Key Concepts in Microbial Ecology

Lecture 1 · Microbial Communities and Interactions

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Today's Roadmap

Foundational Concepts

Community, population, niche, guild

Interactions

Biotic and abiotic drivers

Diversity

Alpha, beta and gamma diversity

Models & Scales

Classic models, space and time

Why This Matters

Health

Gut microbiota and disease

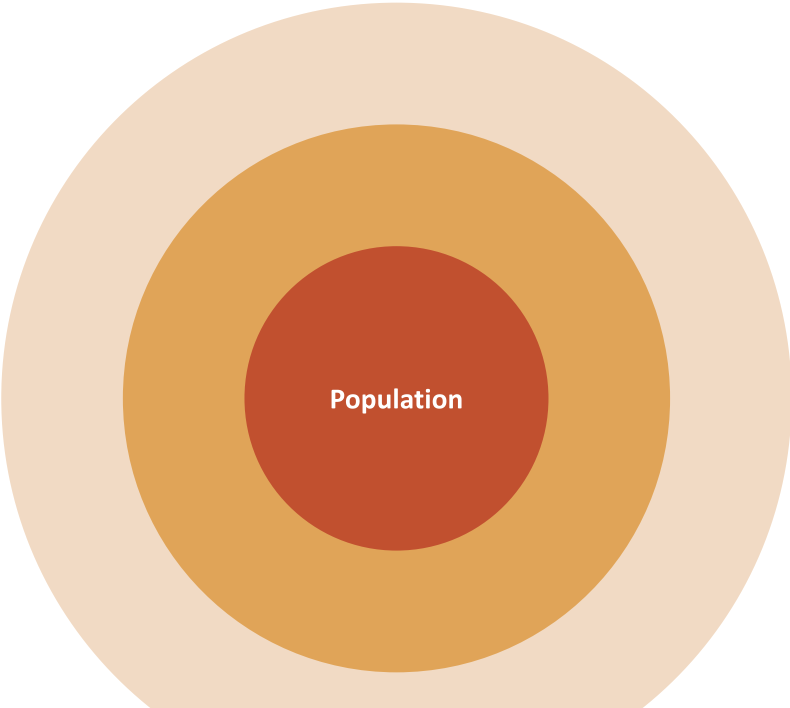
Agriculture

Soil fertility and plant growth

Climate

Global biogeochemical cycles

From Population to Metacommunity



Population

Individuals of one species in a given space and time

Community

Assemblage of populations co-occurring in a habitat

Metacommunity

Communities linked by dispersal across habitats

Niche — the functional role and requirements of a species

Guild — species using the same class of resource

FOUNDATIONAL CONCEPT

Population

A population is a group of individuals of the same species (or taxon) living in a defined area and interacting with one another.

In microbial ecology, the boundaries of a population are often less clear than in macroorganisms due to enormous population sizes; clonal reproduction; horizontal gene transfer; frequent dispersal; taxonomic definitions that may not perfectly correspond to ecological units.

EXAMPLE

A single *Escherichia coli* strain colonizing the human gut is one population.

FOUNDATIONAL CONCEPT

Community

A microbial community is an assemblage of populations of different microorganisms that coexist in a particular environment and interact directly or indirectly.

EXAMPLE

The full set of microorganisms (e.g., bacteria, archaea and fungi) found in one soil sample forms a community.

FOUNDATIONAL CONCEPT

Metacommunity

A metacommunity is a set of local communities connected by the dispersal of organisms among spatially separated habitats.

How do dispersal and spatial connectivity interact with local environmental conditions to determine community composition? (Selection, Dispersal, Drift, Speciation/evolution)

EXAMPLE

Microbial communities along a river network, connected by the flow of water, form a metacommunity.

FOUNDATIONAL CONCEPT

Niche

An ecological niche describes the set of environmental conditions, resources and biotic interactions that determine where and how an organism can survive, grow and reproduce.

The multidimensional space of environmental conditions and resources a species needs to persist — Hutchinson's “n-dimensional hypervolume.”

EXAMPLE

A sulfate-reducing bacterium's niche is defined by anoxia, sulfate availability and a suitable temperature range.

FOUNDATIONAL CONCEPT

Guild

A guild is a group of organisms that exploit the same type of resources or perform similar ecological functions, regardless of their taxonomic relatedness.

Function, not taxonomy!

EXAMPLE

Ammonia-oxidizing bacteria and ammonia-oxidizing archaea belong to the same functional guild.

Summary

Concept	Main question
Population	Who belongs to this population?
Community	Who lives together?
Metacommunity	How are local communities connected?
Niche	What conditions/resources does an organism require and how does it interact with its environment?
Guild	Which organisms perform similar ecological functions?

Niche describes an organism's ecological requirements and role; a guild groups organisms that occupy similar functional roles.
A functional group is a set of organisms that contribute to the same ecosystem process or function.

Quick Check: Foundational Concepts

1. All the bacteria, fungi and archaea living together in one handful of soil.
2. Every genetically similar *E. coli* cell living in one person's gut.
3. Nitrogen-fixing bacteria and nitrogen-fixing archaea doing the same ecological job, despite being unrelated.
4. The specific combination of pH, oxygen and temperature a species needs to survive.
5. Separate soil communities on nearby farms, connected by wind-dispersed spores.

WORD BANK

Guild **Metacommunity** **Population** **Community** **Niche**

Quick Check: Foundational Concepts — Answers

1	**Community**	All co-occurring populations in one habitat
2	**Population**	One species, one place, one time
3	**Guild**	Same functional role, different taxonomy
4	**Niche**	The conditions a species needs to persist
5	**Metacommunity**	Communities linked by dispersal

Biotic Interactions

Competition

(–/–)

Predation / Parasitism

(+/–)

Mutualism

(+/+)

Commensalism

(+/0)

Amensalism

(–/0)

Notation: effect on species A / effect on species B (+ benefit, – harm, 0 no effect)

BIOTIC INTERACTION

Competition

(−/−)

Competition occurs when two organisms require the same limiting resource or otherwise interfere with each other's access to resources or space.
Exploitative competition
Interference competition (e.g., antibiotics; bacteriocins; siderophores; toxic metabolites; contact-dependent inhibition)

EXAMPLE

Siderophore-producing bacteria in the rhizosphere compete with one another for scarce iron.

BIOTIC INTERACTION

Predation / Parasitism

(+/−)

One organism benefits at the direct expense of another.
Predation: one organism actively captures, consumes and kills another organism.
Parasitism: a parasite benefits from a host while exploiting it, generally without immediately killing it.

The distinction is not always absolute, particularly among microorganisms.

EXAMPLE

Bacteriophages replicate inside bacterial cells and lyse (kill) their hosts to spread.

BIOTIC INTERACTION

Mutualism

(+/+)

Mutualism is an interaction in which both partners obtain a net fitness benefit.
(e.g., syntrophy)

Mutualism often involves exchange of resources or services.

EXAMPLE

Rhizobium bacteria fix nitrogen for legume roots in exchange for photosynthetic sugars.

BIOTIC INTERACTION

Commensalism

(+/0)

One organism benefits while the other experiences no measurable net effect.
(e.g., cross-feeding)

True commensalism can be difficult to demonstrate experimentally.

EXAMPLE

Many skin bacteria use host secretions as a nutrient source without measurably affecting the host.

BIOTIC INTERACTION

Amensalism

(−/0)

One organism is negatively affected, while the other experiences no measurable effect.
(e.g., antibiosis)

EXAMPLE

Antibiotic-producing *Penicillium* inhibits nearby competitors that have no reciprocal effect on it.

Biotic Interactions

- **Competition** (–/–)
- **Predation / Parasitism** (+/–)
- **Mutualism** (+/+)
- **Commensalism** (+/0)
- **Amensalism** (–/0)

We have classified microbial interactions according to their effects on the partners. But in real microbial communities, these interactions rarely occur in isolation.

A microorganism can compete with one species, facilitate another, and be preyed upon by a third — all at the same time.

Moreover, many interactions are indirect and are mediated by metabolites or changes in the environment.

Therefore, to understand a microbial community, we need to move from individual pairwise interactions to networks of interacting populations.

Notation: effect on species A / effect on species B (+ benefit, – harm, 0 no effect)

Quick Check: Biotic Interactions

1. Two soil bacteria both suffer while competing for the same scarce iron supply.
2. A virus multiplies inside a bacterium and eventually destroys it.
3. *Rhizobium* fixes nitrogen for a legume and receives sugars in return.
4. A skin bacterium feeds on host oils without affecting the host at all.
5. A mould secretes a compound that inhibits nearby bacteria, which have no effect back on the mould.

WORD BANK

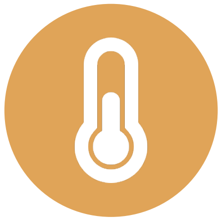
Amensalism | **Mutualism** | **Commensalism** | **Competition** | **Predation / Parasitism**

Quick Check: Biotic Interactions — Answers

1	**Competition**	(–/–) both harmed
2	**Predation / Parasitism**	(+/–) one benefits, one harmed
3	**Mutualism**	(+/+) both benefit
4	**Commensalism**	(+/0) one benefits, other unaffected
5	**Amensalism**	(–/0) one harmed, other unaffected

Abiotic Factors

pH



Temperature

Nutrients

Oxygen

Refresher: Classes by Growth Range

pH	Acidophiles (< pH 3) · Neutrophiles (~pH 5–8) · Alkaliphiles (> pH 9)
Temperature	Psychrophiles (< 15 °C) · Mesophiles (20–45 °C) · Thermophiles (45–80 °C) · Hyperthermophiles (> 80 °C)
Nutrients	Oligotrophs (low-nutrient specialists) · Copiotrophs (nutrient-rich specialists)
Oxygen	Obligate aerobes · Facultative anaerobes · Obligate anaerobes · Microaerophiles · Aerotolerant anaerobes

Quick refresher — the same classes recur throughout the course whenever a factor's range matters

ABIOTIC FACTOR

pH

The acidity or alkalinity of the environment, which shapes which microorganisms can grow.
pH influences microbial growth by affecting enzyme activity, membrane function, nutrient availability and cellular homeostasis.
The pH of the environment determines the energetic and physiological constraints under which microorganisms operate.
Why doesn't an acidophile simply become a neutrophile when placed at neutral pH?

EXAMPLE

Acidophiles such as *Acidithiobacillus* thrive at pH below 3 in acid mine drainage.

ABIOTIC FACTOR

Temperature

Governs enzyme activity and membrane fluidity, setting the limits of microbial growth.
Temperature affects not only whether microorganisms can grow, but also the rate and outcome of their interactions.

EXAMPLE

Hyperthermophiles such as *Pyrococcus* grow near 100 °C at deep-sea hydrothermal vents.

ABIOTIC FACTOR

Nutrients

The availability of carbon, nitrogen, phosphorus and trace elements limits growth and shapes community composition.
Macro and micronutrients, carbon and energy source, electron donor/acceptor
A nutrient can be present but not biologically available
Microorganisms modify the resource landscape for themselves and for other organisms.

EXAMPLE

Phosphorus limitation strongly shapes phytoplankton community composition in freshwater lakes.

ABIOTIC FACTOR

Oxygen

The presence or absence of oxygen determines whether aerobic, anaerobic or facultative organisms dominate.
Oxygen availability creates ecological niches
Oxygen gradients (e.g., biofilms) and facilitation through environmental modification

EXAMPLE

Strict anaerobes such as *Clostridium* are restricted to oxygen-free sediments and gut environments.

Diversity Across Scales

Alpha

Diversity within one habitat

Beta

Turnover between habitats

Gamma

Total regional diversity

DIVERSITY SCALE

Alpha Diversity

Alpha diversity is the diversity within a particular local community or sampling unit.
“How diverse is this community?”

Richness (How many taxa are present?), Evenness (How evenly are individuals distributed among taxa?) and Diversity

EXAMPLE

The number of distinct bacterial taxa found in one soil core.

DIVERSITY SCALE

Beta Diversity

Beta diversity describes differences in community composition among local communities.
“How different are these communities from one another?”
Beta diversity is about **composition**, not simply "how much diversity there is".

EXAMPLE

How different the gut microbiota composition is between two individuals.

DIVERSITY SCALE

Gamma Diversity

Gamma diversity is the total diversity across a larger spatial extent encompassing multiple local communities.
“How much total diversity is present across the whole landscape or region?”

EXAMPLE

The combined bacterial diversity across every soil sampled in a national park.

Quick Check: Diversity Scales

1. The number of bacterial species found in one single soil core.
2. How different community composition is between two nearby lakes.
3. The total diversity of all microbes across an entire national park.

WORD BANK

Gamma | Alpha | Beta

Quick Check: Diversity Scales — Answers

1	**Alpha**	Diversity within one sample/habitat
2	**Beta**	Turnover between samples/habitats
3	**Gamma**	Total diversity across the whole region

Classic Ecological Models Applied to Microbes

Hutchinson's Niche

The multidimensional space of conditions a species can occupy

r/K Selection

Trade-off between reproductive rate and competitive ability

Assembly Rules

Which species can co-occur, and in what order

CLASSIC MODEL

Hutchinson's Niche

A species' niche as a multidimensional space of conditions allowing survival and reproduction.

EXAMPLE

Mapping a microbe's niche simultaneously along temperature, pH and oxygen axes.

Evidence: Hutchinson's Niche

Supporting Study

Moreno-Gámez, S., Anderson, B.W., Vercelli, G.T., Altmann, F., Goodman, A.L., & Cordero, O.X. (2025). Niche partitioning by resource size in the gut microbiome. bioRxiv preprint.

MAIN ARGUMENT

Different Bacteroides species carry structurally distinct glycan transporters that specialize on different fructan chain lengths. This physical difference in resource use predicts which species outcompetes another in vivo — a clear, mechanistic case of niche differentiation.

Challenges This Model

Sloan, W.T., Lunn, M., Woodcock, S., Head, I.M., Nee, S., & Curtis, T.P. (2006). Quantifying the roles of immigration and chance in shaping prokaryote community structure. Environmental Microbiology, 8, 732–740.

MAIN ARGUMENT

Many prokaryote communities fit a neutral model in which taxa are treated as ecologically equivalent and abundance patterns arise from immigration and random birth/death, not niche differences — suggesting niche partitioning is not always the dominant force.

TAKEAWAY

Hutchinson's Niche

Niche and neutral processes **are not mutually exclusive — both operate together in real communities**. Niche differentiation tends to explain more for habitat **specialists** with clear resource trade-offs (like the Bacteroides example), while neutral, stochastic processes often explain more for **generalists** or at broader scales. **The right question is not "which theory is correct?" but "which process dominates in this specific system?"**

CLASSIC MODEL

r/K Selection

A trade-off between fast reproduction in unstable environments (r-strategists) and competitive efficiency in stable ones (K-strategists).

EXAMPLE

Fast-growing copiotrophs bloom after a nutrient pulse, while slow-growing oligotrophs dominate nutrient-poor soils.

Evidence: r/K Selection

Supporting Study

Fierer, N., Bradford, M.A., & Jackson, R.B. (2007). Toward an ecological classification of soil bacteria. Ecology, 88(6), 1354–1364.

MAIN ARGUMENT

Major soil bacterial phyla differ consistently in their response to carbon availability, supporting a copiotroph–oligotroph classification directly analogous to r/K selection — some phyla reliably dominate in resource-rich conditions, others in resource-poor ones.

Challenges This Model

Stone, B.W.G. et al. (2023). Life history strategies among soil bacteria — dichotomy for few, continuum for many. The ISME Journal, 17(4), 611–619.

MAIN ARGUMENT

Using quantitative stable isotope probing, most bacterial taxa showed overlapping, continuous growth responses rather than sorting cleanly into two strategies — only a minority of taxa fit the classic r/K dichotomy at all.

TAKEAWAY

r/K Selection

Treat the copiotroph–oligotroph (r/K) framework as a **useful simplification, not a strict rule**. It correctly predicts broad patterns — such as fast bloomers dominating after a nutrient pulse — but **most taxa fall along a continuum** rather than into two clean categories. Use it to generate hypotheses about a community, not to rigidly classify every organism in it.

CLASSIC MODEL

Assembly Rules

Rules governing which species can co-occur, shaped by traits, history and prior interactions.

EXAMPLE

Priority effects: the microbes that colonize a wound first can determine which species establish later.

Evidence: Assembly Rules

Supporting Study

Debray, R., Herbert, R.A., Jaffe, A.L., Crits-Christoph, A., Power, M.E., & Koskella, B. (2022). Priority effects in microbiome assembly. Nature Reviews Microbiology, 20(2), 109–121.

MAIN ARGUMENT

Across host-associated and environmental microbiomes — gut, phyllosphere, rhizosphere, soil and water — the order and timing of arrival repeatedly shapes which taxa establish, showing historical contingency is a real and widespread assembly rule.

Challenges This Model

Connor, E.F., & Simberloff, D. (1979). The assembly of species communities: chance or competition? Ecology, 60(6), 1132–1140.

MAIN ARGUMENT

Using null models that randomize species distributions, many co-occurrence patterns attributed to competitive “assembly rules” were statistically indistinguishable from patterns expected by chance alone — a caution against over-reading structure as rule-governed.

TAKEAWAY

Assembly Rules

Order-of-arrival and priority effects are real and well-documented in microbial systems — **but not every co-occurrence pattern reflects a deterministic "rule."** Before concluding that competition or history (rather than chance) explains a community pattern, test it against a null model. **Assembly rules are a hypothesis to test, not an assumption to start from.**

Classic Ecological Models Applied to Microbes

Hutchinson's Niche

The multidimensional space of conditions a species can occupy

r/K Selection

Trade-off between reproductive rate and competitive ability

Assembly Rules

Which species can co-occur, and in what order

What makes a good ecological model?

It is not necessarily a model that explains everything. It should:

- make **testable predictions**;
- helps us identify relevant mechanisms;
- work within a defined range of conditions;
- be challenged by empirical evidence;
- can be refined when observations do not fit its predictions.

Now that we have ecological hypotheses, how can we test them in microbial communities?

Quick Check: Classic Ecological Models

1. A fast-growing bacterium blooms right after a nutrient pulse, then is outcompeted by a slower-growing species.

2. Which species can establish in a community depends heavily on which one arrived first.

3. A microbe's tolerance range for temperature, pH and oxygen together defines where it can live.

WORD BANK

Hutchinson's Niche

r/K Selection

Assembly Rules

Quick Check: Classic Ecological Models — Answers

1	**r/K Selection**	Fast vs. slow-growing strategy trade-off
2	**Assembly Rules**	Order and history shape who establishes
3	**Hutchinson's Niche**	Multidimensional space of tolerable conditions

Spatial & Temporal Scales

Spatial

Single cell — Biofilm — Soil aggregate — Ecosystem

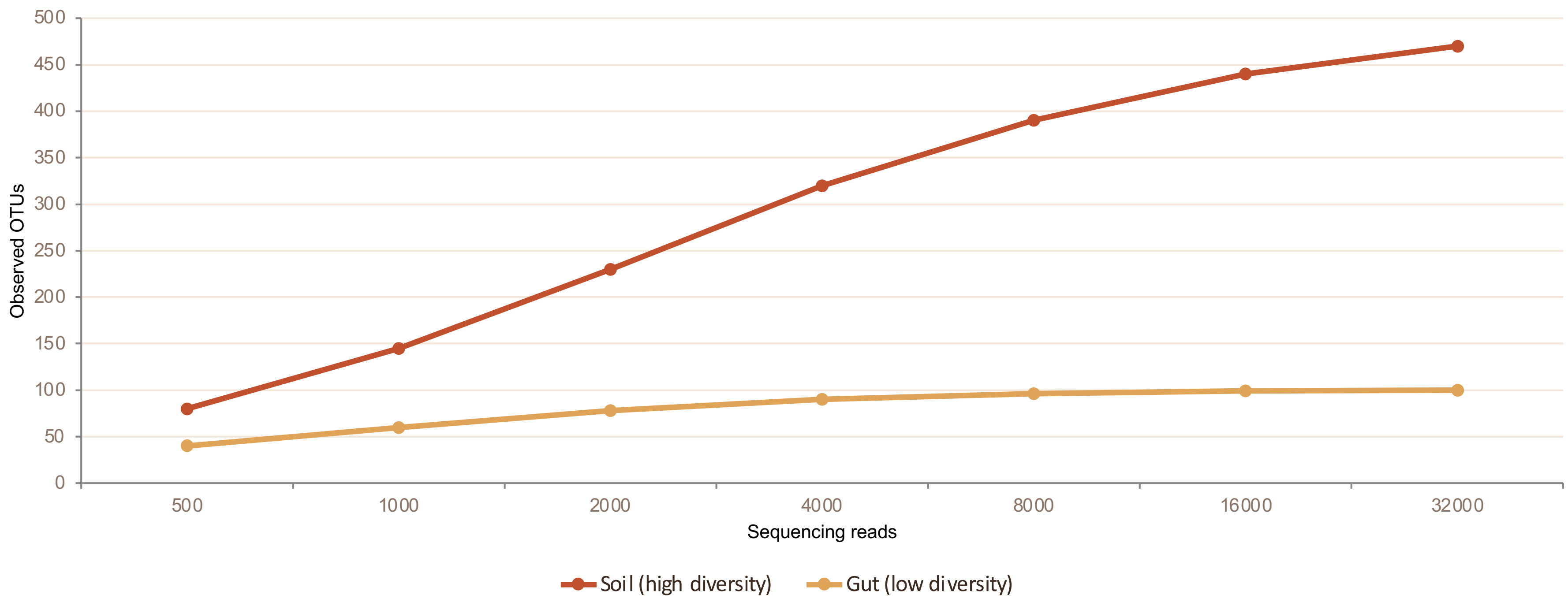
Temporal

Gene expression — Cell division — Succession — Evolution

Let's Look at the Data

Guided exercise · 15–20 minutes

Reading Rarefaction Curves



Illustrative data for teaching purposes — discuss why one curve plateaus earlier than the other

Source: Willis, A. D. (2019). Rarefaction, Alpha Diversity, and Statistics. Frontiers in Microbiology, 10, 2407.

Diversity Indices: The Formulas

Shannon Diversity (H′)

$$H' = -\Sigma\, p_i \cdot \ln(p_i)$$

PARAMETERS

p_i — proportion of individuals belonging to species i

S — total number of species (richness); the sum runs across all S species

ln — natural logarithm

Simpson's Index (1 – D)

$$D = \Sigma\, p_i^2$$

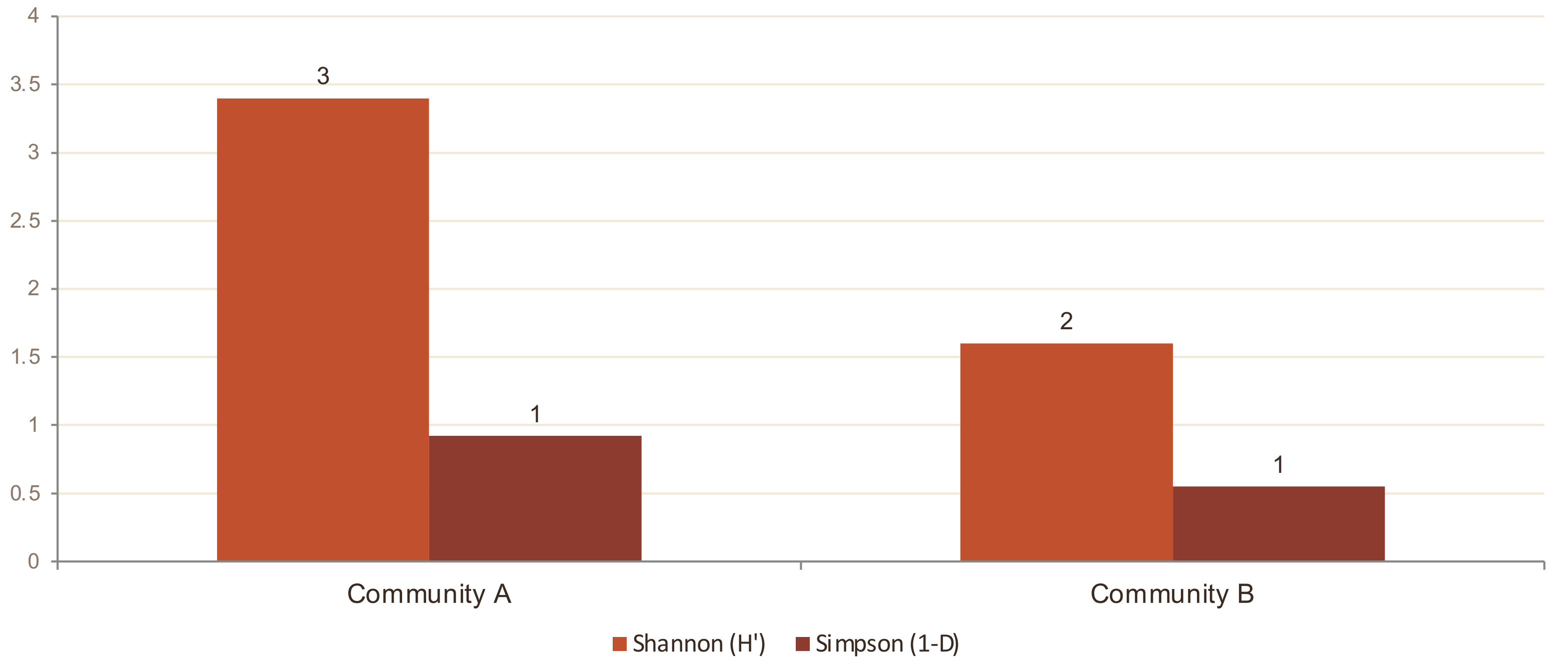
PARAMETERS

p_i — proportion of individuals belonging to species i

D — probability two randomly chosen individuals are the same species

1 – D — reported so that higher values mean higher diversity

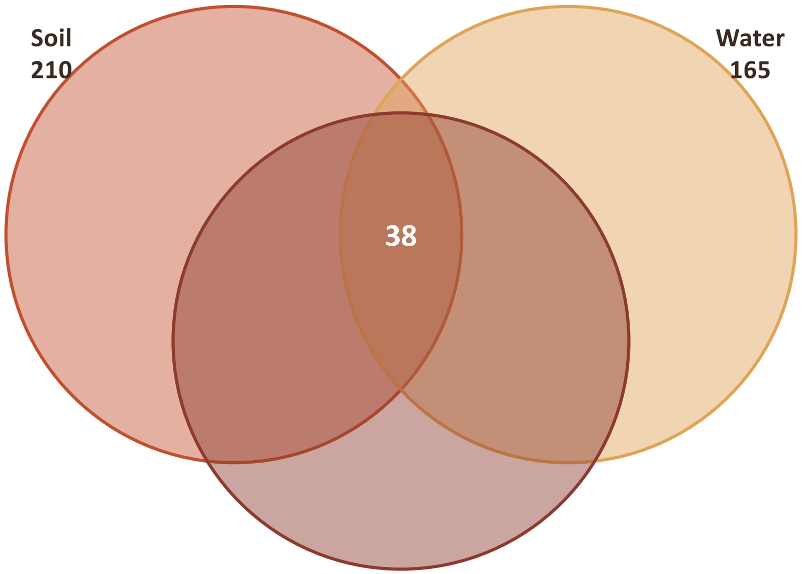
Comparing Diversity: Shannon & Simpson



Illustrative values — higher Shannon/Simpson indicates greater diversity and/or evenness

Source: Shannon, C. E. (1948). A Mathematical Theory of Communication. Bell System Technical Journal, 27, 379–423. · Simpson, E. H. (1949). Measurement of Diversity. Nature, 163, 688.

Shared and Unique OTUs Between Environments



Illustrative example — numbers represent OTU counts unique to, or shared between, each environment

Source: Diagram style after Lex, A., Gehlenborg, N., Strobelt, H., Vuillemot, R., & Pfister, H. (2014). UpSet: Visualization of Intersecting Sets. IEEE Transactions on Visualization and Computer Graphics, 20(12), 1983–1992.

Key Takeaways

Interactions — biotic and abiotic — define microbial communities

Diversity is measured across nested spatial scales: alpha, beta, gamma

Microbial ecology spans scales from micrometres to ecosystems

Next: Lecture 2 — Microbial Symbioses & Interaction Typologies