Title

Gastronomy meets nature positive through the conservation of invisible microbial terroir

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Abstract

Anthropogenic climate change and the expansion of mass-consumption societies pose existential threats to "microbial terroir", the cryptic microbiological assemblages that underpin the organoleptic identity and quality of traditional fermented foods. Here, we propose a framework that bridges microbial diversity, regional gastronomy, and "Microbial PES", an extension of Payments for Ecosystem Services (PES). We introduce the concept of "culture-positive", defined as a paradigm wherein the restoration of microbial diversity actively catalyzes the revitalization of regional culinary heritage. By systematically characterizing the microbial communities of production environments as quantifiable intangible assets, stakeholders can establish robust safeguards against environmental volatility, raw-material collapse, and disaster-induced interruption. We argue that linking microbial resource conservation to economic mechanisms, including premium pricing, place-based fiscal redistribution schemes, and coordinated policy roadmap, is essential for long-term sustainability. This Perspective advocates for the re-evaluation of gastronomy within the "nature-positive" agenda, necessitating proactive collaboration among policy-makers, research institutions, producers, and financial actors to preserve the world's biocultural food diversity.

Introduction

In the Anthropocene, modern gastronomy is rapidly evolving beyond the mere pursuit of culinary refinement and sensory pleasure. Driven by climate change, it is emerging as a critical interdisciplinary domain addressing planetary health, regional economies, and the foundations of human survival. To secure the sustainability of these gastronomic systems, the economic

intervention mechanism known as Payments for Ecosystem Services (PES) offers a promising avenue. While traditional PES frameworks compensate providers for visible environmental benefits, such as mineral water companies remunerating farmers for forest watershed conservation [1], recent discourse has expanded to recognize the foundational role of microbes, introducing the concept of "Microbial PES" [2]. As Ito et al. note, existing PES schemes exhibit a strong bias toward macroscopic organisms; redirecting PES to enhance microbial diversity could profoundly strengthen both soil resilience and public health. Extending this paradigm further, we propose a framework that integrates microbial diversity, regional gastronomy, and Microbial PES (Figure 1). In fermented foods, the cornerstone of global gastronomy, microbial communities are the primary determinants of flavor and quality. Consequently, the erosion of microbial diversity directly drives the impending loss of food culture. By systematically archiving these fermentative microbial assemblages and explicitly linking them to the conservation of biocultural diversity, we can establish positive feedback loops that restore and sustain culinary heritage. We define the active reversal of this intertwined loss of microbial and culinary diversity as a "culture-positive" paradigm. Under this framework, leveraging nature-positive finance to protect microbial resources simultaneously achieves ecological conservation and the capitalization of traditional fermentation processes as intangible assets.

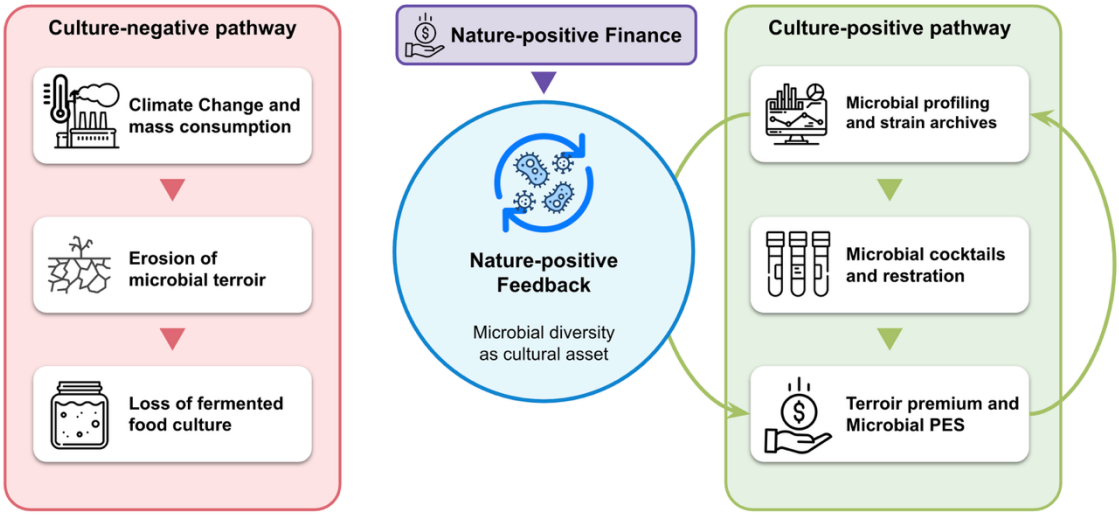

Figure 1. Conceptual framework linking climate-driven risk, microbial-terroir conservation, Microbial PES, and a culture-positive feedback loop.

Microbial terroir shaping fermented foods

Microbes transcend their fundamental ecological roles to become deeply woven into the fabric of human culinary traditions. In the realm of fermented foods, microbial assemblages across the entire production chain, from the soil nurturing the raw materials to the fermentation process itself,

act as the biological engine of *terroir*. While traditionally used in viticulture to describe how local climate, soil, and topography impart unique regional characteristics to a wine, the concept of terroir extends far beyond the vineyard. In diverse traditional fermentation systems, a product's defining organoleptic qualities are shaped not solely by intentionally inoculated starter cultures, but by "wild" microbiota migrating from the surrounding natural environment, historical architecture, and artisanal equipment [3,4]. These region-specific communities, culturally recognized in Japan as *Kuratsuki* microbes (brewery-resident microbes), are responsible for transforming rudimentary raw materials into highly complex, culturally resonant foods and beverages [5,6]. Coupled with the foundational interactions between soil microbiomes and plants that dictate regional crop flavor profiles, these dynamics underscore the profound role of microbial diversity as an "invisible terroir." This cryptic microbial layer serves as a critical biological mediator connecting natural ecosystems with high-value gastronomy. Consequently, culinary diversity can be fundamentally conceptualized as a premier ecosystem service provisioned by microbial life.

Climate change threatening fermented food culture

The erosion of biodiversity, including microbial life, is increasingly recognized as a catalyst for the loss of regional cultures [7]. Climate change exacerbates this crisis; beyond merely diminishing agricultural yields, it poses an existential threat to the microbial terroir that underpins the gastronomic identity of fermented foods. Historically, traditional fermentation ecosystems and the soils nurturing specific crops have relied heavily on climatic stability. Rising temperatures and shifting humidity levels risk pushing essential fermentative microbes, such as key yeasts and lactic acid bacteria, beyond their optimal growth thresholds, simultaneously favoring the proliferation of spoilage competitors [8–10]. Consequently, even with strict adherence to heritage recipes and identical raw materials, producers face the growing inability to replicate historical flavor profiles.

Moreover, beyond the loss of microbial diversity, we must underscore that the creation of traditional fermented foods relies on the intricate integration of multiple ecosystem resources. The vulnerability of Akita *Shottsuru* illustrates this risk at the interface of climate adaptation, marine resource management, and microbial-terroir conservation. Shottsuru is a traditional fish sauce made from *Hatahata* (Japanese sandfish), yet sandfish catches in Akita collapsed dramatically in the late twentieth century and required a three-year fishing moratorium and subsequent resource-management measures [11]. Such cases show that protecting fermented food culture requires prioritizing not only microbial archives but also the ecosystems that supply climate-sensitive raw materials. Conservation planning should therefore integrate climate-change countermeasures, fisheries and habitat management, and the identification and preservation of microbial consortia that could support future production recovery.

To mitigate the risk of fermentation failure, producers are increasingly forced to abandon the

brewery-resident microbes that impart unique regional characteristics and to shift toward robust, commercially standardized single-strain starters. While this ensures stable growth, it effectively eradicates microbial terroir and drives widespread product homogenization. Furthermore, this ecological degradation is compounded by capitalist mass consumption, which incentivizes hyper-efficient production models reliant on a severely restricted repertoire of microbial strains to consistently manufacture uniform, market-preferred flavors.

Therefore, realizing a "culture-positive" paradigm, securing microbial diversity within food systems through nature-positive initiatives, transcends broader environmental conservation goals. It is an absolute prerequisite for safeguarding minority fermentative traditions nurtured globally and ensuring their continued vitality. Priority setting should consider which food cultures are most exposed to irreversible disruption: products dependent on climate-sensitive raw materials, small producer networks, fragile production facilities, and resident microbial consortia that cannot easily be recovered once lost.

Capitalization of Microbial terroir as an intangible asset

To safeguard fermented foods against irreversible environmental degradation, microbial terroir must be redefined and protected not merely as a transient natural phenomenon, but as a quantifiable "intangible asset". Historically, research on brewery-resident microbes has heavily prioritized dominant taxonomic groups, such as specific yeasts, lactic acid bacteria, and *koji* molds. However, recent studies reveal that, driven by variations in manufacturing environments, raw materials, and production methods, a highly diverse array of non-dominant microbes colonizes production facilities and persists in final products, even among identical food types [3,12–15]. Characterizing these previously overlooked microbial communities is essential not only for stabilizing production but also for defining the unique identity of each fermented product, thereby generating a distinct intangible asset for producers.

The widespread adoption of massively parallel sequencing (MPS) [16] now enables comprehensive ecological profiling of microbiomes across production sites, raw materials, and fermenting matrices [17]. This technology facilitates the precise reconstruction of microbial transmission dynamics and temporal successions. Furthermore, high-resolution, strain-level phylogenetic classification, amplicon sequence variant (ASV)-based approaches, and variation or mutation analysis including single-nucleotide polymorphisms (SNPs) in metagenomics, together with environmental DNA/RNA monitoring and mutation-genomics approaches recently reviewed for One Health applications, allow the long-term tracking of microbial dispersal, colonization, and extinction events throughout the manufacturing process [3,18–21]. Based on the homology of sequenced data, it may be possible to redefine genetic diversity and phylogeographic information within a species as elements constituting microbial terroir.

Consequently, it is imperative for producers to fully understand the successional dynamics and functional traits of their specific microbial communities. By identifying the genetic and metabolic profiles of resident strains and archiving them in microbial repositories, traditional production methods can be rigorously codified in scientific terms. Such archives establish a critical baseline for diagnosing quality fluctuations and serve as a robust safeguard against microbial diversity loss driven by climate change or disaster-induced structural damage to historical facilities.

Microbial diversity data as a basis for asset valuation

Microbial community-structure analysis is not only a conservation tool but also a mechanism for translating microbial diversity into economic value. First, multi-site and longitudinal comparisons of phylogeographic information within the same microbial species can reveal genetic variants that are specific to a region or production landscape. Second, nationwide comparisons of *Kuratsuki* microbes can identify brewery- or region-specific community configurations that distinguish one fermentation ecosystem from another. These two layers, strain-level geographic lineage information and community-level uniqueness, make the intangible assets to be conserved clearer in both quantitative and qualitative terms.

When sensory, metabolomic, and fermentation studies clarify how flavor, quality, microbial community structure, and genetic diversity are linked, the value of these assets increases because producers can explain why their terroir is biologically distinctive and culturally irreplaceable. This evidence base then makes it easier to design targeted capital inflows and Microbial PES mechanisms, creating a culture-positive pathway that maintains the diversity of craft production and regional food-making practices (Figure 2).

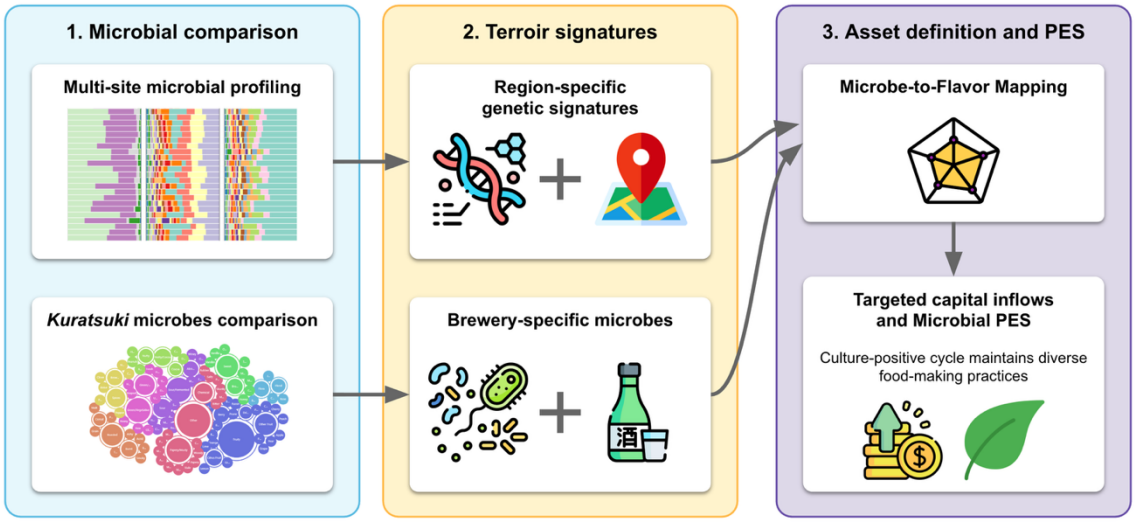

Figure 2. Pathway through which microbial community-structure analysis converts region-specific genetic and community information into intangible asset valuation, Microbial PES design, and

culture-positive finance.

To faithfully recreate the organoleptic complexity of traditional fermented foods, we propose reconstructing regional microbial terroir as "microbial cocktails", leveraging recorded genomic data alongside advanced strain isolation and preservation techniques. Traditionally utilized primarily as analytical standards, microbial cocktails are synthetic communities artificially assembled at specific ratios based on comprehensive database cross-referencing. In this Perspective, we advocate for repurposing these synthetic communities as specialized fermentation starters, thereby establishing the technology necessary to reproduce profound flavor profiles unattainable via single-strain inoculations. The accumulation of such genomic data, combined with physically preserved strains, functions as a definitive "flavor blueprint". This dual repository provides an essential reference base for environmental restoration and quality recovery should a region's microbial terroir be compromised by facility aging, relocation, climatic shifts, or the temporary interruption of production.

Investment for the conservation of fermented foods and their terroir through Microbial PES

Operationalizing this framework requires coupling the protection of microbial resources with concrete payment mechanisms. Applying Microbial PES within gastronomy is a pivotal step toward realizing a "culture-positive" paradigm that simultaneously safeguards microbial and culinary heritage. For high-value, region-specific fermented products, manufacturers must justify premium pricing by providing scientific evidence that explicitly links microbial terroir to organoleptic quality. Evidence of region-specific lineages and distinctive *Kuratsuki* microbes can further define what is being conserved and why it has asset value. A designated "terroir conservation premium" can then be reinvested directly into microbiome analysis, strain cryopreservation, and robust quality assurance systems. Furthermore, the recording and conservation of microbial terroir should be designated as explicit targets for place-based fiscal redistribution schemes and crowdfunding initiatives. For instance, Corporate Hometown Tax (*Kigyo-ban Furusato Nozei*), which redirects individual tax contributions to local municipalities in exchange for regional specialties, presents a highly promising PES vehicle for preserving both local culture and microbial diversity.

However, artisanal producers, who rely most heavily on microbial diversity, often lack the financial resilience to independently implement Microbial PES. To address this disparity, policy-makers must urgently recognize that mitigating microbial diversity loss is foundational to a sustainable food industry. Aligning corporate investments with nature-positive finance and the Taskforce on Nature-related Financial Disclosures (TNFD) framework will facilitate the expansion of Microbial

PES into the gastronomic sector. To translate nature-positive finance into practical action within the gastronomic sector, we propose integrating Microbial PES into existing corporate and regional economic frameworks, drawing on biocultural conservation models (Table 1). First, under the TNFD framework, large food and beverage enterprises can deploy supply chain finance to support artisanal producers. Analogous to corporate investments in upstream watershed conservation, conglomerates can provide technical subsidies or transition loans for microbiome monitoring and biobanking at small historic breweries, integrating these efforts into their own supply-chain (Scope 3) nature-related disclosures. Second, regional governments can utilize Corporate Hometown Tax (*Kigyo-ban Furusato Nozei*) schemes to establish localized "Microbial Terroir Funds." This mechanism allows corporations to make tax-deductible donations to municipalities, which can be explicitly earmarked for the maintenance of aging traditional facilities, such as wooden fermentation vats (*Kioke*) and strain cryopreservation. Finally, to establish sustainable consumer-driven finance, microbial diversity indicators should be integrated into Geographical Indications (GI) and premium eco-labeling. Much like Japan's "Crested Ibis-certified rice" (Sado) and "Stork-friendly farming" (Toyooka), which successfully channel consumer premiums into habitat restoration, certifying the use of validated indigenous *Kuratsuki* microbes allows producers to command a "terroir premium." This multi-tiered approach ensures that nature-positive capital flows directly into the tangible preservation of both microbial assets and the traditional production environments that sustain them. Catalyzing these multi-layered financial inflows at a national scale requires unprecedented collaboration between environmental conservation agencies and agricultural authorities. Rather than treating "nature-positive" initiatives as an isolated environmental mandate, agricultural sectors must proactively harness nature-positive finance to conserve their domestic food cultures. Failing to support food and the environment as an integrated system risks the irreversible loss of both microbial and culinary diversity under the pressures of climate change.

Table 1

Target Activities (Use of Funds)	Strategic Incentives & Frameworks	Analogous Conservation Models
Microbiome monitoring, microbial biobanking at small historic breweries.	Alignment with TNFD framework; Scope 3 nature-related disclosures; ESG goals.	Corporate investments in upstream watershed conservation.
Establishment of "Microbial Terroir Funds"; maintenance of	Tax-deductible donations; regional	Place-based fiscal redistribution schemes; Individual *Furusato*

aging traditional facilities (e.g., wooden *kioke*); strain cryopreservation.	economic revitalization; fulfillment of localized CSR.	*nozei*.
Microbiome analysis, quality assurance systems, preservation of *Kuratsuki* microbes.	Market incentives; "terroir premium" pricing justified by scientific evidence of quality.	"Crested Ibis-certified rice" (Sado) & "Stork-friendly farming" (Toyooka).

Simultaneously, a paradigm shift within the scientific community is essential to translate these secured funds into actionable solutions. Public and private biological resource centers, traditionally tasked with the ex situ preservation of microbes, must transcend their roles as mere genetic repositories. They should actively help identify, validate, and preserve microbial consortia that allow production to restart even after climate-related raw-material shortages, facility damage, or temporary closure. Through integrated administrative support and proactive research collaboration, we can safeguard the traditional production systems of small- and medium-sized enterprises worldwide. The time is ripe to comprehensively reframe gastronomy rooted in the conservation and valuation of microbial diversity within the nature-positive agenda.

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