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Farm-level strategies for conserving crop genetic diversity in marginal environments

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Abstract
In marginal environments—regions characterized by climatic uncertainty, soil degradation, and infrastructural limitations—conserving crop genetic diversity becomes a cornerstone of agricultural sustainability. While institutional genebanks contribute significantly to ex situ conservation, the role of farmers in maintaining dynamic in situ diversity on their own land is critical yet under-acknowledged. This paper systematically explores farm-level strategies used to conserve crop genetic diversity in challenging agroecological zones. Drawing on global case studies, peer-reviewed research, and indigenous knowledge systems, we examine mechanisms such as landrace maintenance, seed selection, intercropping, and community seed systems. The analysis reveals that farmer-driven diversity conservation not only sustains genetic resources but also reinforces adaptive resilience in the face of climate change. Institutional support, participatory breeding, and policy frameworks are also evaluated to understand how in situ efforts can be mainstreamed into national agricultural systems.

Keywords: In situ conservation, agrobiodiversity, landraces, seed systems, climate adaptation, marginal agriculture, traditional knowledge

1. Introduction
Crop genetic diversity underpins global food security. It provides the raw material for breeding climate-resilient varieties and maintaining ecosystem services in farming landscapes (FAO, 2010) [8]. This is particularly vital in marginal environments—areas that are ecologically fragile, economically constrained, and agriculturally sub-optimal. These regions, despite their constraints, are often biodiversity hotspots due to centuries of localized crop adaptation and farmer selection (Brush, 2004) [6].

The Green Revolution's focus on high-yielding uniform varieties led to widespread genetic erosion in such areas. Homogenized cropping systems have replaced diverse landraces, leaving farming communities vulnerable to pests, droughts, and market shocks (Bellon, 2006) [5]. However, many smallholder farmers continue to maintain traditional varieties, adapting them through generations.

This paper focuses on those on-farm strategies—practices farmers use at the household or community level to conserve crop diversity under real-world production pressures. It integrates agronomic, ecological, and social dimensions of conservation.

2. Marginal Environments: Definitions and Importance
Marginal environments are defined by low-input, high-risk farming conditions. These may include arid and semi-arid zones, hill tracts, and flood-prone or degraded lands. Such regions are often underrepresented in formal breeding programs but harbor high levels of agricultural biodiversity (Jarvis *et al*., 2011) [9].

Traditional varieties grown here—such as drought-tolerant millets, hardy pulses, or deep-rooted sorghums—represent locally adapted genetic pools. Their traits include:

- Resistance to abiotic stresses (e.g., drought, salinity),
- Resistance to local pests/diseases,
- Compatibility with mixed cropping and subsistence systems.

Table 1 highlights key features of landraces maintained in marginal zones.

Table 1: Characteristics of Landraces in Marginal Environments

Feature	Description	Example
Genetic Heterogeneity	Broad intra-varietal diversity	Ethiopian barley
Environmental Adaptation	Evolved under drought/frost/low input	Indian minor millets
Farmer-Driven Selection	Selected based on taste, rituals, storage	Nepali rice landraces
Seed Sovereignty	Retained and exchanged by local networks	Sahelian sorghum

(***Source***: Bellon, 2006; Ceccarelli & Grando, 2007) [5, 7]

3. On-Farm Conservation Strategies

3.1. Seed Selection and Maintenance

Farmers routinely select seeds based on traits like grain quality, maturity, pest resistance, or cultural value. This seasonal selection process serves as a mechanism of both conservation and microevolution.

For instance, in Oaxaca, Mexico, maize farmers select from within-field variability to maintain both yellow and white kernels based on food processing needs (Louette *et al*., 1997) [11]. Such practices enhance adaptive diversity while retaining cultural integrity.

"Farmers select not only for performance but also for memory, symbolism, and shared identity" — Brush (2004) [6].

3.2. Intercropping and Agroecological Heterogeneity

Diverse cropping systems buffer risk and promote niche-specific genotype expression. Intercropping cereals with legumes (e.g., maize-beans, sorghum-cowpea) is common across Africa and Latin America.

This heterogeneity allows multiple varieties to coexist, enabling temporal and spatial conservation. Soil fertility, moisture use, and pest cycles are also better managed under polycultures (Altieri *et al*., 2012) [2].

3.3. Cultivation of Multiple Landraces

In Nepal and Ethiopia, households often cultivate 4-6 landraces of a single crop like rice or barley (Joshi *et al*., 2013) [10]. Each variety serves different uses—cooking, brewing, festivals—or is suited to specific microclimates.

This risk-spreading strategy is more common among women farmers and Indigenous communities who act as custodians of traditional germplasm.

"The more landraces you keep, the less likely you are to lose everything" — Local proverb, Tigray, Ethiopia

3.4. Farmer-to-Farmer Seed Exchange

Informal seed systems dominate in marginal areas, with up to 80% of seeds exchanged outside formal markets (Almekinders & Louwaars, 2002) [1]. These networks facilitate genetic flow and prevent genetic drift or isolation. Figure 1 visualizes how decentralized exchange systems maintain diversity.

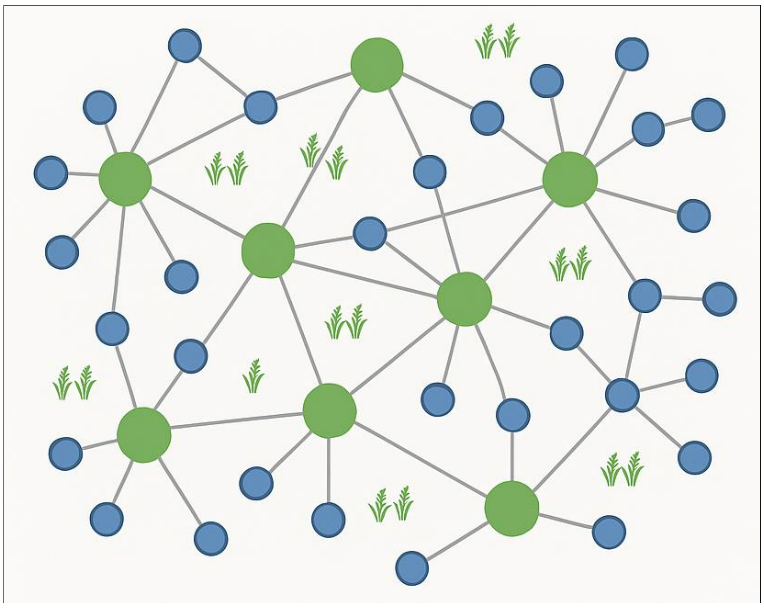

Fig 1: Role of Community Seed Networks in Conserving Diversity (Source: Adapted from Badstue *et al*., 2007) [4].

Central nodes = Seed-rich households, Edges = Exchange pathways

=Diversity hubs emerge from frequent exchange

4. Institutional and Policy Support Mechanisms

In the landscape of farm-level conservation, institutional and policy support mechanisms play a pivotal role in bridging grassroots practices with broader agricultural systems. While traditional farming communities have long nurtured agrobiodiversity through seed selection and informal exchange networks, their efforts can be significantly bolstered through structured interventions that enhance access, security, and continuity of genetic resources. One of the most effective institutional models supporting on-farm conservation is the community seed bank. These are locally managed repositories where farmers collectively store, multiply, and share traditional varieties. Unlike commercial seed stores, these banks focus not on profit but on conservation, resilience, and local food security. By preserving landraces within the agroecological zones they evolved in, community seed banks maintain the evolutionary dynamics of crop populations, enabling them to adapt continually to changing conditions. Initiatives such as Navdanya in India and millet banks in West Africa exemplify how local ownership over seed resources fosters empowerment and ecological stewardship.

Beyond local seed banks, participatory plant breeding (PPB) has emerged as an effective strategy for integrating scientific research with farmer knowledge. PPB invites farmers to co-develop varieties that reflect local preferences, farming practices, and environmental challenges. These programs reject the one-size-fits-all approach of centralized breeding and instead generate varieties that are genetically diverse, ecologically fit, and socially relevant. In many regions, this has led not only to better yields but also to the conservation of traits otherwise overlooked in formal breeding pipelines. In Syria, for instance, farmers engaged in barley breeding were able to improve both yield and stress tolerance while retaining the crop's local adaptability and genetic richness.

Policy and legal frameworks further shape the viability of on-farm conservation. The recognition of Farmers' Rights under the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) represents a global commitment to protect the traditional custodians of crop diversity. Countries like India and Ethiopia have attempted to embed these rights into national policies by acknowledging traditional knowledge, seed sovereignty, and community-based conservation efforts. However, despite these advances, contradictions remain. Commercial seed laws, which emphasize certification and uniformity, often marginalize the informal seed sector. Intellectual property rights (IPRs) create legal and economic barriers for farmers wishing to share or replant seeds of traditionally cultivated varieties. These regulatory tensions highlight the need for legal reforms that prioritize conservation over commercialization, and local knowledge over corporate ownership.

Supportive policies must therefore strike a balance—ensuring that biodiversity conservation is not restricted to scientific institutions or cold-storage genebanks, but is recognized as a living, dynamic process sustained by communities in marginal environments. This involves not only legal recognition but also investment in infrastructure, training, and institutional linkages that enhance the capacity of farmers to conserve, innovate, and exchange genetic resources. In the face of climate uncertainty and ecological degradation, such integrated institutional and policy support becomes essential to secure the future of global agrobiodiversity.

5. Case Study: Millets in India's Deccan Plateau

The Deccan Plateau of India, stretching across parts of Karnataka, Andhra Pradesh, Telangana, and Maharashtra, presents a compelling example of how farm-level conservation can revive agrobiodiversity, empower local communities, and enhance climate resilience. Millets, once central to the food systems of this region, had witnessed a steep decline due to the Green Revolution's emphasis on high-yielding cereals like rice and wheat. These minor cereals—sorghum, finger millet, foxtail millet, and others—had traditionally thrived in the plateau's dry, low-fertility soils. However, they were gradually marginalized by policies, subsidies, and market systems that favored input-intensive crops. Despite these challenges, grassroots initiatives led by local communities and civil society organizations have orchestrated a remarkable turnaround in millet cultivation.

At the heart of this revival lies a farmer-led conservation movement that treated millets not just as crops, but as cultural and nutritional anchors of the region. The Deccan Development Society (DDS), a well-known grassroots organization, has been instrumental in empowering women farmers, especially from marginalized Dalit communities, to reclaim their millet-based agroecological traditions. By establishing decentralized seed banks, organizing seed festivals, and training farmers in ecological farming practices, DDS facilitated the reintroduction of over 60 traditional millet varieties that were on the verge of extinction. These varieties were selected, stored, and exchanged by farmers themselves, ensuring that seeds remained in the community, adapted to local conditions, and retained their genetic richness.

The millet revival in the Deccan Plateau is not merely about conserving crop varieties; it represents a holistic approach to sustainability. Millets are inherently resilient to drought, require minimal water, and can grow in degraded soils with little or no chemical inputs. Their return to prominence has helped farmers reduce dependency on expensive external inputs while restoring the health of local agroecosystems. Moreover, millets hold significant cultural value in rural diets, rituals, and festivals. The process of reviving them has thus led to a cultural reawakening, especially among women who have emerged as seed custodians and knowledge holders.

Institutional support has played a catalytic role in this transformation. Programs encouraging public procurement of millets for government nutrition schemes have created stable markets, while policy advocacy has led to greater recognition of millets as "nutri-cereals." This case illustrates how farm-level conservation, when supported by community mobilization and enabling policies, can become a powerful strategy for sustainable development. The Deccan millet story underscores that conserving genetic diversity is not a backward-looking endeavor, but a dynamic process that reconnects agriculture with food sovereignty, ecological balance, and social justice

6. Broader Benefits of Farm-Level Conservation

Farm-level conservation offers a multidimensional set of benefits that go beyond merely preserving crop genetic resources. At its core, this approach reinforces ecological resilience, social equity, and cultural continuity—elements that are increasingly vital in a world facing climate volatility, market fluctuations, and biodiversity loss. One of the most critical benefits lies in its contribution to climate resilience. Diverse traditional varieties maintained on farms often harbor genetic traits that make them more tolerant to drought, heat, salinity, and other environmental stresses. Unlike modern uniform cultivars that may fail under extreme conditions, landraces provide a buffer, allowing farming systems to remain productive and adaptive amidst changing climates. Their genetic variability is not static; it continues to evolve through natural selection and farmer practices, offering a living reservoir of traits crucial for future breeding programs.

Another significant advantage of farm-level conservation is the strengthening of food sovereignty. When farmers save, exchange, and replant their own seeds, they reduce dependency on external inputs and corporate seed systems.

This autonomy enhances local control over food systems, fosters innovation at the grassroots level, and ensures that farming remains economically and culturally sustainable. In marginal areas, where access to commercial seeds may be limited or inappropriate, this seed sovereignty becomes essential for livelihood security.

Cultural heritage is also deeply embedded in on-farm conservation practices. Many landraces are not just agronomic resources but hold ritualistic, medicinal, and culinary significance for local communities. The maintenance of these varieties ensures the continuity of traditional knowledge systems and community identity. For example, red rice varieties used in Sri Lankan festivals or specialty millets consumed during tribal ceremonies in India reflect how biodiversity and culture are intertwined. Conserving these crops keeps alive the histories, languages, and traditions of Indigenous and local communities.

Furthermore, farm-level conservation provides critical raw material for scientific plant breeding. Landraces often contain unique genes for disease resistance, nutrient efficiency, or environmental tolerance that are absent in modern cultivars. These traits can be incorporated into new varieties to improve yield stability or adapt crops to emerging challenges such as new pathogens or erratic rainfall patterns. By conserving diverse crop populations in situ, farmers inadvertently serve as frontline contributors to national and global food security.

Lastly, the ecosystem services promoted by diverse farming systems—such as improved soil health, pest regulation, and pollinator support—further underscore the ecological value of farm-level conservation. Unlike monocultures, which often degrade ecosystems, diversified farms enhance resilience at the landscape level. Taken together, these benefits reveal that farm-level conservation is not merely a rural practice—it is a strategic and holistic approach to building sustainable food systems that align ecological integrity with human wellbeing.

7. Challenges and Future Outlook

Despite its critical importance, farm-level conservation faces a range of challenges that threaten its sustainability and expansion, particularly in marginal environments. One of the most pressing concerns is the dominance of market forces that prioritize uniform, high-yielding crop varieties tailored for industrial agriculture. These varieties are often promoted through seed subsidies, extension services, and supply chains that exclude traditional crops. As a result, landraces—although better suited to local conditions—are pushed to the margins, deemed uncompetitive or "obsolete" in modern agricultural discourse. This commodification of agriculture reduces the incentive for farmers to maintain diverse traditional varieties, leading to erosion not just of genetic resources but also of the knowledge systems that support them.

Demographic shifts also contribute to the fragility of farm-level conservation. The migration of rural youth to urban centers, driven by economic aspirations and lack of opportunities in agriculture, weakens the intergenerational transmission of seed knowledge. As elders pass on, the stories, criteria, and experiences that underpin seed selection and crop adaptation risk being lost. Formal education systems, which often disregard traditional agricultural knowledge, further widen this disconnect. Additionally, many minor crops cultivated in marginal areas suffer from neglect in public research agendas and funding priorities, receiving little attention compared to globally traded staples like wheat, rice, or maize.

Yet within these challenges lie new and emerging opportunities. Digital tools such as mobile apps, community-based seed mapping platforms, and open-source databases offer innovative means to document, share, and protect traditional crop knowledge. These technologies can be tailored to local languages and contexts, enabling farmers—especially women and Indigenous groups—to actively participate in agrobiodiversity monitoring and knowledge exchange. Moreover, participatory seed fairs, farmer-scientist collaborations, and citizen science models are gaining traction as effective mechanisms to integrate experiential knowledge with scientific data. Such efforts not only validate traditional practices but also open new avenues for decentralized innovation.

On the policy front, there is growing global recognition of agrobiodiversity as a form of climate infrastructure. Climate adaptation frameworks and sustainability programs increasingly acknowledge the role of diverse local crops in buffering shocks, ensuring nutrition, and reducing input dependency. Redirecting climate finance and agricultural subsidies toward smallholder-led conservation could transform these systems from informal, under-supported practices into recognized pillars of resilience and sustainability. Education and capacity-building programs, especially those that include traditional custodians of biodiversity in the design and delivery of curricula, are essential to re-embed conservation values within both formal institutions and community life.

The future of farm-level conservation depends on a collective paradigm shift—one that values diversity over uniformity, local wisdom over top-down prescription, and sustainability over short-term gain. By integrating farmer knowledge, scientific tools, and supportive policies, it is possible to safeguard the living diversity that sustains both ecological systems and cultural identities. What is needed is not only protection but active investment in the people, landscapes, and practices that have long preserved our agricultural heritage under some of the most challenging conditions on Earth.

8. Conclusion

Farmers in marginal environments are not merely recipients of technology but active stewards of genetic resources. Through their daily decisions, they conserve traits essential for resilience, nutrition, and future breeding. Recognizing, documenting, and supporting these systems is not just an ethical imperative—it is a strategic investment in global food security. Moving forward, farm-level conservation must be embedded in climate policy, research funding, and agricultural education to ensure that diversity thrives not in cold storage, but in living landscapes.

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