

COURSE SYLLABUS

Trait-Based Approach in Community Ecology: *Theory and Applications*

Course Description

This intensive 5-day course introduces Master, doctoral students and early-career researchers to the conceptual foundations and analytical methods of trait-based ecology, with a deliberate focus on Neotropical freshwater fishes and Amazonian ecosystems. Functional traits — measurable morphological, physiological or behavioural characteristics that influence individual performance and mediate ecosystem processes — have become central to community and ecosystem ecology. The Amazon basin, hosting more than 6,000 fish species (>75% of the world's freshwater fish functional diversity; Su et al. 2021), provides an exceptional natural laboratory in which to learn and apply these tools.

The course follows a deliberate pedagogical arc. Days 1–2 establish conceptual and methodological foundations from plant ecology (where the framework matured) before transitioning to fish-specific applications. Day 3 introduces multivariate analyses linking traits to environmental gradients and quantifies the functional consequences of species extinction (FUSE). Day 4 immerses students in the morphological trait framework for fishes (Villéger et al. 2017): from anatomical landmarks measured on photographs to the ten standardised functional traits used in FishMorph (Brosse et al. 2021). Day 5 introduces geometric morphometrics (Procrustes analysis) and the partitioning of intraspecific shape variation across Amazonian populations. Each session combines theory (50–70%) with hands-on R practicals on real and pedagogical Amazonian datasets.

Learning Outcomes

Upon successful completion of this course, students will be able to:

- Define and classify functional traits and justify the trait-based framework in community and ecosystem ecology, with concrete examples from Amazonian fish communities.
- Import, clean and explore trait datasets from global databases (TRY, FishMorph, FishBase) using R and {tidyverse}.
- Compute and interpret community-weighted means (CWM) and multidimensional functional diversity indices (FRic, FEve, FDiv, FDis, RaoQ).
- Apply RLQ ordination and fourth-corner permutation tests to quantify trait–environment relationships in Amazonian fish assemblages.
- Simulate extinction scenarios on Neotropical fish communities and compute FUSE scores (Functionally Unique, Specialised and Endangered; Pimiento et al. 2020).

- Place 12 anatomical landmarks on fish photographs (ImageJ / Fiji) and derive the 10 standardised morphological traits of Villéger et al. (2017).
- Conduct geometric morphometric analyses (Generalised Procrustes Analysis, shape PCA, RRPP-MANOVA, allometry) using {geomorph}.
- Quantify and interpret intraspecific trait variability (ITV) of body shape using hierarchical mixed models, and contrast traditional with geometric morphometric approaches.
- Produce a reproducible R workflow ({renv} environment, well-documented scripts, Rmarkdown report).

Prerequisites

Students are expected to have:

- A working knowledge of fundamental ecological concepts (community ecology, species interactions, ecosystem functioning).
- Basic proficiency in R (≥ 4.3): data import, elementary {tidyverse} operations, {ggplot2} plotting.
- Elementary statistics: linear regression, ANOVA, principal component analysis.
- Familiarity with Neotropical freshwater fish taxonomy is helpful but not required.

Software Requirements

All practicals are implemented in R (≥ 4.3). Students must install before Day 1:

- Core: {tidyverse} {ggplot2} {patchwork} {ggrepel} {corrplot}
- Day 2 (Functional diversity): {FD} {funrar} {vegan} {ape}
- Day 3 (RLQ + FUSE): {ade4} {adespatial} {FD} {funrar}
- Day 4 (Fish FD): {FD} {vegan} {irr}; ImageJ / Fiji (free)
- Day 5 (Geometric morphometrics): {geomorph} ≥ 4.0 , {lme4}, {MuMIn}, {RRPP}
- Reproducibility: {renv} {rmarkdown} {knitr}

A starter R project containing all datasets, annotated scripts and exercise sheets will be distributed via USB stick on Day 1 and through the course Github repository.

Detailed Programme

Day 1 — Foundations of Trait-Based Ecology

Learning objective: understand the conceptual shift from species-centred to trait-centred ecology and acquire proficiency in trait data handling in R.

Theory 70% / Practical (R) 30%

Topics: definition of a functional trait (Violle et al. 2007); response vs. effect traits; the Leaf Economics Spectrum and global trait spectra; trait databases (TRY, FishMorph, FishBase); data

quality, gap-filling, phylogenetic imputation; transition from plants to fishes; preliminary look at Amazonian fish trait data.

R Practical: import the TRY-format long table; reshape with {tidyr}; merge with species metadata; produce summary trait spectra and detect implausible values.

Key references

- Violle et al. (2007) *Oikos* 116: 882–892 — formal definition of functional trait
- Wright et al. (2004) *Nature* 428: 821–827 — Leaf Economics Spectrum
- Kattge et al. (2020) *Global Change Biology* 26: 119–188 — TRY v5
- Brosse et al. (2021) *Scientific Data* 8: 254 — FishMorph database

Day 2 — Functional Diversity Metrics

Learning objective: compute and interpret community-level functional descriptors and multidimensional functional diversity indices.

Theory 55% / Practical (R) 45%

Topics: from species diversity to functional diversity; community-weighted mean (CWM); functional richness (FRic), evenness (FEve), divergence (FDiv) and dispersion (FDis); Rao's quadratic entropy; choice of distance metrics (Gower, Euclidean) and dimensionality of the functional space; sensitivity to species pool and trait selection; preliminary application to a small Amazonian fish dataset.

R Practical: compute the four FD indices with {FD::dbFD} on the course dataset; visualise functional space with PCoA biplots; sensitivity analysis on number of axes retained.

Key references

- Mason et al. (2005) *Oikos* 111: 112–118 — CWM and FD
- Villéger et al. (2008) *Ecology* 89: 2290–2301 — FRic/FEve/FDiv
- Laliberté & Legendre (2010) *Ecology* 91: 299–305 — FDis and Rao
- Mouillot et al. (2013) *TREE* 28: 167–177 — functional diversity functioning

Day 3 — Trait–Environment Relationships & Extinction Consequences

Learning objective: statistically link functional traits to environmental gradients in Amazonian fish assemblages, and quantify the functional consequences of species extinction.

Theory 50% / Practical (R) 50%

Topics — Part 1 (Trait–environment): the response–effect framework (Lavorel & Garnier 2002); the L–Q–R three-table problem; correspondence analysis as a foundation; RLQ ordination (Dolédec et al. 1996); fourth-corner test (Dray & Legendre 2008); permutation models 2 and 4 and the max-test (Ter Braak et al. 2012); interpretation of significance heatmaps with FDR correction.

Topics — Part 2 (Extinction & ecosystem functioning): biodiversity–ecosystem functioning (BEF) mechanisms (sampling effect vs. complementarity); rare and threatened species as functional

outliers (Mouillot et al. 2013); FUSE = $F_{Un} \times F_{Spec} \times IUCN \text{ weight}$ (Pimienta et al. 2020); three extinction scenarios (random / least abundant first / most threatened first).

R Practical: build R, L and Q tables for an Amazonian fish dataset (12 sites \times 30 species \times 10 traits + 8 environmental variables); run `{ade4::rlq}` and `{ade4::fourthcorner}` with FDR-corrected p-values; produce trait \times environment heatmaps; simulate the three extinction scenarios with `{FD::dbFD}` and plot FRic and FDis loss curves; compute FUSE scores using `{funrar}` and IUCN weights of Mooers et al. (2008).

Key references

- Dray & Legendre (2008) Ecology 89: 3400–3412 — fourth-corner
- Ter Braak et al. (2012) Methods Ecol. Evol. 3: 217–226 — max-test
- Lavorel & Garnier (2002) Functional Ecology 16: 545–556 — response–effect
- Mouillot et al. (2013) PLoS Biology 11: e1001569 — rare species & vulnerable functions
- Pimienta et al. (2020) Science Advances 6: eaay7650 — FUSE
- Toussaint et al. (2016) Scientific Reports 6: 22125 — Neotropical fish FD

Day 4 — Fish Morphological Traits & Landmark Measurements

Learning objective: apply the standardised morphological trait framework of Villéger et al. (2017) to Neotropical fishes, from anatomical landmark measurement to functional diversity computation.

Theory 50% / Practical (ImageJ + R) 50%

Topics: why morphological traits for fishes — direct mechanistic link to locomotion and trophic ecology, measurability on preserved specimens and photographs, taxonomic universality; the 10 standardised traits (6 locomotion + 4 trophic): body elongation, lateral compression, pectoral aspect ratio, pectoral position, caudal peduncle throttling, caudal aspect ratio, body size, mouth position, oral gape, eye size; the 12 anatomical landmarks on the lateral view; protocols for image standardisation, scale calibration and quality control (TEM, ICC); functional space of Amazonian fish — main strategies (piscivores, surface predators, benthic detritivores, midwater frugivores).

Practical (ImageJ): students measure landmarks on standardised photographs of 5 Amazonian species (*Cichla ocellaris*, *Hoplias malabaricus*, *Hypostomus plecostomus*, *Brycon amazonicus*, *Astyanax bimaculatus*), compute pixel distances, calibrate with a scale bar and export to CSV.

R Practical: derive the 10 traits from raw measurements; aggregate to species means; scale and centre; compute FD indices on a 12-site Amazonian community matrix; relate FRic and FDis to a degradation gradient; visualise functional space and identify guilds.

Key references

- Villéger et al. (2017) Ecography 40: 1–7 — fish morphological traits
- Brosse et al. (2021) Scientific Data 8: 254 — FishMorph database
- Su et al. (2021) Science 371: 835–838 — global freshwater fish FD
- Toussaint et al. (2016) Scientific Reports 6: 22125 — Neotropical FD

- Sá-Oliveira et al. (2015) PLoS ONE 10: e0125261 — Amazonian fish & disturbance

Day 5 — ITV of Landmarks: Geometric Morphometrics & Procrustes Analysis

Learning objective: separate size from shape using Procrustes superimposition, partition intraspecific shape variation across Amazonian populations, and integrate traditional and geometric morphometric perspectives.

Theory 40% / Practical (R) 60%

Topics: traditional morphometrics (TM) versus geometric morphometrics (GM) — strengths and limitations; the Procrustes paradigm (translation, scaling to unit centroid size, rotation) and the resulting shape coordinates; tangent space and shape PCA (gm.prcomp); deformation grids (thin-plate spline) for biological interpretation; allometry (shape \sim log-centroid size); RRPP permutation tests (procD.lm) for habitat and population effects; sources of intraspecific shape variation in fishes — phenotypic plasticity, local genetic adaptation, ontogeny; partitioning ITV into between-species, between-population and within-population components with hierarchical mixed models (lmer).

R Practical: perform Generalised Procrustes Analysis on a multi-population Amazonian dataset (5 species \times 4 populations \times 12 individuals); run shape PCA with {geomorph::gm.prcomp}; produce deformation grids; fit hierarchical mixed models for variance partitioning; compare TM-based and GM-based functional diversity rankings; final synthesis of the 5 days and discussion of student research projects.

Key references

- Adams & Otárola-Castillo (2013) *Methods Ecol. Evol.* 4: 393–399 — geomorph
- Klingenberg (2016) *Devel. Genes Evol.* 226: 113–137 — visualisation of shape change
- Violle et al. (2012) *TREE* 27: 146–153 — return of the variance (ITV)
- Wainwright et al. (2002) *Integr. Comp. Biol.* 42: 256–262 — many-to-one mapping
- Albert et al. (2020) *BioScience* 70: 411–426 — Neotropical freshwater fish biogeography

Assessment

Students are assessed through two complementary components.

1. Practical portfolio (60%)

At the end of each day, students submit annotated R scripts and output figures from the take-home exercises. Submissions are evaluated on correctness, code quality, ecological interpretation and Amazonian contextualisation.

2. Analytical short report (40%)

Students produce a 1,000–1,500-word reproducible report in Rmarkdown analysing a trait dataset of their choice (their own data or a course dataset), applying at least three of the methods covered in the course. The report must (i) be embedded in a {renv} environment, (ii)

include all source data and a runnable .Rmd, (iii) discuss explicitly the strengths and limitations of the methods used.

Core Bibliography

Students are expected to read the key reference assigned to each day before the corresponding session. Full PDFs are distributed in the course repository.

- Adams D.C. & Otárola-Castillo E. (2013) geomorph: an R package for the collection and analysis of geometric morphometric shape data. *Methods in Ecology and Evolution* 4: 393–399.
- Albert J.S. et al. (2020) Neotropical freshwater fishes: a review of biodiversity science. *BioScience* 70: 411–426.
- Brosse S. et al. (2021) FishMorph: a global database on morphological traits of freshwater fishes. *Scientific Data* 8: 254.
- Dray S. & Legendre P. (2008) Testing the species traits–environment relationships: the fourth-corner problem revisited. *Ecology* 89: 3400–3412.
- Kattge J. et al. (2020) TRY plant trait database — enhanced coverage and open access. *Global Change Biology* 26: 119–188.
- Lavorel S. & Garnier E. (2002) Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Functional Ecology* 16: 545–556.
- Mason N.W.H. et al. (2005) Functional richness, functional evenness and functional divergence: the primary components of functional diversity. *Oikos* 111: 112–118.
- Mouillot D. et al. (2013) Rare species support vulnerable functions in high-diversity ecosystems. *PLoS Biology* 11: e1001569.
- Pimiento C. et al. (2020) Functional diversity of marine megafauna in the Anthropocene. *Science Advances* 6: eaay7650.
- Su G. et al. (2021) Human impacts on global freshwater fish biodiversity. *Science* 371: 835–838.
- Ter Braak C.J.F. et al. (2012) Improved testing of species traits–environment relationships in the fourth-corner problem. *Methods in Ecology and Evolution* 3: 217–226.
- Toussaint A. et al. (2016) Global functional diversity of freshwater fish is concentrated in the Neotropics. *Scientific Reports* 6: 22125.
- Villéger S. et al. (2008) New multidimensional functional diversity indices for a multifaceted framework in functional ecology. *Ecology* 89: 2290–2301.
- Villéger S. et al. (2017) Functional ecology of fish: current approaches and future challenges. *Aquatic Sciences* 79: 783–801.
- Violle C. et al. (2007) Let the concept of trait be functional! *Oikos* 116: 882–892.
- Violle C. et al. (2012) The return of the variance: intraspecific variability in community ecology. *TREE* 27: 146–153.
- Wright I.J. et al. (2004) The worldwide leaf economics spectrum. *Nature* 428: 821–827.

Additional Resources

Online databases

- FishBase — <https://www.fishbase.org>
- FishMorph — <https://borisleroy.com/fishmorph/>
- TRY Plant Trait Database — <https://www.try-db.org>
- BIEN Botanical Information and Ecology Network — <https://biendata.org>
- IUCN Red List — <https://www.iucnredlist.org>

R packages and tutorials

- {geomorph} vignettes — <https://cran.r-project.org/package=geomorph>
- {ade4} fourth-corner tutorial — <https://pbil.univ-lyon1.fr/ade4/>
- Swenson N.G. (2014) Functional and Phylogenetic Ecology in R. Springer.
- R Task View: Environmetrics — <https://cran.r-project.org/web/views/Environmetrics.html>

Notes

This course was designed to bridge plant- and fish-centred trait ecology by progressively shifting examples and datasets towards Neotropical freshwater fishes. All Amazonian datasets used during practicals are pedagogical reconstructions consistent with values reported in the primary literature (FishMorph, IUCN, FishBase). Students are encouraged to bring their own data for the final analytical report.

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