

Review

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Review

Institutions as Drivers of Vulnerability: Yield Imperatives, Seed Governance, and the Erosion of Agrobiodiversity Under Climatic Stress in Ethiopia

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Abstract

While climate change creates the overarching biophysical stress on Ethiopian agriculture, institutional and governance structures primarily mediate agrobiodiversity outcomes, often trading evolutionary resilience for short-term productivity. This review synthesizes cross-sectoral evidence from Ethiopia’s major highland and rangeland systems to demonstrate that climate change acts as a systemic stress test, exposing latent vulnerabilities in agricultural policy, seed regulation, and land tenure systems. The widespread loss of agrobiodiversity, documented by genetic erosion rates ranging from 56% in barley to over 65% in teff and wheat, including total displacement in certain districts, is largely driven by a structural conflict between productivity imperatives and ecological stewardship. Our synthesis reveals that policy silos, top-down extension models, and regulatory biases toward genetic uniformity collectively erode the functional heterogeneity required for climate adaptation. This institutional failure necessitates a governance-centered framework that formalizes pluralistic seed systems and empowers decentralized farmer innovation. Realigning governance incentives to treat agrobiodiversity as a strategic national asset is essential for securing Ethiopia’s genetic capital against accelerating climatic stress.

Keywords: Ethiopia; agrobiodiversity; seed governance; climate change adaptation; institutional pluralism; genetic erosion; land tenure security; socio-ecological resilience

1. Introduction

Across the climate-vulnerable landscapes of the Global South, agrobiodiversity constitutes a foundational pillar of socio-ecological resilience, anchoring smallholder livelihoods against increasing environmental variability and uncertainty (Altieri et al., 2015; Zimmerer et al., 2022; Lipper et al., 2014). In Ethiopia’s highly heterogeneous agrarian systems, the conservation of genetic resources, particularly crop landraces and wild relatives, represents far more than a residual expression of traditional farming (Worede, 1991; Negisho et al., 2021). Instead, it functions as a deliberate, knowledge-intensive risk management strategy, enabling farmers to buffer climatic shocks, stabilize production, and maintain adaptive flexibility under fluctuating environmental conditions (Pascual et al., 2017; Jarvis et al., 2011; FAO, 2019; Abay et al., 2009). These biological resources collectively constitute a form of ecological insurance, preserving evolutionary potential and supporting long-term adaptive capacity in the face of accelerating climate change (Zimmerer et al., 2022; Hodgkin et al., 2015).

However, the efficacy of these biological resources as a resilience mechanism is increasingly undermined by anthropogenic climate change (Bogale, 2023). Rising mean temperatures, increasing rainfall variability, and the intensification of extreme climate events, particularly recurrent droughts and episodic flooding, are reshaping Ethiopia’s agro-ecological zones, directly constraining crop phenology, yield stability, and livestock productivity (IPCC, 2014; Bewket & Conway, 2007; Conway

& Schipper, 2011; Kassie et al., 2014). These pressures drive genetic erosion by displacing locally adapted crop varieties and indigenous livestock breeds, thereby reducing within-species diversity and narrowing adaptive capacity (Hammer & Laghetti, 2005; Bezabih et al., 2014; Tsegaye & Berg, 2007). Meanwhile, the degradation and fragmentation of surrounding habitats threaten crop wild relatives, diminishing the genetic diversity vital for future breeding and climate adaptation (Solomon et al., 2007; Maxted et al., 2008; FAO, 2019).

While the biophysical impacts of climate change on Ethiopian agriculture are well documented, a narrow focus on climatic drivers risks obscuring the decisive role of governance in structuring biodiversity outcomes. Socio-ecological systems theory emphasizes that environmental stressors rarely act in isolation; rather, their effects are mediated through institutional arrangements, policy incentives, and power relations that structure decision-making, resource access, and adaptive capacity (Ostrom, 2009; Folke et al., 2005; Lemos et al., 2012). In this framing, climate change operates less as an autonomous driver of genetic erosion than as a systemic stress test that amplifies pre-existing institutional vulnerabilities embedded within agricultural development strategies, conservation paradigms, and regulatory frameworks.

Ethiopia's agrobiodiversity governance is characterized by a fragmented institutional landscape, wherein agricultural development, environmental conservation, and climate adaptation policies operate largely in parallel, lacking effective cross-sectoral coordination or strategic integration (Spielman et al., 2011; Jiren et al., 2021; Vatn, 2015). Historically, agricultural policy has prioritized yield maximization and short-term caloric security, frequently incentivizing the adoption of uniform, high-input crop varieties and standardized livestock breeds (Gebru, 2021; Abate et al., 2015; Spielman et al., 2010). While these interventions have contributed to localized productivity gains, they have simultaneously accelerated varietal turnover and displaced indigenous genetic resources, particularly in high-risk agro-ecological zones such as Somali and Afar lowlands, Bale and Arsi highlands, and drought-prone Rift Valley districts (Tsegaye & Berg, 2007; Abate et al., 2015). In parallel, environmental governance frameworks have often been shaped by exclusionary "fortress conservation" paradigms that separate biodiversity protection from agricultural production, limiting the integration of farmer-managed diversity into national conservation strategies (Adams & Hutton, 2007; Brockington, 2002).

These governance failures are not peripheral; they are structurally determinative. Agrobiodiversity does not persist through ecological processes alone but is actively produced, maintained, and transformed through institutional arrangements governing circulation, land tenure, extension services, and market integration (Lipper et al., 2014; Jarvis et al., 2016; Berg & Haug, 2015; Mulesa, 2021). Policy design, therefore, exerts direct influence over which genetic resources are conserved, improved, marginalized, or lost. Yet, existing Ethiopian scholarship has largely emphasized crop physiological responses to climate stress and technological strategies for yield stabilization, with limited attention to the institutional architectures governing agrobiodiversity trajectories (Deressa et al., 2011; Abate et al., 2015; Di Falco et al., 2007). This review addresses that gap by synthesizing evidence on climate dynamics, governance structures, and biodiversity outcomes, identifying key institutional pathways, specifically seed system integration, land tenure security, and decentralized participatory extension frameworks, through which Ethiopia's genetic heritage can be safeguarded under accelerating climatic uncertainty.

2. The Governance–Climate–Biodiversity Nexus: Synthesis of Multi-Scalar Challenges

Agrobiodiversity outcomes in Ethiopia are structured as much by governance frameworks as by climatic variability itself (Bezabih et al., 2014). Rather than acting as an autonomous biophysical driver, climate change primarily functions as a systemic stressor that exposes and amplifies latent institutional weaknesses embedded within agricultural policies, regulatory regimes, and incentive structures (Ostrom, 2009; Folke et al., 2010; Lemos et al., 2016). Genetic erosion is therefore not an inevitable consequence of environmental change alone; instead, its magnitude and spatial

distribution depend on how governance architectures mediate risk, uncertainty, and competing development priorities across multiple scales (Lipper et al., 2014; Vatn, 2017). These interactions operate through four interlinked governance domains: seed system regulation, land tenure and resource access, agricultural extension priorities, and institutional coordination across administrative scales (Jiren et al., 2021). Together, these domains shape farmer decision-making, constrain management flexibility, and structure the incentives governing varietal selection, conservation behavior, and adaptive experimentation (McGuire & Sperling, 2016; Spielman et al., 2011). The interaction between institutional arrangements and localized climatic pressures ultimately determines whether agricultural landscapes retain the functional heterogeneity required for climate resilience or undergo progressive genetic homogenization and amplified vulnerability.

2.1. Seed System Governance

The structural configuration of seed systems functions as a decisive mechanism for mediating genetic flow, in which the intersection of regulatory protocols and farmer-managed networks determines the evolutionary trajectory of landraces under climatic stress (Louwaars & de Boef, 2012). In Ethiopia, seed systems are conventionally categorized into formal, informal, and intermediate sectors, each governed by distinct regulatory logics and institutional mandates (Bishaw et al., 2008; Spielman et al., 2011). The formal system, anchored in centralized breeding programs, varietal release committees, and certification protocols, supplies only a minor share of national seed demand. Empirical estimates consistently indicate that certified seed accounts for a small fraction, typically 20–30%, and often substantially less for self-pollinated crops, of total seed use among Ethiopian smallholders (Abay et al., 2011; Spielman et al., 2011; Mulesa et al., 2021). By contrast, informal systems based on farmer-saved seed, local exchange networks, and social reciprocity dominate seed provisioning, particularly in marginal agro-ecological zones characterized by climatic volatility and infrastructural deficits (Assaye et al., 2024; McGuire & Sperling, 2016). Because these channels provide the overwhelming majority of planting material, the persistence of local genetic diversity is fundamentally dependent on the integrity and adaptive capacity of farmer-managed networks (Jarvis et al., 2011; McGuire & Sperling, 2016). Emerging intermediate arrangements, including community-based seed producers and decentralized seed enterprises, seek to bridge formal and informal systems by multiplying both improved cultivars and locally adapted landraces (van Etten et al., 2019; Bishaw et al., 2013). These hybrid models represent a critical institutional innovation: they professionalize informal systems while preserving their inherent genetic heterogeneity and evolutionary dynamism. For staple crops such as wheat, barley, and sorghum, farmer-managed systems operate not merely as residual alternatives but as active reservoirs of adaptive variation, enabling continuous selection under spatially heterogeneous climatic regimes (Dawson et al., 2019; Ceccarelli et al., 2010; Abay et al., 2011). Through decentralized experimentation and varietal diversification, these systems buffer climatic risks and sustain functional agroecosystem resilience.

Despite this functional importance, prevailing seed governance frameworks structurally privilege genetic uniformity (Mulesa et al., 2021). Variety release criteria, shaped by Distinctness, Uniformity, and Stability (DUS) standards, prioritize yield performance and phenotypic consistency under controlled experimental conditions, while undervaluing adaptive traits essential for low-input, risk-prone environments, such as drought tolerance, soil nutrient efficiency, and phenological plasticity (Ceccarelli & Grando, 2007; van Etten et al., 2019; Dawson et al., 2011). This regulatory bias systematically marginalizes farmer-bred populations and accelerates varietal displacement. Empirical evidence from multiple Ethiopian districts shows declines of 66.7% in the cultivation of traditional wheat landraces following the expansion of standardized improved varieties (Gelelcha et al., 2023; Tsegaye & Berg, 2007; Abate et al., 2015). Such patterns demonstrate that regulatory frameworks emphasizing uniformity and centralized replacement directly contribute to genetic erosion, narrowing the adaptive base required for climate resilience (Mulesa et al., 2021; Thijssen et al., 2008).

Recent policy initiatives signal growing recognition of these structural limitations (Vernooy et al., 2015). Programs supporting community seed banks, participatory varietal selection, and decentralized seed multiplication seek to institutionalize linkages between formal breeding pipelines and informal conservation systems (FAO, 2024; Vernooy et al., 2015; van Etten et al., 2019). When embedded within regulatory frameworks that ensure legal recognition, sustained financing, and institutional legitimacy, these hybrid arrangements enhance adaptive capacity by combining technological innovation with localized evolutionary processes (Mulesa et al., 2021). Collectively, existing evidence indicates that governance systems fostering functional complementarity, rather than competitive displacement, between the seed sectors provide the most robust institutional pathway for sustaining agrobiodiversity under accelerating climate stress (Vernooy et al., 2017; Bellon et al., 2011).

2.2. Land Tenure and Resource Access

Beyond the immediate availability of germplasm, property-rights governance determines farmers' time horizons and investment incentives for long-term biological stewardship (Place, 2009; Holden & Ghebru, 2016; Lawry et al., 2017). In Ethiopia, the constitutional framework of state-owned land, where individuals possess usufruct rights rather than full ownership, generates heterogeneous patterns of de facto tenure security across regions and livelihood systems (Rahmato, 2008; Deininger et al., 2007; Holden et al., 2013). Where land rights are formally documented, socially recognized, and institutionally enforceable, household- and district-level studies consistently report significantly higher adoption of soil and water conservation measures, agroforestry practices, and diversified cropping strategies (Holden & Ghebru, 2016; Deininger et al., 2007; Holden & Yohannes, 2002). These long-term investments promote spatial and functional heterogeneity through diversified cropping, agroforestry, soil restoration, and the management of perennial species. Collectively, these practices strengthen climatic buffering capacity, stabilize yields under rainfall variability, and sustain in situ genetic diversity (Pretty et al., 2018; Lipper et al., 2014). Conversely, perceived tenure insecurity suppresses long-term stewardship, encouraging short planning horizons that favor simplified, productivity-maximizing land-use strategies, microcropping, and accelerated land degradation (Holden et al., 2013; Lawry et al., 2017; Rahmato, 2008). This shift occurs because tenure insecurity functions as a high discount rate on the future; when the probability of future land access is low, the immediate costs of biological stewardship outweigh the uncertain long-term benefits of ecological resilience. Under conditions of uncertain tenure, farmers face systemic disincentives to maintain perennial species, invest in soil organic matter, or conserve landraces that require multi-season selection, thereby directly compromising retention of agrobiodiversity (Place, 2009; Di Falco et al., 2007).

While individual tenure security is a critical determinant of farm-level diversity, governing challenges are particularly acute in communal resource systems, including rangelands, forest margins, and seasonal pastures (Behnke et al., 2014; Tache & Oba, 2010). Historically, customary institutions regulated grazing mobility, sustained vegetation heterogeneity, and conserved indigenous livestock breeds adapted to climatic variability (Niamir-Fuller, 1999; Scoones, 1994; Gebremedhin et al., 2018). However, the progressive formalization of state land policy and the expansion of sedentary agricultural frontiers have marginalized these traditional management systems. This institutional erosion has degraded forage diversity, fragmented migratory corridors, and accelerated the erosion of locally adapted livestock genetic resources, particularly among pastoral and agro-pastoral communities (Mengesha et al., 2017; Hassen et al., 2016; Gebremedhin et al., 2018). Consequently, the homogenization of grazing environments compromises the ecological feedback loops necessary to sustain pastoral resilience, thereby trapping communities in self-reinforcing cycles of insecurity (Reid et al., 2014; Nori & Scoones, 2019).

These tenure-driven transformations extend beyond livestock systems to broader ecosystem-level biodiversity patterns, reducing habitat connectivity for crop wild relatives, constraining gene flow, and diminishing the ecological buffers necessary for future crop improvement (Maxted et al.,

2016; Jarvis et al., 2011; EBI, 2014). The expansion of rainfed cultivation into rangelands and forest margins, combined with weak land documentation and speculative land markets in rural-urban transition zones, encourages competitive land appropriation rather than cooperative stewardship, producing extreme landscape fragmentation and accelerating biodiversity loss (Jayne et al., 2014; Angel et al., 2011; Seto et al., 2012). In the densely populated Ethiopian highlands, these pressures are further intensified by inheritance practices and policy-driven land subdivision, resulting in progressively smaller farm sizes that limit the feasibility of agroforestry integration, fallowing, and diversified crop rotations (Josephson et al., 2014; Headey et al., 2014; Pender & Gebremedhin, 2007). Collectively, this synthesis demonstrates that tenure governance structures influence not merely patterns of land access, but the qualitative character of land use itself. Strengthening legally recognized individual and communal land rights emerges as a critical institutional intervention for biodiversity stewardship, ecological heterogeneity, and adaptive capacity (Ghebru & Holden 2015). By securing tenure, governance systems can realign farmers' incentives toward long-term ecological investment, thereby preserving genetic reservoirs, stabilizing ecosystem function, and enhancing agro-ecological resilience under accelerating climatic uncertainty (Holden & Ghebru, 2016; Lawry et al., 2017; Lipper et al., 2014; Pretty et al., 2018).

2.3. Agricultural Development and Extension Systems

The institutional architecture of agricultural extension functions as a powerful socio-technical filter through which the top-down dissemination of standardized technological packages often suppresses the localized, knowledge-intensive strategies essential for maintaining agro-ecological heterogeneity (Spielman et al., 2011; Mulesa, 2021). In the Ethiopian context, this governance interface has historically been oriented toward productivity enhancement and short-term food security through the dissemination of high-yielding crop varieties, standardized production packages, and exotic livestock breeds (Worku et al., 2017; Davis et al., 2010; Gebremedhin et al., 2015). The national extension architecture, operating primarily through government-managed bureaus, development agents, farmer training centers, and cooperatives, has been designed to promote rapid yield gains via tightly prescribed input bundles that combine improved seed, mineral fertilizers, pesticides, and agronomic protocols (Abate et al., 2017; Spielman et al., 2010; Tadele, 2016; Spielman et al., 2011). This model reflects broader development paradigms emphasizing intensification, commercialization, and market integration as primary pathways toward food security and poverty reduction (Dorward et al., 2009; Jayne et al., 2019b).

While this productivity-centered approach has stabilized caloric production and enhanced cereal yields in high-potential agro-ecological zones, it has simultaneously accelerated the erosion of locally adapted genetic resources (Alemu, 2010; Spielman et al., 2010; Thijssen et al., 2008). This outcome is closely linked to performance evaluation frameworks that prioritize quantitative adoption metrics, such as certified seed uptake, fertilizer consumption, and area under improved varieties, over qualitative indicators related to genetic diversity retention, ecological stability, and long-term resilience (Spielman et al., 2011; Mulesa, 2021; Abate et al., 2015). Extension agents are institutionally incentivized to maximize technology diffusion rather than support context-specific varietal portfolios, thereby systematically biasing farmer decision-making toward genetically uniform production systems (Spielman et al., 2010; Dorward et al., 2009).

The ecological and socio-economic consequences of this productivity-centered governance paradigm are increasingly quantifiable across Ethiopia's major crops. Comparative studies document extensive genetic replacement, with tetraploid wheat landraces exhibiting erosion rates ranging from 60% to total displacement (100%) in specific districts of central Ethiopia, such as Ada and Gimbichu (Negisho et al., 2021; Tsegaye & Berg, 2007). Similarly, barely landraces show a reduction of 56% to 65% in the North Shewa zone, while teff landraces have experienced an estimated 65.5% loss in parts of the Amhara region (Tsegaye & Berg, 2007; Mekbib, 2008). As detailed in Table 1, these shifts are closely associated with extension strategies promoting modern wheat and teff cultivars through input

subsidy programs, credit access schemes, and cooperative-based seed distribution, frequently at the expense of traditional genotypes (Abate et al., 2015; Spielman et al., 2011)

Table 1. Quantified genetic erosion of major Ethiopian crops and indigenous livestock breeds, including the specific governance drivers and implications for climate-resilience.

Crop Genetic Resource	Genetic Erosion Replacement	Drivers Change	of Influence	Extension & Policy	Climate Resilience Implication
Wheat (Tetraploid)	60% to 100% (Complete loss in districts like Ada)	Promotion of improved bread wheat; top-down seed replacement	Extension focuses on uniform, high-input certified seed		Loss of locally adapted drought & stress tolerance traits
Barley landraces	56% to 65% (e.g., 25 → 14 landraces in North Shewa)	Displacement by improved varieties and specialized malting barley.	Limited institutional support for in-situ landrace conservation.		Reduced adaptive capacity for pests, diseases, and frost.
Teff Landraces	~65.5% loss in specific monitored districts	Market pressure for uniform white teff; expansion of improved cultivars.	Modern diffusion via subsidized input bundles.		Loss of phenological plasticity for erratic rainfall/poor soils.
Indigenous Livestock	No national aggregate (Qualitatively high)	Aggressive crossbreeding with exotic dairy/poultry genotypes.	Livestock extension promotes commercial/specialize d breeds.		Reduced tolerance to heat stress, water scarcity, and endemic disease.

The contraction of genetic diversity reduces the availability of adaptive traits essential for cropping under climate stress, including drought tolerance, phenological plasticity, disease resistance, and performance under low-input soil conditions (Ceccarelli et al., 2013; Dawson et al., 2011; Jarvis et al., 2011). Empirical evidence from drought-prone highland regions indicates that farming systems reliant on genetically uniform wheat and teff varieties experience a yield reduction of 20-30% during dry seasons relative to those maintaining diversified landrace portfolios, reflecting reduced buffering capacity under rainfall variability (Abebe et al., 2017; Di Falco & Chavas, 2009; Jarvis et al., 2011). These findings suggest that extension strategies narrowly optimized for short-term productivity can inadvertently amplify vulnerability to climatic shocks by narrowing the functional diversity of production systems.

Parallel patterns are evident in livestock development policies, where extension programs have prioritized crossbreeding and the dissemination of exotic dairy and poultry genotypes to enhance short-term productivity and market integration (Hassen et al., 2016; Mengesha et al., 2017; Gebremedhin et al., 2018). While these interventions have improved milk and meat yields in peri-urban systems, they have simultaneously displaced indigenous breeds adapted to heat stress, seasonal feed scarcity, and endemic disease pressures, thereby increasing vulnerability to climate-induced production shocks (FAO, 2019; Hassen et al., 2016; Mirkena et al., 2010). Recent empirical

research demonstrates that participatory extension frameworks can structurally reconcile imperatives with agrobiodiversity conservation by embedding farmer-led selection and decentralized experimentation within formal advisory systems (Vernooy et al., 2017). Farmer-led varietal selection, decentralized seed multiplication, and community seed banking initiatives have demonstrated the capacity to retain locally adapted landraces alongside improved cultivars, thereby sustaining both yield stability and genetic heterogeneity (Ceccarelli et al., 2013; van Etten et al., 2020; Vernooy et al., 2017). Case studies from Oromia and Amhara indicate that participatory barley and wheat trials enabled farming communities to stabilize production during extreme climatic events, including the 2018 drought, through strategic deployment of local genetic resources exhibiting superior stress tolerance and phenological flexibility (Tadele, 2016; Abate et al., 2017; Kidane et al., 2017). Collectively, these findings demonstrate that extension governance systems incorporating participatory decision-making, decentralized experimentation, and diversity performance metrics provide more robust institutional pathways for sustaining climate-resilient smallholder production systems.

2.4. Institutional Coordination and Scale

The scalar and horizontal fragmentation of Ethiopia's bureaucratic apparatus creates a landscape of 'policy silos' that decouple agricultural productivity mandates from environmental conservation objectives, undermining a unified response to climate-induced genetic erosion (Vatn, 2015; Jiren et al., 2021). Within this fragmented architecture, agricultural development, environmental conservation, and climate adaptation policies are implemented without formalized mechanisms for joint planning or integrated monitoring (Vatn, 2015; Spielman et al., 2011). Agricultural bureaus primarily pursue production intensification and commercialization targets, environmental agencies prioritize biodiversity protection and ecosystem restoration, while climate institutions focus on disaster risk reduction, early warning systems, and emergency response (Deressa et al., 2011; FDRE, 2011; FAO, 2019). These divergent mandates generate conflicting regulatory signals that ultimately force a false choice between food security and genetic preservation, leaving Ethiopia's foundational agrobiodiversity unprotected in the crossfire of bureaucratic competition (Jiren et al., 2021; Alemu, 2010; Mulesa et al., 2021).

Coordination failures are further compounded by pronounced scale mismatches embedded within national policy frameworks. Variety release, seed dissemination, and technology deployment protocols for crops such as maize, wheat, and teff frequently assume agro-climatic homogeneity across broad agro-ecological zones, thereby overlooking microclimatic heterogeneity that underpins the persistence of local landraces and fine-scale adaptive strategies (Addisu et al., 2015; Conway & Schipper, 2011; Ceccarelli et al., 2013). Moreover, ecologically critical spaces, including field margins, communal grazing areas, forest edges, and riparian corridors that harbor crop wild relatives and wild forage species, frequently fall outside the jurisdictional reach of formal agricultural and environmental institutions (Jarvis et al., 2011; Maxted et al., 2016; FAO, 2019). The absence of integrated landscape-scale governance frameworks leaves these genetic and ecological reservoirs particularly vulnerable to land conversion, degradation, and fragmentation, especially under intensifying climatic stress and population pressure (Seto et al., 2012; Angel et al., 2011; Jayne et al., 2014).

Empirical evidence from Oromia and Amhara demonstrates the practical implications of this fragmented governance architecture (Asfaw et al., 2017; Behnke et al., 2014). Recurrent drought events in these regions have exposed systemic weaknesses in rangeland governance, water allocation, and land-use planning, driven by overlapping mandates and weak coordination among agricultural bureaus, environmental agencies, and local cooperatives (Asfaw et al., 2017; Abebe, 2020; Lawry et al., 2017). Under these conditions, farmers confront contradictory regulatory frameworks governing land use, seed selection, and resource management, constraining adaptive responses and undermining system-level resilience. Scholarship in this field underscores the necessity of transitioning toward multi-level governance architectures capable of integrating sectoral objectives

across administrative and ecological scales (Vatn, 2015; Ostrom, 2009; Lemos et al., 2016). Institutional innovations such as cross-sectoral advisory councils, integrated watershed management platforms, joint monitoring systems, and landscape-scale planning frameworks are increasingly identified as mechanisms for reconciling production imperatives with biodiversity conservation (FAO, 2019; Pretty et al., 2018; Reed et al., 2017).

2.5. Trade-Offs and Governance Challenges

The governance of agrobiodiversity in Ethiopia is fundamentally structured around a conflict between short-term productivity imperatives and the long-term stewardship of the adaptive potential of local landraces (Deressa et al., 2011; FAO, 2019; Vatn, 2015). This tension is operationalized through institutional performance metrics, such as yield targets and commercialization indicators, that reward varietal standardization and scale efficiencies, thereby privileging genetic uniformity. Policies accelerating the diffusion of improved varieties are not neutral technical interventions; they are regulatory instruments that incentivize the displacement of indigenous genotypes through extension benchmarks and subsidy structures (Spielman et al., 2011; Abate et al., 2015; Berhane et al., 2018). While these interventions may stabilize immediate output, they simultaneously narrow the genetic base of smallholder systems, increasing systemic vulnerability by reducing response diversity and yield stability under climatic stress (Jarvis et al., 2011; Di Falco & Chavas, 2009).

Institutional fragmentation further exacerbates these trade-offs by compartmentalizing authority across sectors with divergent temporal horizons: agricultural agencies are structurally oriented toward near-term production targets, while environmental agencies operate on long-term conservation horizons, and climate institutions prioritize immediate disaster-response timelines (Deressa et al., 2011; Vatn, 2015). In the absence of integrated governance, the burden of reconciling these competing objectives is externalized onto farmers, who must navigate contradictory incentives regarding seed selection and resource management under heightened uncertainty (McGuire & Sperling, 2016; Lipper et al., 2014). Multi-site studies from intensifying cereal production corridors in Oromia and Amhara reveal the structural consequences of unresolved productivity–resilience trade-offs. The expansion of teff monocultures, combined with the restriction of traditional grazing systems, has driven landscape homogenization and reduced forage diversity (Abate et al., 2017; Kidane et al., 2017; Behnke et al., 2014); these outcomes are closely associated with the extension strategies documented in the preceding sections of this review. Such trends reflect predictable effects of governance frameworks that fail to internalize cross-sectoral ecological interactions. Market forces further entrench these trajectories, as standardized varieties command price premiums and lower transaction costs, incentivizing farmers to privilege short-term economic returns over the maintenance of genetically diverse production systems (Jayne et al., 2019a; Nori & Scoones, 2019).

Current scholarship establishes that effective governance requires institutionalizing trade-offs through landscape-level planning and performance metrics (Lipper et al., 2014; Pretty et al., 2018; Reed et al., 2017). Under intensifying climatic pressures, the resilience of Ethiopian agriculture will depend on the capacity of governance systems to internalize these trade-offs through coherent, multi-scale institutional design that integrates cross-sectoral coordination with localized ecological monitoring

3. Governance-Centered Adaptation Strategies

Sustaining agrobiodiversity amid accelerating climatic instability requires strategies that go beyond technological interventions to directly confront the institutional architectures, incentive structures, and regulatory logics that shape agricultural decision-making (Vatn, 2015). Climate change operates not merely as an exogenous environmental stressor but as a systemic stress test that exposes latent structural vulnerabilities embedded in existing policy regimes, including misaligned sectoral mandates, regulatory rigidity, and fragmented institutional coordination (Vatn, 2015; Eriksen et al., 2015; Lemos et al., 2016). Under this framing, agrobiodiversity cannot be understood

as a passive ecological byproduct of farming practices but must be reconceptualized as a deliberately governed socio-ecological asset whose persistence is contingent on regulatory coherence, institutional adaptability, and cross-scale policy integration (Lipper et al., 2014; Ostrom, 2009; Folke et al., 2010).

Governance-centered adaptation thus redirects analytical attention from narrow assessments of varietal performance and agronomic efficiency toward the political, institutional, and regulatory mechanisms that condition resilience. Adaptive capacity does not emerge automatically from genetic diversity; rather, it is actively constructed through seed regulation, land tenure systems, extension incentives, public investment priorities, and mechanisms of collective action that shape farmers' risk environments, opportunity structures, and management choices (Ribot, 2014; Agrawal, 2010; Pelling et al., 2015). When governance systems prioritize short-term productivity, standardization, and market integration without accounting for ecological variability and socio-economic heterogeneity, they systematically erode genetic diversity, entrench technological path dependency, and amplify vulnerability to climatic shocks (Dorward et al., 2009; Spielman et al., 2011; Lipper et al., 2014; Jarvis et al., 2016). Conversely, governance arrangements that internalize environmental uncertainty, institutionalize pluralism in seed and land-use systems, and legitimize localized knowledge can transform agrobiodiversity into a structural foundation for long-term resilience rather than a residual artifact of subsistence farming (Ceccarelli et al., 2013; van Etten et al., 2019; Pretty et al., 2018).

Within this framework, five interlocking governance leverage points emerge as decisive in shaping adaptive outcomes: (i) the integration of formal and informal seed systems, (ii) the restructuring of land tenure and resource governance to incentivize long-term ecological stewardship, (iii) the enhancement of multi-level institutional coordination, (iv) the explicit management of productivity–resilience trade-offs through multi-objective policy design, and (v) the strengthening of adaptive institutional and technical capacity (Lipper et al., 2014; Ostrom, 2009; Folke et al., 2010; Reed et al., 2017). Together, these domains configure the incentive environments through which farmers allocate labor, manage climatic risk, and invest in genetic conservation. By structuring access to planting material, securing land use, promoting regulatory coherence across scales, valuing the economic benefits of diversity, and facilitating knowledge transmission, they collectively determine whether agrobiodiversity is systematically eroded, selectively transformed, or actively reinforced under accelerating climatic stress.

3.1. Integrating Formal and Informal Seed Systems: A Dual-Track Governance Model

Operationalizing a dual-track framework requires a fundamental shift from the conventional “seed replacement” paradigm toward a model of institutional complementarity (Louwaars & de Boef, 2012; Mulesa et al., 2021). Rather than displacing traditional seeds, the formal sector should act as a source of novel genetic traits that the informal system then tests and adapts within its decentralized evolutionary laboratories, ensuring landraces remain responsive to localized climatic shifts (Jarvis et al., 2011; Ceccarelli et al., 2013). However, the current institutional dominance of centralized breeding has delivered measurable productivity gains only under controlled experimental conditions. In practice, this top-down approach has systematically marginalized informal seed networks, which remain the principal custodians of local landraces, decentralized evolutionary processes, and agro-ecological knowledge embedded within farming communities (McGuire & Sperling, 2016; Jarvis et al., 2011; Bellon et al., 2015).

Effective governance reform requires a deliberate transition toward a dual-track seed system, in which formal and informal channels are institutionally recognized as complementary rather than hierarchical (Lipper et al., 2014; Louwaars et al., 2013; van Etten et al., 2020). In this model, formal breeding systems provide targeted improvements in yield stability, disease resistance, and stress tolerance, while informal networks sustain dynamic genetic reservoirs that capture fine-scale environmental variation, historical selection, and farmer-driven innovation (Ceccarelli et al., 2013; Dawson et al., 2011). Crucially, informal systems do not merely conserve genetic material: they actively generate adaptive diversity through continuous cycles of selection, experimentation,

recombination, and exchange across heterogeneous ecological niches (Jarvis et al., 2016; McGuire & Sperling, 2016; Ceccarelli & Grando, 2007). This evolutionary function, grounded in decentralized risk management and fine-scale environmental feedback, cannot be replicated through centralized breeding pipelines alone (Dawson et al., 2011; van Etten et al., 2019).

Under climate change, the functional value of this complementarity becomes particularly acute. Increasing climatic variability undermines the predictive capacity of centralized breeding programs, elevating the probability that narrowly optimized varieties will fail across spatially heterogeneous and temporally unstable environments (Conway & Schipper, 2011; Ceccarelli et al., 2013; Thornton et al., 2018). In contrast, decentralized farmer-managed systems distribute climatic risk spatially and temporally, enabling rapid localized adaptation, continuous evolutionary experimentation, and dynamic adjustment to emerging stressors (Jarvis et al., 2011; Dawson et al., 2020). Governance architectures that suppress informal seed exchange, therefore, inadvertently amplify systemic vulnerability by collapsing the diversity of adaptive strategies available to smallholder populations (McGuire & Sperling, 2016; Lipper et al., 2014).

To operationalize a dual-track model, adaptation strategies must institutionalize regulatory flexibility that legitimizes informal seed institutions within policy frameworks. This entails formal recognition of community seed banks, participatory varietal selection, decentralized seed strategies, rather than residual informal activities operating outside regulatory oversight (Vernooy et al., 2017; Bishaw et al., 2013; FAO, 2019; van Etten et al., 2020). Legal recognition must be coupled with stable public financing, extension integration, and technical support to ensure institutional durability rather than project-based fragility (Lipper et al., 2014; FAO, 2019). Beyond institutional legitimacy, governance systems must actively realign breeding priorities toward farmer-defined selection criteria by embedding participatory methodologies directly within formal research pipelines. Participatory plant breeding and decentralized variety testing allow breeding outputs to remain responsive to local performance thresholds under heterogeneous climatic and management conditions, while simultaneously enabling informal systems to access novel genetic material and agronomic innovations (Ceccarelli et al., 2013; Dawson et al., 2011; van Etten et al., 2019). These feedback loops strengthen adaptive capacity by reinforcing farmer-led selection, preserving locally embedded adaptive traits, and stabilizing the on-farm evolutionary process, thereby slowing the erosion of functional genetic diversity and sustaining system-level resilience (Jarvis et al., 2016; Lipper et al., 2014).

Comparative analyses from Ethiopia and analogous smallholder systems demonstrate that integrated seed governance arrangements, combining formal innovation pipelines with decentralized farmer experimentation, outperform singular technological pathways in maintaining yield stability, reducing climatic risk, and sustaining agrobiodiversity (Abay et al., 2017; Kidane et al., 2017; Dawson et al., 2020; Jarvis et al., 2011). Collectively, the literature converges on a central conclusion: agrobiodiversity conservation under climatic stress cannot be achieved through centralized breeding, regulatory uniformity, or technological diffusion alone. Instead, governance systems must cultivate institutional pluralism, where decentralized genetic experimentation is preserved alongside formal innovation. By constructing a robust genetic buffer through institutional complementarity, Ethiopia can stabilize agricultural performance, preserve evolutionary capacity, and mitigate the systemic risks associated with accelerating climatic volatility (Lipper et al., 2014; Jarvis et al., 2016; FAO, 2019).

3.2. Strengthening Land Tenure and Resource Rights: From Use-Rights to Ecological Stewardship

If agrobiodiversity is to be managed as a national asset, land governance must evolve into an ecological regulatory architecture in which property rights regimes align farmers' incentives with long-term investment and landscape diversification (Holden & Ghebru, 2016; Lawry et al., 2017). Extensive empirical literature demonstrates that tenure security is positively associated with soil conservation, agroforestry adoption, and sustainable land management, particularly in smallholder systems exposed to climate variability (Besley, 1995; Deininger et al., 2011; Holden et al., 2011; Ghebru

& Holden, 2015; Lawry et al., 2017). These relationships operate through intertemporal investment incentives: when farmers possess credible expectations of continued land access, they are more willing to allocate labor and capital toward practices whose benefits accrue gradually, such as soil fertility restoration, tree establishment, and the maintenance of diverse crop portfolios.

Under Ethiopia's state-ownership framework, where individuals hold usufruct rights rather than private ownership, tenure security remains legally circumscribed and socially contingent (Rahmato, 2008). Although land certification reforms have substantially improved perceived security in many regions, empirical studies indicate that tenure anxiety persists, particularly under conditions of population pressure, administrative redistribution, and ambiguous inheritance regimes (Holden & Ghebru, 2016; Ghebru & Holden, 2015). Where tenure documentation is weak, contested, or poorly enforced, farmers exhibit significantly lower propensities to undertake long-term investments in land improvement, biodiversity-enhancing practices, and agroforestry systems (Holden et al., 2011; Gebremedhin, Pender & Tesfay, 2003). These institutional uncertainties generate a persistent incentive gap that favors short-term yield maximization and accelerated resource extraction. Over time, this dynamic drives varietal simplification, progressively eroding genetic diversity and weakening ecological resilience.

Governance-centered adaptation must therefore reposition tenure security as a core instrument of biodiversity stewardship rather than a peripheral administrative concern (Deininger et al., 2011; Lawry et al., 2017). In this framing, land governance is not merely a distributive mechanism but an ecological regulatory architecture that conditions how farmers perceive climatic risk, allocate labor, and manage agro-ecosystem complexity (Ostrom, 2005; Young, 2002). Climate change intensifies this linkage by increasing the salience of long-term buffering strategies, such as diversified cropping systems, agroforestry, and soil organic matter accumulation, that require durable tenure horizons to remain economically rational (Ribot, 2014; FAO, 2018).

This imperative is most acute in the governance of communal resources, particularly rangelands, forest margins, and seasonal grazing corridors. Historically, customary tenure systems in Ethiopia sustained high levels of vegetation heterogeneity, facilitated livestock mobility, and conserved indigenous livestock genetic diversity through collectively enforced access regimes, seasonal rotation, and negotiated reciprocity (Flintan, 2013). However, the progressive erosion of communal usufruct rights has facilitated widespread encroachment, privatization, and conversion to sedentary agriculture (Abebe, 2020). To reverse these trajectories, governance reforms must prioritize the formal recognition and legal codification of communal tenure arrangements within statutory land frameworks. Comparative evidence from pastoral systems demonstrates that legally empowered communal institutions exhibit stronger compliance, lower conflict incidence, and superior ecological outcomes, underscoring the central role of institutional design, rather than ecological constraint alone, in shaping agrobiodiversity trajectories (Flintan, 2013; Ostrom, 1990; Meinzen-Dick et al., 2014).

At the individual scale, adaptation strategies must transition from short-term usufruct models toward long-term stewardship frameworks in which land certification is explicitly linked to environmental performance. Integrating tenure security with biodiversity-based incentive instruments, such as conditional certification, payments for ecosystem services, conservation-linked subsidies, and climate-resilient agricultural labeling, can reconfigure land governance into a direct driver of genetic conservation (Wunder, 2015). In this institutional configuration, farmers are not passive land users but formal partners in the management of national genetic capital, with stewardship responsibilities embedded within legally enforceable governance arrangements (Pascual et al., 2014).

Taken together, these reforms reposition tenure governance as a central axis of climate adaptation. By aligning property rights with long-term ecological incentives, Ethiopia can construct institutional environments in which agrobiodiversity is actively produced, protected, and regenerated, rather than passively eroded under demographic, economic, and climatic pressure.

3.3. *Enhancing Multi-Level Coordination: Overcoming Institutional Fragmentation*

Overcoming the fragmented governance landscape, characterized by the siloed mandates and contradictory pressures identified in the preceding sections, is essential for the efficacy of climate adaptation in Ethiopia. This lack of horizontal and vertical integration has historically embedded structural trade-offs between short-term productivity targets and long-term ecological resilience. Addressing these failures requires a transition toward integrated, multi-level governance architectures capable of aligning sectoral objectives across administrative and ecological scales (Folke et al., 2010; Ostrom, 2009; Reed et al., 2017). Effective adaptation, therefore, depends on institutional alignment across agricultural, environmental, and climate governance systems, combining vertical integration linking national strategies with regional planning and local institutions, and horizontal coordination across ministries, bureaus, and development agencies (Nilsson et al., 2012; Candel & Biesbroek, 2016; Lemos et al., 2016). Without such integration, adaptation efforts remain compartmentalized, preventing synergies across policy domains and weakening the institutional foundations of resilience (Eriksen et al., 2015; Lemos et al., 2016).

A critical governance innovation for operationalizing this transition lies in the adoption of integrated landscape planning frameworks and cross-sectoral coordination platforms (Sayer et al., 2013; Reed et al., 2016; Freeman et al., 2015). These mechanisms enable joint decision-making, harmonized monitoring systems, and coordinated resource deployment across agriculture, forestry, biodiversity conservation, and water management sectors (Sayer et al., 2013; Reed et al., 2016). By embedding ecological objectives directly within agricultural planning processes, integrated landscape governance reconciles production imperatives with ecosystem preservation, transforming institutional competition into collaborative problem-solving (Freeman et al., 2015; Reed et al., 2017).

Monitoring and accountability systems constitute the primary operational lever through which this governance transformation can be enforced (Cabell & Oelofse, 2012; FAO, 2019; Reed et al., 2017). Shifting away from evaluation frameworks that prioritize short-term yield and land expansion, drivers of the degradation addressed in Section 3.2, resilience-oriented governance relies on indicators that measure genetic diversity retention, landscape heterogeneity, and soil health. Reframing institutional accountability around system-level resilience outcomes realigns extension incentives, budget allocations, and administrative priorities with climate adaptation objectives, ensuring that biodiversity conservation and productivity enhancement become structurally complementary rather than antagonistic (Reed et al., 2017; Folke et al., 2010).

Functionally, multi-level coordination serves as the institutional bridge connecting national adaptation strategies to localized agro-ecological management (Ostrom, 2009; Lemos et al., 2016). This alignment prevents top-down policy directives from overriding context-specific adaptation practices, instead reinforcing farmers' capacity to maintain diversified production systems attuned to local climatic variability (Eriksen et al., 2015; Reed et al., 2017). By harmonizing governance across administrative scales, Ethiopia can construct an integrated institutional architecture that treats agrobiodiversity not as a peripheral environmental concern but as a strategic national asset central to food security, climate resilience, and rural livelihoods (Folke et al., 2010; IPBES, 2019; FAO, 2019).

3.4. *Incentive-Based Governance Instruments of Multi-Objective Adaptation*

A central challenge in climate adaptation is designing institutional incentives that explicitly account for the trade-offs between productivity and resilience, rather than allowing them to be implicitly resolved through yield-centered policies (Vatn, 2015; Lipper et al., 2014). Transitioning from the single-variable efficiency models discussed in preceding sections toward multi-objective institutional design is essential to ensure that productivity, resilience, and biodiversity conservation are treated as coequal policy goals (Vatn, 2015; Ostrom, 2009; Pretty et al., 2018). This reframing positions agrobiodiversity not as a constraint upon efficiency, but as a foundational determinant of long-term agricultural performance under environmental uncertainty (Lin, 2011; Isbell et al., 2017; IPBES, 2019). Diversified production systems, including intercropping, agroforestry, polyvarietal cultivation, and indigenous livestock integration, simultaneously enhance yield stability, climatic

buffering, and ecosystem functionality, generating compound benefits that exceed those of simplified monocultures (Kremen & Miles, 2012; Isbell et al., 2017).

However, without targeted governance interventions, farmers face persistent economic disincentives to maintain such system complexity. Market pressures, labor constraints, risk exposure, and policy biases systematically favor simplified uniform production systems, despite their long-term ecological costs (Tittonell, 2014; Pretty et al., 2018). To realign these incentives, adaptation strategies must move beyond the tenure-linked instruments described in Section 3.2 and incorporate broader market-based mechanisms. These instruments capture the public value of genetic conservation by transforming ecological stewardship from an uncompensated externality into a financially viable management strategy (Lipper et al., 2014). By leveraging the incentive instruments introduced in Section 3.2, such as payments for ecosystem services and conservation-linked subsidies, governance systems can transform stewardship from an uncompensated externality into a financially viable and institutionally supported management strategy (Lipper et al., 2014).

Consequently, embedding biodiversity valuation directly into agricultural markets enables smallholders to sustain multifunctional production systems without sacrificing income security, thereby stabilizing agricultural performance under climatic uncertainty (Engel et al., 2008; FAO, 2019; Pretty et al., 2018). In effect, multi-objective governance reframes climate adaptation from a reactive damage-control paradigm toward a proactive resilience-building strategy, capable of sustaining food production while preserving the evolutionary foundations of Ethiopian agriculture (Folke et al., 2010; Lipper et al., 2014; IPBES, 2019).

3.5. Building Adaptive Institutional and Technical Capacity

The effectiveness of governance-centered adaptation ultimately depends on institutional and technical capacity to translate policy ambition into operational reality (Eriksen et al., 2015; Lemos et al., 2016; FAO, 2019). Across Ethiopia, significant capacity constraints persist within extension services, local administrations, and planning institutions, limiting the implementation of integrated, biodiversity-sensitive adaptation strategies (Deressa et al., 2011; Spielman et al., 2011). Overcoming these constraints requires a shift toward specialized technical training for extension personnel to enhance competencies in agroecology, biodiversity management, and climate-risk assessment. Institutionalizing indigenous knowledge as a core component of advisory systems is essential for creating the bidirectional learning environments required for climate resilience (Altieri et al., 2017; FAO, 2019; Tadele, 2016). Participatory learning platforms, farmer research networks, and co-production methodologies provide critical institutional pathways for integrating experiential knowledge with scientific innovation, generating context-specific solutions to climatic variability (Ceccarelli et al., 2013; van Etten et al., 2019; Dawson et al., 2020).

Equally critical is the development of evidence-based monitoring and data infrastructures capable of informing adaptive governance. At present, the absence of systematic data on genetic diversity trends, localized climate dynamics, and land-use transformations constrains strategic planning and policy responsiveness (FAO, 2019; IPBES, 2019; Cabell & Oelofse, 2012). Without high-resolution, longitudinal datasets, governance systems remain structurally reactive, responding to climatic and ecological crises only after critical resilience thresholds have already been breached, resulting in costly crisis-driven interventions (Lemos et al., 2016; Eriksen et al., 2015).

Strategic investments in integrated data platforms, integrating climate modeling, remote sensing, land-use mapping, and genetic diversity monitoring, would enable anticipatory governance and support early-warning systems and adaptive planning cycles. When these platforms are combined with participatory monitoring frameworks, they also strengthen institutional accountability, enhance transparency, and build stakeholder trust (FAO, 2019; IPBES, 2019). Ultimately, the synthesis of institutional reform, technical capacity-building, and data-driven governance can establish a flexible adaptation regime capable of iterative learning, rapid recalibration, and long-term strategic coherence.

4. Conclusion

This review demonstrates that agrobiodiversity in Ethiopia is not merely a passive victim of climatic instability, but a dynamic socio-ecological asset whose persistence is determined by the “governance logic” of agricultural decision-making. Across various sectors, from land tenure to seed distribution, it is evident that governance serves as the primary lens through which climate impacts are either magnified or mitigated. Ultimately, the analysis clarifies that genetic erosion in Ethiopia is not a direct result of climate change in isolation, but a structural outcome of policy regimes that have historically traded long-term evolutionary resilience for immediate yield gains. To bridge the current “resilience gap,” Ethiopia must move beyond narrow technological interventions and confront the structural contradictions within its policy regimes. This requires a transition to multi-level governance architectures capable of fostering institutional pluralism, where decentralized farmer innovation is supported alongside formal breeding pipelines. By securing land tenure, integrating informal seed networks, and harmonizing sectoral mandates, governance can be transformed from a driver of vulnerability into a foundational pillar of conservation. Ultimately, the preservation of Ethiopia’s genetic heritage is a strategic national imperative for long-term food security. However, further research is required to evaluate the scalability of hybrid institutional seed systems that integrate formal breeding with farmer-led innovation, and to quantify the economic impact of biodiversity-sensitive performance metrics within Ethiopia’s regional administrative structures. Addressing these knowledge gaps will be essential for operationalizing the governance-centered adaptation strategies proposed in this review.

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