org/10.1093/aob/mcr230>
 73. Schoelynck J, Müller F, Vandevenne F, Bal K, Barão L, Smis A, et al. Silicon–vegetation interaction in multiple ecosystems: a review. *J Veg Sci.* 2014;25:301–13. <https://doi.org/10.1111/jvs.12055>
 74. Pörtner HO, Bock C, Mark FC. Oxygen- and capacity-limited thermal tolerance: bridging ecology and physiology. *J Exp Biol.* 2017;220:2685–96. <https://doi.org/10.1242/jeb.134585>

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