Synthetic microbial communities for engineering climate-smart biofertilizers

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Research Background

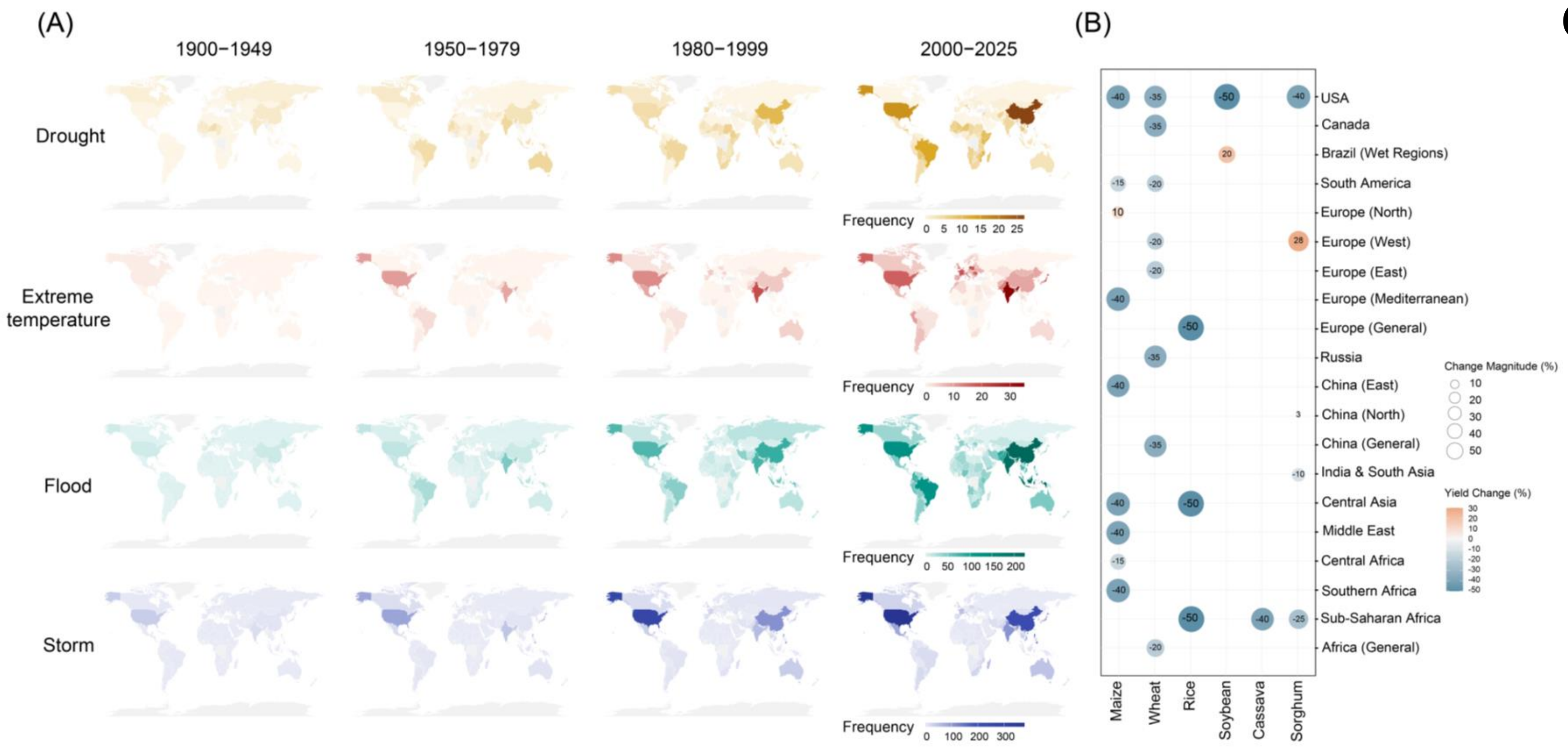


Figure S1 Historical climatic extremes and projected impacts on agricultural productivity in the future

Climate Change Threatens Food Production

- Increased frequency of extreme heat, droughts, and severe flooding.
- Declining staple crop yields with spatial heterogeneity.
- Conventional breeding and input strategies are insufficient to fully cope.

➢ Harnessing the “adaptive potential of crop microbiomes” as a novel approach.

Core Concepts

A new pathway for climate-smart agriculture (CSA): from "crop genes" to the "crop holobiont".

Traditional breeding and management

- Genotype-determined morphological and growth traits.
- Direct yield regulation through chemical fertilizers and conventional inputs.

Current climate instability

- Genetics alone cannot counter extreme weather (drought/heat/flood).
- Crop-associated microbiomes are vital but often neglected.

Crop holobiont

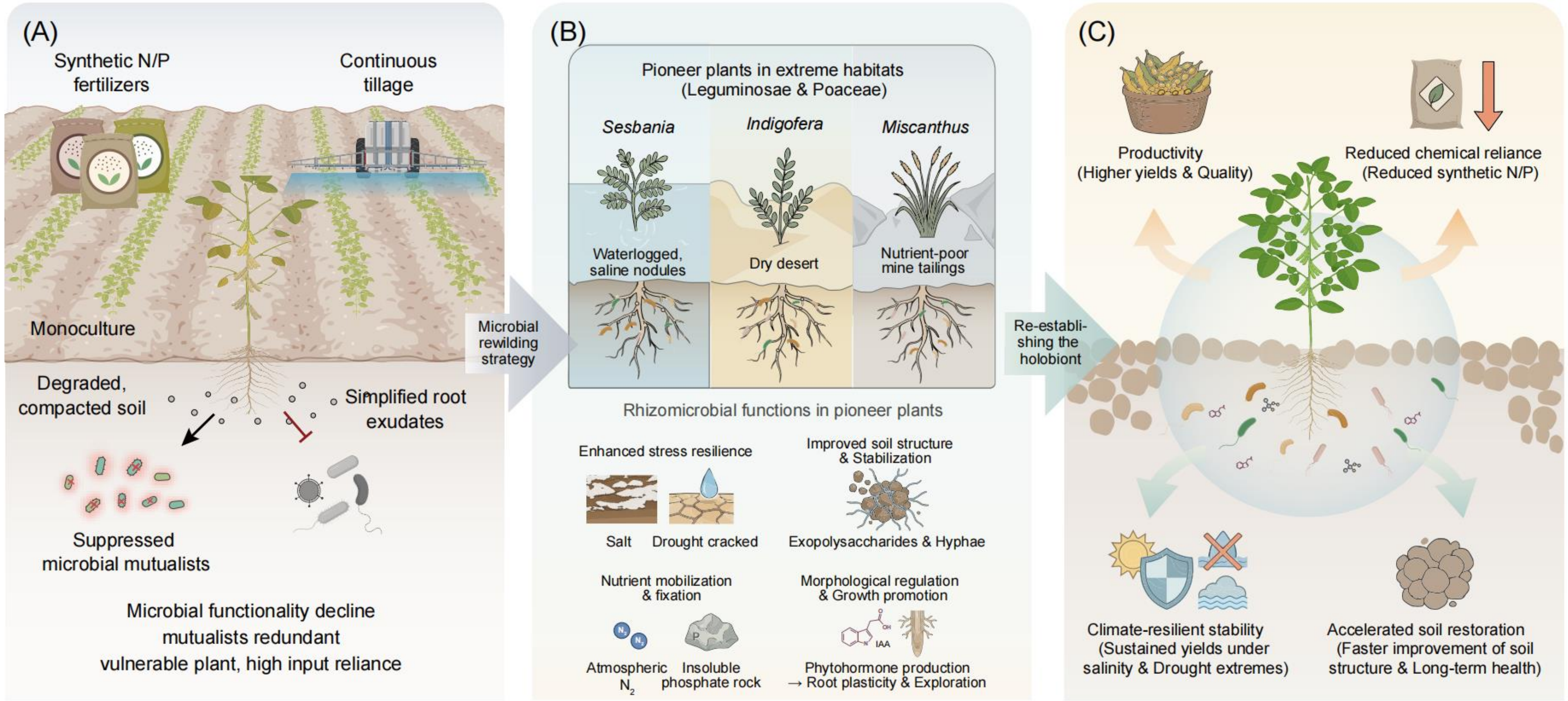
- Crop functions are not determined solely by static genes.
- Crops and their associated microbes form a synergistic system.
- Microbes modulate growth, nutrient acquisition, and stress response through various pathways.

Holobiont-driven pathways for CSA

- Empowering microbes as "functional regulators".
- Supporting the three core pillars of CSA: boosting yield and productivity, enhancing climate resilience, reducing reliance on synthetic fertilizers and inputs.

Future CSA needs to shift from a "crop-centric model" to "crop-microbiome systems engineering". This paper proposes using synthetic microbial communities (SynComs) to engineer and reproducibly deploy this regulatory capacity in the field.

Plant Microbiome Rewilding



- Traditional agriculture leads to a decline in microbial functions.
- Microbial rewilding: recovering "lost ecological functions".
- Screening for stress-adapted microbes in the rhizosphere of plants from extreme habitats.
- Constructing SynComs to achieve plant growth promotion and stress resilience.

Figure 1 Leveraging pioneer plant-associated microbes for microbial rewilding

Using plants from extreme habitats as a "microbial resource bank" to reintegrate growth-promoting and stress-resilient functions back into agricultural systems via microbial rewilding and SynCom engineering.

SynCom Construction Strategies: Top-down & Bottom-up

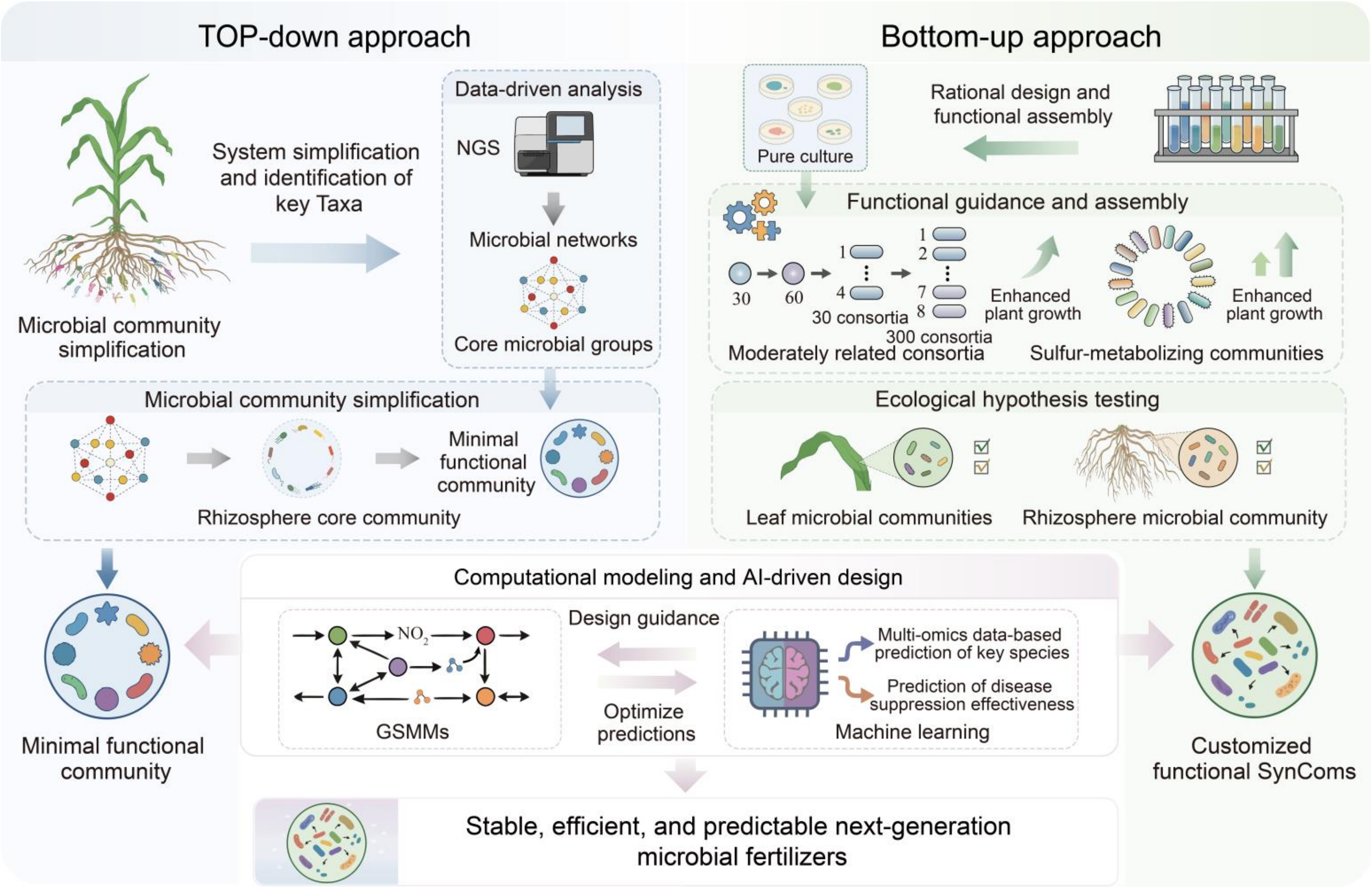


Figure S2 Design strategies for SynComs

- The top-down approach distills complex natural microbial communities into minimal functional units through network-based analysis.
- The bottom-up approach utilizes well-characterized microbial isolates to construct communities guided by ecological principles.
- Integrating computational modeling enables the rational engineering of SynComs by simulating interspecies interactions, endowing them with predictable metabolic complementarity and stability.

SynComs as "Climate Buffers" to Support Climate-Smart Agriculture

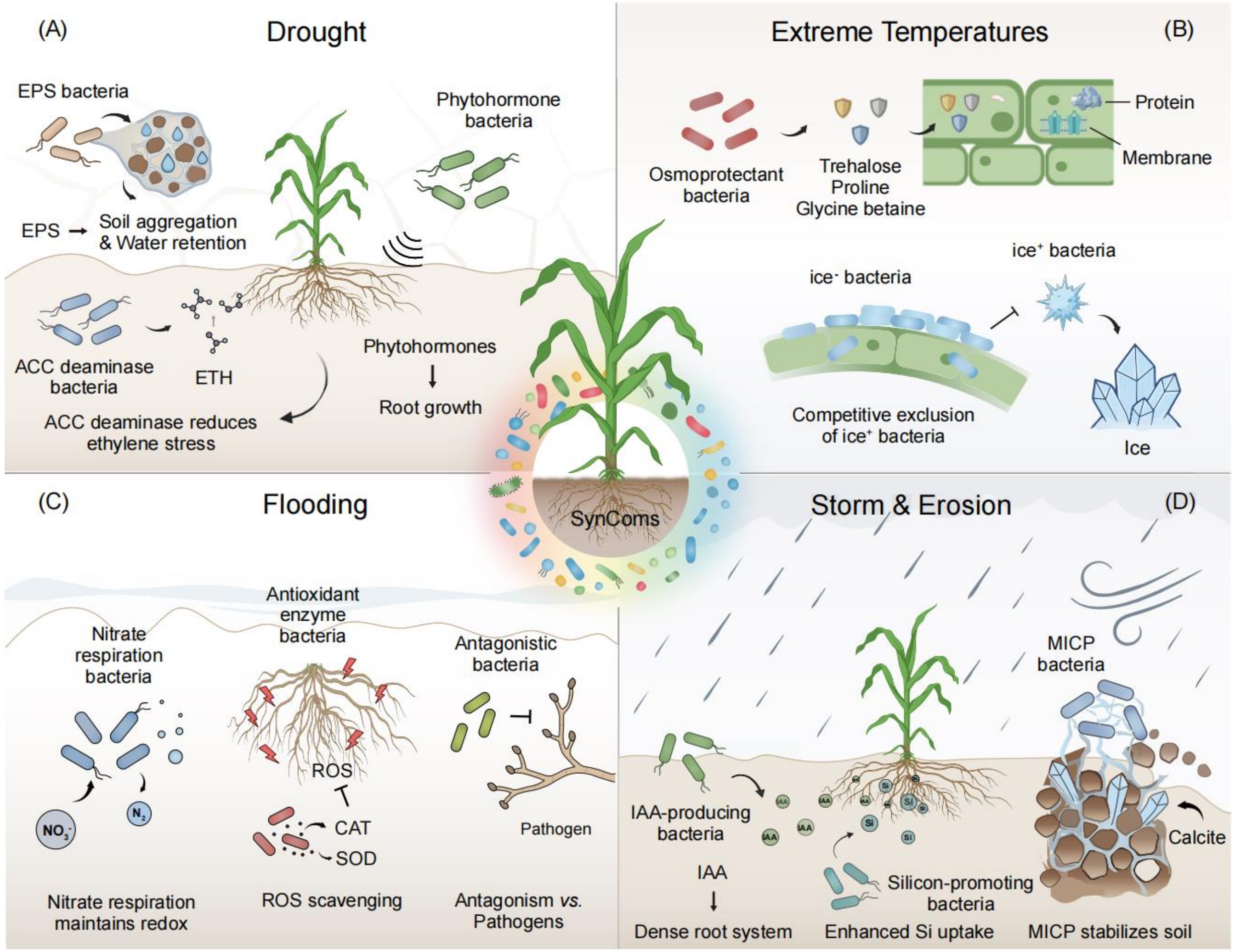


Figure 2 Proposed SynComs improve crop resilience to drought, extreme temperatures, flooding, and storms to support CSA.

- Drought: EPS/osmoprotectants/ACC deaminase/root regulation → improve drought tolerance.
- Extreme temperatures: Osmoprotectants and membrane protein protection; inhibiting ice-nucleating bacteria for cold stress → stabilize cell structures.
- Flooding: Nitrate respiration maintains redox balance; CAT/SOD mitigates ROS; inhibition of root rot pathogens.
- Storms & Erosion: MICP (microbially induced calcite precipitation) to consolidate soil; silicon strengthens cell walls; IAA regulates root systems; biofilms protect wounds.

Bringing SynComs to Practical Field Application

Key Implementation Bottlenecks

- SynCom field colonization ability
- Insufficient functional stability
- Inadequate evaluation of ecological safety and long-term risks

Proposed Solutions

- Priority effects: for better niche occupation.
- Engineered delivery systems: for root attachment and survival.
- Functional modules/guilds: for rational assembly design.
- Enhanced fitness & resilience: against environmental disturbances.
- Lab-to-field validation: for mechanistic verification.
- Long-term risk assessment: for ecological safety.

Future Research Directions

- Improving in-field predictability
- Enhancing cross-seasonal persistence
- Establishing a scalable safety assessment framework
- Integrating with existing agricultural practices

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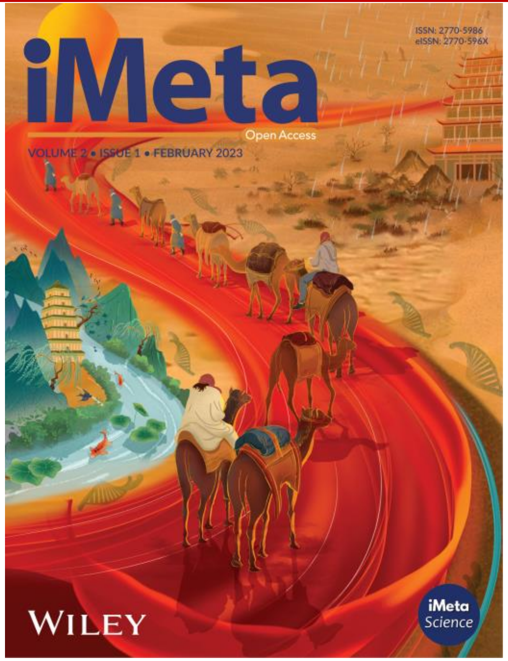

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