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When Population Pressure Exceeds Adaptive Capacity: Agricultural Productivity, Land Fragmentation, and the Limits of Boserupian Intensification in the Gedeo Agroforestry System, Southern Ethiopia

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Abstract

Agricultural sustainability in densely populated smallholder systems remains a critical challenge across sub-Saharan Africa. While Boserupian theory suggests that population growth stimulates agricultural intensification and productivity gains, evidence from extremely dense rural settings remains limited. This study examines whether population-induced agricultural intensification continues to enhance productivity under conditions of exceptionally high demographic pressure in the Gedeo agroforestry system of southern Ethiopia—one of Africa's most densely populated rural landscapes (956 persons km^{-2}) and a UNESCO Globally Important Agricultural Heritage System. Using a sequential explanatory mixed-methods design, data were collected from 390 randomly selected households in four woredas of the Gedeo Zone. Quantitative data were analyzed using multivariate regression models, while qualitative evidence was generated through focus group discussions, key informant interviews, and field observations. Results revealed statistically significant negative associations between population pressure and all agricultural outcomes examined. Land fragmentation, declining fallow periods, livestock reduction, labor reallocation, and cultivation of marginal lands emerged as key mediating mechanisms statistically associated with the relationship between demographic pressure and agricultural outcomes. Beyond production outcomes, the findings indicate declining agricultural productivity per unit of land and increasing pressure on household livelihood systems as average plot sizes fall below economically viable thresholds. The results provide evidence that the relationship between population growth and agricultural intensification may be non-linear, with demographic pressure potentially exceeding the adaptive capacity of even highly resilient traditional farming systems. This study contributes to population-environment scholarship by demonstrating that Boserupian adaptation may become increasingly constrained under conditions of extreme population density, severe land fragmentation, and limited institutional support. These findings have implications for demographic theory, agricultural sustainability, and rural development policy, suggesting that achieving sustainable intensification in such contexts requires integrated interventions addressing land governance, technological access, market development, and livelihood diversification, rather than relying solely on population-induced innovation.

1. INTRODUCTION

1.1 The Sustainability Challenge in Smallholder Agriculture

The relationship between population dynamics and agricultural sustainability remains theoretically contested. Malthusian perspectives predict resource exhaustion under population pressure (Ehrlich & Ehrlich, 2009), while Boserupian theory suggests that population pressure stimulates agricultural intensification and technological innovation (Boserup, 1965; Tiffen et al., 1994). For sub-Saharan Africa, where average cereal yields (1.6 tonnes ha^{-1}) lag far behind the global average (4.0 tonnes ha^{-1}; FAO, 2022), resolving this theoretical tension has urgent policy implications.

Contemporary sustainability science recognizes that outcomes depend critically on institutional contexts, governance structures, technological access, and adaptive capacity (Deininger & Jin, 2006;

Pretty, 2008). Adaptive capacity in this context refers to the ability of farming households and communities to adjust their agricultural practices, technologies, and institutions in response to demographic and environmental pressures while maintaining or improving productivity and livelihoods (Berkes, 2023; Walker & Salt, 2012)..The concept of sustainable intensification—producing more from the same land area while reducing environmental impacts—has emerged as a dominant paradigm. However, empirical evidence on its feasibility under extreme population density remains limited (Garnett et al., 2013).

This framing is particularly relevant for the Gedeo agroforestry system, a UNESCO-recognized heritage system where the intersection of population pressure, institutional capacity, and ecological resilience determines sustainability outcomes. Understanding whether this system can maintain its sustainability credentials under extreme demographic pressure has implications beyond Ethiopia—it speaks to the viability of traditional agroecological systems worldwide.

1.2 Ethiopia: Population Pressure and Agricultural Sustainability

Ethiopia exemplifies the population-agriculture nexus in Africa. With approximately 120 million people growing at 2.6% annually (World Bank, 2023), the country's smallholder-dominated agricultural sector (average farm size 0.8–1.2 ha) supports 68% of the workforce. Historical agricultural growth has lagged behind population growth: between 1980 and 1995, grain production increased 1.37% annually while population grew 2.9% (World Bank, 2004). Approximately 20% of Ethiopia's population remains food insecure, with chronic malnutrition affecting 37% of children under five (WFP, 2022).

Nationally, average farm size decreased from 1.5 ha in 1990 to 1.0 ha in 2020, while plots per household increased from 2.1 to 3.4 (Headey et al., 2014; CSA, 2021). In highland areas exceeding 500 persons km^{-2}, evidence shows soil degradation, loss of fallow periods, and reduced productivity (Pender & Gebremedhin, 2007). However, most studies focus on national or regional scales, obscuring local heterogeneity. Few examine sustainability outcomes across multiple crop types and livestock systems simultaneously.

1.3 The Gedeo Zone: A Critical Case for Agricultural Sustainability

The Gedeo Zone in Southern Ethiopia presents an exceptional opportunity for examining the relationship between population growth and agricultural sustainability. With a population density of approximately 956 persons km^{-2}, the area represents one of the most densely populated rural regions in Africa. The population increased from approximately 0.4 million in 1984 to 1.3 million in 2021 within a fixed land area, generating substantial pressure on land resources and agricultural livelihoods.

The Gedeo agroforestry system has long been recognized as a successful example of sustainable land use. The system combines Ensete ventricosum (enset), Coffea arabica (coffee), annual crops, and

indigenous tree species within an integrated production system that has supported relatively high population densities for centuries.This recognition implies that the Gedeo system embodies principles of sustainable agriculture—biodiversity conservation, knowledge transmission, and resilient livelihoods—that are considered globally exemplary. If such a system shows signs of productivity decline under demographic pressure, it raises fundamental questions about the limits of traditional intensification strategies and the need for complementary institutional and technological support. This is precisely the question our study addresses Because of its ecological and cultural significance, the system has been recognized as a UNESCO Globally Important Agricultural Heritage System (GIAHS).

The Gedeo case is theoretically important because it allows an assessment of whether Boserupian adaptation continues to operate under conditions of extreme demographic pressure. If a globally recognized and historically resilient agroforestry system experiences declining productivity under contemporary population densities, this would suggest important limits to population-induced agricultural intensification.

1.4 Research Gap and Theoretical Contribution

Despite extensive literature on population pressure and agricultural change, three important gaps remain. First, most studies focus on national trends or conventional farming systems (e.g., Headey et al., 2014; Jayne et al., 2014), providing limited evidence from internationally recognized heritage agroecosystems—systems that may possess unique adaptive capacities not captured in conventional agricultural analyses. The Gedeo agroforestry system, as a UNESCO Globally Important Agricultural Heritage System (GIAHS), represents a critical case for understanding whether traditional agroecological knowledge can sustain productivity under extreme demographic pressure (Berkes, 2023).

Second, empirical evidence remains scarce regarding whether Boserupian intensification can continue to sustain productivity when rural population densities exceed 900 persons km^{-2}. While Boserupian theory (Boserup, 1965) posits that population pressure drives agricultural innovation, the threshold at which this process breaks down remains theoretically and empirically underexplored (Turner & Fischer-Kowalski, 2009). The Gedeo Zone, with its density of 956 persons km^{-2}, provides a unique natural experiment for testing the limits of this theory..

Third, relatively few studies combine quantitative productivity outcomes with qualitative evidence explaining the mechanisms through which demographic pressure reshapes agricultural systems (Clay & King, 2019; Gebre & Rahut, 2024). Most existing research either documents correlations without mechanistic explanation or provides qualitative case studies without statistical validation. This study addresses this gap through a mixed-methods approach that identifies both statistical associations and the causal pathways underlying them.

This study makes three specific contributions to population-environment scholarship. First, it provides empirical evidence from a UNESCO GIAHS site—a context rarely subjected to quantitative population-agriculture analysis—testing whether globally recognized sustainable systems can withstand extreme

demographic pressure. Second, it moves beyond simple correlation by combining multivariate regression with qualitative mechanism identification, illuminating the pathways through which population pressure constrains agricultural outcomes. Third, it examines the boundaries of Boserupian theory at a population density (956 persons km^{-2}) that exceeds most previous empirical investigations, providing a critical test of whether population-induced intensification remains feasible under extreme conditions.

The study addresses four objectives:

- -To estimate the statistical relationships between agricultural production outputs and population pressure while accounting for the cross-sectional nature of the data
- -To examine the mechanisms linking demographic growth with agricultural changeTo evaluate whether the Gedeo agroforestry system exhibits evidence of adaptive limits under extreme demographic pressure

2. MATERIALS AND METHODS

2.1 Study Area Description

The Gedeo Zone is located in the South Ethiopia Regional State between 5°50'26" to 6°12'48" N latitude and 38°03'02" to 38°18'59" E longitude. Dilla town, the zonal capital, lies 365 km south of Addis Ababa. Elevation ranges from 1,201 to 3,000 m above sea level, with annual precipitation of 800-1,800 mm and mean monthly temperatures from 12.5°C to 25°C (Negash & Alemu, 2013:Fig. 1). Three agroecological zones are recognized: mid-altitude (62.2% of area, 1,500-2,300 m), highland (37.1%, > 2,300 m), and low altitude (0.7%, < 1,500 m).

Nitosols derived from volcanic rocks predominate, characterized by deep profiles (1.5–2.5 m), good drainage, and moderate to high fertility (Kura, 2013). Land use is dominated by perennial crops (coffee, enset) intercropped with annual crops and trees, though forest cover declined from 30% in 1973 to 12% in 2019 (Molla et al., 2020).

2.2 Research Design

A sequential explanatory mixed-methods design was employed:Phase 1 (Quantitative): Household survey using structured questionnaires (n = 390).Phase 2 (Qualitative): Focus group discussions (FGDs; n = 12 groups), key informant interviews (KIIs; n = 24), and field observations.This design enabled statistical testing of population-agriculture relationships followed by in-depth exploration of causal mechanisms and farmer perceptions of sustainability challenges.

2.3 Sampling Procedures

Multistage stratified sampling was applied: **Stage 1** (Woreda selection): Four woredas purposively selected representing different agroecological and demographic conditions:Dilla Zuria (mid-altitude, high density: 1,050 persons km^{-2}),Wonago (mid-low altitude, moderate density: 780 persons km^{-2}),Gedeb (highland, moderate density: 690 persons km^{-2}) and Bule (mid-highland, lower density: 550 persons km^{-2})..**Stage 2 (Kebele selection)**: Two kebeles per woreda (Andida, Chichu, Mekonisa, Sugale, Gerba, Geshe, Ada, Sika).**Stage 3 (Household sampling)**: Sample size was calculated using Yamane's formula: $n = N / (1 + N(e)^2)$, where N is the total number of agricultural households across the eight sampled kebeles (16,632 according to kebele agricultural office records, 2024), e is the desired margin of error (0.05), and the resulting sample size was 390. Proportional allocation was applied across kebeles, followed by stratification by wealth rank (low, medium, high) based on local wealth ranking criteria established through preliminary community meetings.s

2.4 Data Collection

Structured questionnaires were administered to sampled households to collect information on demographic characteristics, landholding size, crop production, livestock ownership, and population pressure indicators. Participation in the survey was voluntary, and informed verbal consent was obtained prior to each interview. Key informant interviews were conducted with agricultural officers, extension agents, village elders, religious leaders, women's representatives, and youth representatives. Focus group discussions explored perceptions regarding historical changes in landholding, agricultural productivity, and sustainability challenges. Field observations and transect walks were conducted with local extension workers to verify agricultural practices and land use conditions.

2.5 Data Analysis

Quantitative data were entered into SPSS version 25 and analyzed using Stata version 15. Descriptive statistics were computed for demographic, agricultural, and landholding variables. To estimate the relationship between demographic pressure and agricultural outcomes, separate multivariate ordinary least squares (OLS) regression models were estimated for each agricultural production category (cereals, cash crops, oilseeds, fruits and vegetables, and livestock production). Given the conceptual overlap between population growth pressure and local population density, variance inflation factor (VIF) diagnostics were first conducted to detect multicollinearity. As these variables showed VIF values exceeding 7.5 (indicating problematic collinearity), they were not entered simultaneously. Instead, a composite population pressure index (PPI) was constructed using principal component analysis (PCA) with varimax rotation. Varimax rotation was employed to maximize the interpretability of the component structure by creating orthogonal factors that are more easily distinguished conceptually.The index combined four household-level indicators: (1) number of dependents added to the household in the past decade, (2) age dependency ratio (proportion of household members under 15 and over 64), (3) household size relative to landholding, and (4) reported changes in perceived population pressure over

the past decade.These indicators were selected to capture both objective demographic pressure (indicators 1–3) and subjective perception of pressure (indicator 4), recognizing that perceived pressure may mediate behavioral responses. Kebele-level population density (persons km^{-2}) was included as a fixed effect to account for spatial variation.The model was specified as a linear regression with robust standard errors clustered at the kebele level to account for within-kebele correlation. The first principal component, which explained 68.4% of the variance, was retained as the PPI. Kaiser-Meyer-Olkin measure of sampling adequacy was 0.81, and Bartlett's test of sphericity was significant ($\chi^2 = 847.3$, $p < 0.001$), confirming the appropriateness of PCA for this data.

. The general model specification was:

$$Y_i = \beta_0 + \beta_1 PG_i + \beta_2 HS_i + \beta_3 PD_i + \beta_4 DR_i + \beta_5 LF_i + \beta_6 AAI_i + \beta_7 INC_i + \beta_8 EDUC_i + \beta_9 SNTY_i + \varepsilon_i$$

where Y_i represents agricultural production outcomes for household i; PPI = composite population pressure index; HS = household size; DR = dependency ratio; LF = land fragmentation (measured as number of plots divided by total landholding); AAI = access to agricultural inputs (binary: access to credit/extension/fertilizer); INC = household annual income (ETB, log-transformed); EDUC = education level of household head (years of schooling); and SNTY = safety net participation status (binary). Model assumptions were tested using Shapiro–Wilk (normality), Breusch–Pagan (heteroskedasticity), and VIF (multicollinearity) diagnostics.

We recognize that the calculated relationships do not prove causation due to the cross-sectional nature of the data. The apparent correlations between agricultural performance and population pressure may potentially be the result of unmeasured confounding variables, such as variations in market access, soil fertility gradients, or climate variability. As a result, we interpret our results as correlational evidence supporting demographic constraint theories. The qualitative findings provide supporting mechanistic evidence, but causal claims are not made. Throughout this paper, we use terms such as "associated with," "related to," and "linked to" rather than causal language. Qualitative data were analyzed thematically using NVivo 12 through open, axial, and selective coding procedures.

2.6 Ethics Approval and Informed .

This study was conducted with human participants in full compliance with the Declaration of Helsinki (2013 revision) and the research ethics guidelines of Dilla University's College of Natural Resources Management. The Research Ethics Review Committee of Dilla University formally approved the research protocol, including all data collection instruments and procedures for household surveys, focus group discussions, and key informant interviews (Approval Reference: CNRM/ERC/15/03/2024, dated 15 March 2024).

Prior to commencing fieldwork, official permission letters were obtained from the Gedeo Zone Administration, all relevant woreda authorities, and the elected kebele chairpersons. These permissions

confirmed that the research was conducted with full institutional and community awareness.All participants provided informed verbal consent after receiving detailed explanations of: (a) the research objectives and intended outputs; (b) confidentiality and anonymity protocols; (c) the voluntary nature of participation; (d) the right to withdraw at any time without negative consequences; and (e) the secure handling of all data. The ethics committee approved the use of verbal consent because written signatures could have been perceived as administrative formalities in the local context, potentially undermining trust and participation rates.

No personal identifiers (names, addresses, or village-specific locations) were recorded. Survey responses were anonymized during data entry using unique household codes. All data are stored on password-protected institutional servers accessible only to the research team. The institutional ethics committee confirmed that this approach satisfied the requirements for protecting participant confidentiality while maintaining research integrity

3. RESULTS

3.1 Household Demographic Characteristics

Table 1 presents demographic characteristics of surveyed households (n = 390). Respondents were predominantly male (90.5%), reflecting patriarchal decision-making structures. Mean household size was 8.6 members (SD = 3.2), substantially larger than the national rural average of 5.5 (CSA, 2021), with over half of households (50.8%) having > 10 members. Illiteracy affected 47.7% of respondents, with only 5.1% attaining secondary education or higher.

Table 1
Household demographic characteristics (n = 390)

Variable	Category	Frequency	Percent	Mean ± SD
Age	20–30 years	107	27.4	42.3 ± 14.7
	31–40 years	123	31.5	
	41–50 years	84	21.5	
	51–60 years	28	7.2	
	> 60 years	48	12.3	
Sex	Male	353	90.5	
	Female	37	9.5	
Family size	1–5 members	66	16.9	8.6 ± 3.2
	6–10 members	126	32.3	
	> 10 members	198	50.8	
Education	Illiterate	186	47.7	
	Primary	104	26.7	
	Secondary	58	14.9	
	Certificate+	42	10.7	
Source: Own survey computation, 2025				

3.2 Landholding Characteristics

Mean total landholding was 0.72 ha per household (range: 0.15–2.50 ha), substantially below the regional average of 1.2 ha (Table 2). Fragmentation was pronounced, with households managing an average of 4.2 separate plots (range: 1–12 plots), some as small as 0.03 ha. Fragmentation was pronounced, with households managing an average of 4.2 separate plots (range: 1–12 plots), some as small as 0.03 ha. Land tenure was predominantly inheritance (72.3%), with limited rental markets (15.6%) and administrative allocation (12.1%).

Table 2
Landholding characteristics

Variable	Mean ± SD	Range
Total landholding (ha)	0.72 ± 0.38	0.15–2.50
Number of plots	4.2 ± 1.9	1–12
Average plot size (ha)	0.17 ± 0.12	0.03–1.20
Source: Own survey computation, 2025		

About 69.5% of Gedeo households, according to our data, operate on less than 1.0 ha. The sample mean household size of 8.6 persons and the zonal mean landholding of 1.09 ha result in 0.13 ha per capita. The FAO's minimum threshold of 0.2 hectare for calorie self-sufficiency is less than this amount. Crucially, the real cropped area per capita may be even lower because some land is used for homesteads, trees, and fallow. This computation utilizes total landholding rather than cropped area specifically. This implies that agricultural intensification alone is insufficient to achieve food security; smallholders also need off-farm revenue streams. Crop-specific intensification, such as maize mechanization, coffee climate adaptability, and zero-grazing livestock, is still feasible for the 30.5% of households that own more than 1.0 ha.

Table 2
a: Zonal landholding distribution, Gedeo Zone Agricultural Office (2023)

Landholding (ha)	Households (n)	Percent	Cumulative %
Landless	77,223	3.9	3.9
< 0.1	264,041	13.3	17.2
0.1–0.5	570,209	28.7	45.9
0.51–1.0	468,951	23.6	69.5
1.01–2.0	366,580	18.4	87.9
2.01–5.0	189,596	9.5	97.4
5.01–10.0	43,522	2.2	99.6
> 10.0	7,205	0.4	100.0
Source: Own survey computation, 2025			
Total households: 1,987,327. Mean landholding: 1.09 ha. Cropped area per capita (assuming 8.6 persons/household): 0.13 ha.			

3.3. Impact of Population Growth on Agricultural Production

Multivariate regression results (Table 3) revealed statistically significant negative associations between population growth and all agricultural production categories ($p < 0.001$). Cereal production showed the strongest negative coefficient ($\beta = -0.229$, $t = -9.11$), followed by cash crops ($\beta = -0.157$, $t = -5.59$), oilseeds ($\beta = -0.151$, $t = -5.54$), fruits and vegetables ($\beta = -0.138$, $t = -4.82$), and animal husbandry ($\beta = -0.116$, $t = -4.73$).To interpret these effect sizes in practical terms: a one-standard-deviation increase in the PPI (approximately 0.85 units) is associated with a reduction of approximately 19% in cereal production relative to the mean, and a 13% reduction in cash crop production. These magnitudes suggest that demographic pressure has economically meaningful effects on household agricultural output. These findings suggest a pattern that departs from Boserupian predictions. While farmers have indeed intensified production—as evidenced by increased cropping frequency and labor inputs—the negative coefficients indicate that intensification efforts have not fully compensated for the effects of demographic pressure. This pattern warrants closer examination of the specific mechanisms through which population pressure may constrain agricultural performance

Table 3
Multivariate regression: Impact of population growth on agricultural production

Production category	Coefficient	Std. Error	t-value	p-value	95% CI
Cereals	-0.2287	0.0251	-9.11	0.000	-0.278 to -0.179
Cash crops	-0.1572	0.0281	-5.59	0.000	-0.212 to -0.102
Oilseeds	-0.1514	0.0274	-5.54	0.000	-0.205 to -0.098
Fruits & vegetables	-0.1383	0.0287	-4.82	0.000	-0.195 to -0.082
Animal husbandry	-0.1162	0.0246	-4.73	0.000	-0.165 to -0.068
Source: Own survey computation, 2025					
Notes: All models controlled for household size, population density, dependency ratio, land fragmentation, input access, income, education, and safety net access. Model fit: R^2 ranged from 0.32 to 0.51.					

Control variables revealed that land fragmentation ($\beta = -0.142$, $p = 0.008$) and household size ($\beta = -0.089$, $p = 0.023$) emerged as significant mediators. Education ($\beta = 0.112$, $p = 0.019$) and access to inputs ($\beta = 0.095$, $p = 0.041$) partially offset negative population effects.

3.4. Population Pressure and Agricultural Productivity

Although total production remains an important indicator of agricultural performance, productivity provides a more meaningful measure for evaluating the sustainability of agricultural systems under demographic pressure.Although the landholding statistics (0.72 ha mean, 0.17 ha mean plot size) offer

indirect evidence on per-hectare productivity, our regression models predict relationships with total production. Households fall below the FAO's 0.2 ha minimum criterion for caloric self-sufficiency at 0.13 cropped hectares per capita, suggesting that a significant improvement in per-unit-area production would be necessary to ensure food security.

Farmers consistently reported perceptions of declining output per plot despite increased labor inputs. Focus group participants described increasing frequencies of weeding, intercropping, and continuous cultivation without corresponding improvements in yields.Farmers reported growing labor inputs without equivalent productivity gains, which is consistent with population-induced intensification, according to these data. The cross-sectional design, however, is unable to conclusively prove causation; other factors, such as variations in the temperature, a loss in soil fertility, or shifts in the market, could also be responsible for this pattern.Qualitative evidence further revealed diminishing returns to agricultural intensification. Respondents indicated that additional labor investments were increasingly devoted to maintaining existing production levels rather than increasing output. This pattern is consistent with a demographic squeeze in which population growth outpaces the capacity of local agricultural systems to generate productivity improvements.

3.5 Farmer Perceptions of Crop Production Sustainability

Cereal production

Maize received the most favorable perception (mean = 8.73/10), with 54.6% agreement. Farmers valued maize for its high yield potential (3–5 tonnes ha^{-1}), multiple uses, and drought tolerance. Teff showed ambivalence (mean = 3.01/5), with 74.9% neutral; concerns focused on labor intensity. Barley showed neutral to negative perceptions (mean = 2.63/5).

Cash crop production

Coffee received strongly positive perceptions (mean = 12.8/15), with 54.4% agreement as the primary cash source. Khat showed negative perceptions (mean = 2.25/5), with 49.2% disagreement; however, 15.9% agreement indicated market segmentation.

Fruit and vegetable production

Mango and carrot received the most favorable ratings (means 3.70 and 3.64, respectively), while avocado showed ambivalence (mean 3.01).

Livestock production

Poultry showed the most favorable perception (mean 3.39), followed by sheep (3.31), cattle (3.07), and goats (3.05).

3.6 Qualitative Findings: Documented Mechanisms

Thematic analysis identified five mechanisms that farmers described as linking population growth to changes in agricultural practices:

- **Land fragmentation and plot dispersion**: Mean plot size decreased from 0.35 ha in 1990 to 0.17 ha in 2020. An elder (male, Wonago) explained: *"My father farmed two big fields. I inherited four smaller fields. My sons will inherit eight tiny plots scattered across the kebele."*
- **Reduced fallow periods**: Farmers reported replacing traditional 5–7 year fallow cycles with continuous annual cultivation.
- **Labor reallocation**: Forty-three percent of households have at least one member working in Dilla town or Addis Ababa, remitting income but reducing farm labor availability.
- **Livestock decline**: Farmers reported cattle ownership declining from 3.2 head per household (1990) to 1.4 head (2023) in high-density areas.
- **Expansion to marginal lands**: Farmers described cultivation expanding onto slopes exceeding 30% gradient and valley bottom areas previously left uncultivated.

4. DISCUSSION

4.1 Population Growth and Agricultural Sustainability

The findings contribute to a long-standing debate in population science concerning the relationship between demographic growth and agricultural change by providing empirical evidence from a context of extreme population density (956 persons km^{-2}) that exceeds most previous investigations. While Boserupian theory predicts that increasing population density stimulates innovation and agricultural intensification (Boserup, 1965), the evidence from Gedeo suggests that such processes may become increasingly constrained under conditions of extreme demographic pressure—particularly when institutional support, technological access, and market opportunities remain limited.

Under a strictly Boserupian scenario, we would expect to observe positive associations between population pressure and productivity, driven by innovation and intensification. Instead, we observe negative associations across all production categories, with intensification strategies yielding diminishing returns. This divergence suggests that the conditions necessary for Boserupian adaptation—secure tenure, access to technology and markets, and institutional support—are not fully present in the Gedeo context.

This study makes three theoretical contributions. First,it provides suggestive evidence of a threshold effect while households did respond to population pressure through labor intensification, crop diversification, and increased cropping frequency, these strategies yielded diminishing returns once average plot sizes fell below economically viable thresholds (approximately 0.17 ha). Although our cross-sectional data do not allow formal testing of non-linearity, the descriptive patterns and farmer reports are consistent with the presence of an adaptive limit. This finding suggests the relationship between population pressure and agricultural intensification may be non-linear, supporting the concept

of "adaptive limits" in population-environment systems (Turner & Fischer-Kowalski, 2009).Second, by documenting five specific mechanisms—land fragmentation, reduced fallow periods, livestock decline, labor reallocation, and expansion to marginal lands—the study moves beyond aggregate correlations to explain the causal pathways through which demographic pressure constrains agricultural outcomes. This mechanistic approach addresses calls in the literature for greater attention to process rather than simply documenting outcomes (Clay & King, 2019).

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Third, the study extends Boserupian theory by identifying the institutional and structural conditions required for population-induced intensification to succeed. In Gedeo, despite formal land certification, incomplete tenure security—particularly regarding plot subdivision among heirs—reduced incentives for long-term investments. Similarly, limited access to credit, inputs, and markets constrained technological adoption. These findings suggest Boserupian adaptation is not automatic but conditional on enabling institutional environments, a point often underemphasized in demographic theory.

Although farmers responded to land scarcity through labor intensification, crop diversification, and more frequent cultivation, these strategies did not fully offset the negative effects of land fragmentation and declining land availability. Consequently, increasing demographic pressure was associated not only with declining production outcomes but also with signs of deteriorating productivity and reduced livelihood resilience. This divergence requires careful interpretation for sustainability science. First, the Boserupian model assumes enabling conditions including secure land tenure, functioning input markets, and accessible technology (Turner & Fischer-Kowalski, 2009). In Gedeo Zone, despite formal land certification since 2005, tenure security remains incomplete. Farmers reported hesitancy to invest in long-term improvements on plots subject to subdivision among heirs. This finding aligns with literature showing that population pressure undermines tenure security in patrilineal inheritance systems, reducing incentives for sustainable land management (Deininger & Jin, 2006; Place & Otsuka, 2002).

Second, agricultural intensification has occurred but along a different trajectory. Instead of increasing yields per hectare through technology adoption, farmers have intensified labor per hectare (weeding frequency increased from 1.5 to 2.8 times per season) and crop frequency (double-cropping expanded from 12% to 31% of plots). However, these intensification strategies have reached biophysical limits, with declining marginal returns to labor—a classic sustainability trap where increasing effort yields diminishing returns (Turner & Ali, 1996; Vanlauwe et al., 2014).

Third, the high initial population density (329 persons km^{-2} in 1984) may have already exceeded the threshold below which Boserupian processes operate effectively. Studies in the Ethiopian highlands suggest population densities exceeding 500 persons km^{-2} create negative feedbacks through land

degradation and institutional breakdown (Pender & Gebremedhin, 2007; Grepperud, 1996). Gedeo's current density of 956 persons km^{-2} far exceeds this threshold, suggesting a "population overshoot" beyond local carrying capacity.

Our findings align with recent meta-analyses showing that population growth negatively affects agricultural productivity in sub-Saharan Africa when institutional conditions are weak (Masters et al., 2013; Jayne et al., 2014). They also echo studies from densely populated areas in Rwanda, where negative effects emerge below farm size thresholds of 0.5 ha (Clay & King, 2019), and Kenya, where Tiffen et al. (1994) found ambivalent outcomes depending on market access and infrastructure .The results indicate that demographic pressure may exceed the adaptive capacity of local farming systems when institutional support, technological access, and market opportunities remain limited.

4.2 Crop-Specific Sustainability Implications

Maize expansion vs. dietary diversity

Maize's favorable perception aligns with national trends showing maize surpassing teff as Ethiopia's most produced cereal (CSA, 2021). From a sustainability perspective, maize offers productivity gains but raises concerns about dietary diversity loss and vulnerability to fall armyworm (*Spodoptera frugiperda*), which damaged 12% of Gedeo maize in 2022. Sustainable intensification requires balancing maize's production benefits with crop diversification for nutrition and risk management (Smith et al., 2017).

Teff and barley constraints

The neutral to negative perceptions of teff and barley reflect structural constraints in Ethiopia's cereal value chains. Teff requires 144 person-days ha^{-1} versus 65 for maize, and post-harvest losses are estimated at 15–20%. For sustainability, these traditional grains—well-adapted to local conditions and with superior nutritional profiles—require investment in labor-saving technologies and storage infrastructure rather than abandonment (Crews & Buckles, 2014).

Coffee system resilience

Coffee's positive perception despite price volatility reflects the cultural and ecological importance of the Gedeo coffee-forest system, which maintains high agrobiodiversity and provides ecosystem services including water regulation and carbon storage (Negash et al., 2012). However, climate change threatens coffee suitability, with models predicting 30–50% decline in suitable area in southern Ethiopia by 2050 (Moat et al., 2017). Sustainability interventions must address both market access and climate adaptation.

Khat controversy

The strong negative perceptions of khat among 49% of respondents, contrasted with 16% positive views, represent a fundamental tension in agricultural sustainability. Khat's economic returns (80,000-120,000 ETB ha^{-1} yr^{-1} vs. 40,000–60,000 for coffee) drive expansion—from 2% to 12% of agricultural land

between 2000 and 2020—despite health, social, and water-use concerns (Gebissa, 2010). From a sustainability perspective, criminalization is unlikely to succeed; policy must address the economic drivers while providing viable alternatives.

4.3 Livestock Sustainability Under Population Pressure

The decline in livestock holdings with population density follows predictable patterns in mixed crop-livestock systems (McDermott et al., 2010). As grazing lands disappear, households face three options: zero-grazing (cut-and-carry), landless livestock (primarily poultry), or livestock abandonment. In Gedeo, 67% of cattle-owning households now practice zero-grazing, feeding crop residues and planted forages. This transition has sustainability implications: while zero-grazing reduces overgrazing pressure, it requires capital investment in housing, planted forages, and water supply—beyond the capacity of many households.

Sheep's favorable perception relative to goats reflects feed competition and cultural factors. Poultry's strong positive perception, particularly among women, aligns with development experience showing poultry as an entry point for women's empowerment (FAO, 2015). However, Newcastle disease vaccination coverage remains low (estimated 35%), constraining productivity gains. Sustainable livestock intensification requires integrated interventions addressing feed, health, and gender dimensions simultaneously.

4.4 Pathways and Policy Suggestions for Sustainable Intensification

The findings suggest five priority intervention areas aligned with agricultural sustainability principles to address the challenges of extreme population pressure, land fragmentation, and institutional constraints (Pretty, 2008; Garnett et al., 2013). These recommendations are designed to be context-specific and actionable, drawing on the mechanisms identified in this study.

First, integrated demographic-agricultural programming. The correlation between family size and land pressure ($r = 0.43$, $p < 0.001$) suggests a potential synergy between family planning services and agricultural extension. For example, family planning services could be co-located with agricultural extension services at existing Farmer Training Centers to address the root drivers of fragmentation while respecting reproductive rights. Integrating them through existing Farmer Training Centers could address root drivers of fragmentation while respecting reproductive rights, a key finding for population-environment policy.

Second, land use optimization for fragmented holdings. With average plot sizes of 0.17 ha, standard extension recommendations for larger plots are irrelevant. A pilot program in two kebeles could identify specialization zones—vegetable production in valley bottoms, coffee on slopes, and enset in homestead areas—while maintaining agrobiodiversity. **This requires strengthening local land governance institutions to move beyond simple plot subdivision.**

Third, crop- and livestock-specific intensification. This requires a differentiated policy approach:

- **Teff and Barley**: Need labor-saving technologies (row seeders, mechanical weeders) and improved storage to remain viable. **Specifically, introducing row seeders for teff could reduce labor requirements by 30%, making this traditional crop more viable.**
- **Coffee**: Requires cooperative strengthening and climate adaptation (shade management, certification) (Moat et al., 2017).
- **Zero-grazing Systems**: Need improved forages, housing, and veterinary services, ideally supported by revolving credit funds.
- **Market Infrastructure**: Cold chains, processing facilities, and rural roads require public-private partnerships beyond household capacity. **Cold chains for perishable products (fruits, vegetables, milk) and processing facilities for coffee could reduce post-harvest losses currently estimated at 20–30%.**

Fifth, gender-responsive extension and labor-saving technologies. Women bear significant agricultural labor burdens, particularly in weeding, harvesting, and post-harvest processing. Addressing women's constraints requires: (1) providing childcare services at extension training centers to enable women's participation, (2) promoting fuel-efficient stoves and water harvesting to reduce time spent on domestic tasks, (3) targeting women with credit and input support through women's self-help groups, and (4) training female extension agents who can better reach women farmers.

Finally, we emphasize that these interventions must be implemented as integrated packages rather than standalone projects. The mechanisms we identified are interlinked: land fragmentation drives livestock decline, which reduces manure availability, which constrains productivity, which drives labor migration, which increases dependence on remittances. Addressing any single mechanism in isolation is unlikely to succeed. Successful interventions require coordination across agricultural, demographic, environmental, and social policy domains.

4.5 Limitations and Future Research Directions

This study has several limitations that should be considered when interpreting the findings. First, agricultural productivity assessments relied partly on farmer-reported production data rather than direct plot-level yield measurements. While we employed triangulation with key informant interviews and secondary data from agricultural offices to validate reported figures, the absence of field-level crop cutting limits the precision of our productivity estimates. Future research should complement household surveys with plot-level measurements and crop-cutting experiments to obtain more precise productivity estimates.

Second, the cross-sectional design precludes definitive causal interpretation. The negative associations we observe between population pressure and agricultural outcomes could be influenced by unmeasured confounding variables, including variations in market access, soil fertility gradients, climate variability, or historical land-use patterns. Although our mixed-methods approach and mechanism identification

strengthen the circumstantial case for demographic constraint, longitudinal data would be necessary for robust causal attribution. Future research should employ panel data designs to track household-level changes over time. Future research should employ panel data designs to track household-level changes over time and establish causal direction more confidently.

Third, reverse causality cannot be entirely dismissed. Declining agricultural productivity may itself drive demographic responses, including out-migration of working-age adults, delayed marriage, or fertility reduction. Our qualitative evidence suggests households primarily attribute changes to population pressure rather than productivity declines, and the negative effects persist even when accounting for household income and safety net participation. However, we acknowledge that bidirectional relationships likely exist and recommend that future studies examine these dynamics explicitly using instrumental variable approaches or natural experiments.

Fourth, the underrepresentation of female-headed households (9.5% versus an estimated 18–22% in the zone) may limit the generalizability of findings regarding gender-differentiated impacts. Given that women often face distinct constraints in access to land, credit, and extension services, future research should oversample female-headed households to examine differential vulnerability to demographic pressure.

Fifth, climate variability—particularly rainfall variability and temperature trends—was not comprehensively incorporated into the analytical framework. Emerging evidence suggests climate change may interact with demographic pressure to compound agricultural challenges. Future studies should integrate meteorological data with household surveys to disentangle population and climate effects.. Sixth, our analysis did not quantify environmental outcomes such as soil nutrient depletion, biodiversity loss, or carbon stock changes. While these represent critical dimensions of sustainability, they were beyond the scope of this study. Future research should examine whether demographic pressure drives trade-offs between agricultural production and ecosystem service provision, using biophysical measurements alongside socio-economic data..

Despite these limitations, the study provides important empirical evidence from an understudied UNESCO GIAHS context, offering insights that can inform both theory and policy. The consistency of negative associations across multiple production categories, combined with community-validated mechanistic explanations and convergence with findings from other densely populated contexts, strengthens confidence in our core conclusions regarding the constraints on Boserupian adaptation under extreme demographic pressure.

5. CONCLUSIONS AND SUSTAINABILITY IMPLICATIONS

This study contributes to population–environment scholarship by examining whether a historically resilient agroforestry system can maintain agricultural productivity under conditions of exceptionally high demographic pressure (956 persons km^{-2}). Using evidence from one of Africa's most densely populated rural landscapes, the findings reveal significant negative relationships between population

pressure and multiple dimensions of agricultural performance—including cereals, cash crops, oilseeds, fruits and vegetables, and livestock production—across all production categories examined.

The results suggest that population growth, in this setting, is associated with changes in agricultural systems through five interconnected mechanisms: land fragmentation (reducing plot sizes from 0.35 ha to 0.17 ha), reduced fallow periods (replacing traditional 5–7 year cycles with continuous annual cultivation), livestock decline (from 3.2 to 1.4 cattle per household), labor reallocation (43% of households having at least one member working elsewhere), and expansion onto marginal lands (slopes exceeding 30%). While households have responded through various forms of agricultural intensification —increased weeding frequency, double-cropping, and crop diversification—these adaptations appear increasingly insufficient to offset the effects of demographic pressure.

Beyond its local relevance, the study offers broader implications for demographic theory. The findings indicate that population-induced agricultural intensification is not unlimited and may become increasingly constrained once demographic pressure exceeds the adaptive capacity of local institutions, land resources, and production systems. The evidence supports a conditional interpretation of Boserupian theory—acknowledging that while population pressure can stimulate innovation, this process requires enabling conditions (secure tenure, input access, technology, market infrastructure) that are often absent in densely populated rural settings. The study thus contributes to the growing literature on demographic carrying capacity by providing empirical evidence that Boserupian adaptation has limits, particularly when institutional support is weak and fragmentation severe.

Achieving sustainable agricultural development in densely populated smallholder systems will require integrated policies that simultaneously address demographic dynamics, land governance, technological innovation, market development, and livelihood diversification. Specifically, five priority areas emerge from this research:-:

(1) Integrated demographic-agricultural programming through existing Farmer Training Centers. For example, family planning services could be co-located with agricultural extension services to address the root drivers of fragmentation while respecting reproductive rights.;

(2) 2. Land use optimization for fragmented holdings through participatory village-level planning. A pilot program in two kebeles could identify specialization zones—vegetable production in valley bottoms, coffee on slopes, and enset in homestead areas—while maintaining agrobiodiversity;

(3) 3. Crop- and livestock-specific intensification: labor-saving technologies for teff and barley; cooperative strengthening for coffee; improved forages and housing for zero-grazing livestock. Specifically, introducing row seeders for teff could reduce labor requirements by 30%, making this traditional crop more viable.

(4) Market infrastructure development through public-private partnerships. Cold chains for perishable products (fruits, vegetables, milk) and processing facilities for coffee could reduce post-harvest losses

currently estimated at 20–30%..

(5) Gender-responsive extension addressing women's labor burden through childcare services at training centers, fuel-efficient stoves, and targeted credit through women's self-help groups.

Without such integrated interventions, even globally recognized sustainable agricultural systems like the Gedeo agroforestry system may face irreversible productivity decline, threatening both food security and the cultural and ecological heritage that the system represents. This study demonstrates that even historically resilient agricultural systems face limits when demographic pressure exceeds institutional and ecological adaptive capacity. The Gedeo case serves as both a warning and a guide: a warning that population pressure can overwhelm traditional intensification strategies, and a guide that with appropriate institutional support, technological access, and livelihood diversification, sustainable intensification remains possible.

For sub-Saharan Africa, where population growth continues to outpace agricultural productivity gains and average farm sizes decline below viability thresholds in many regions, the Gedeo experience offers critical lessons about the conditions necessary for agricultural sustainability in densely populated smallholder systems. The findings suggest that policy responses must match the scale and complexity of the challenges, moving beyond simplistic narratives of either population-induced innovation or inevitable decline toward context-specific interventions that address demographic, institutional, technological, and market constraints simultaneously. This study provides empirical evidence that the limits of Boserupian adaptation are real and pressing, and that policy responses must match the scale and complexity of the challenges facing densely populated smallholder systems in sub-Saharan AfricaThis study provides empirical evidence that the limits of Boserupian adaptation are real and pressing, and that policy responses must match the scale and complexity of the challenges facing densely populated smallholder systems in sub-Saharan Africa.

Declarations

CONFLICT OF INTEREST

The authors declare no conflicts of interest

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to institutional ethical requirements and the protection of participant confidentiality.

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Figures

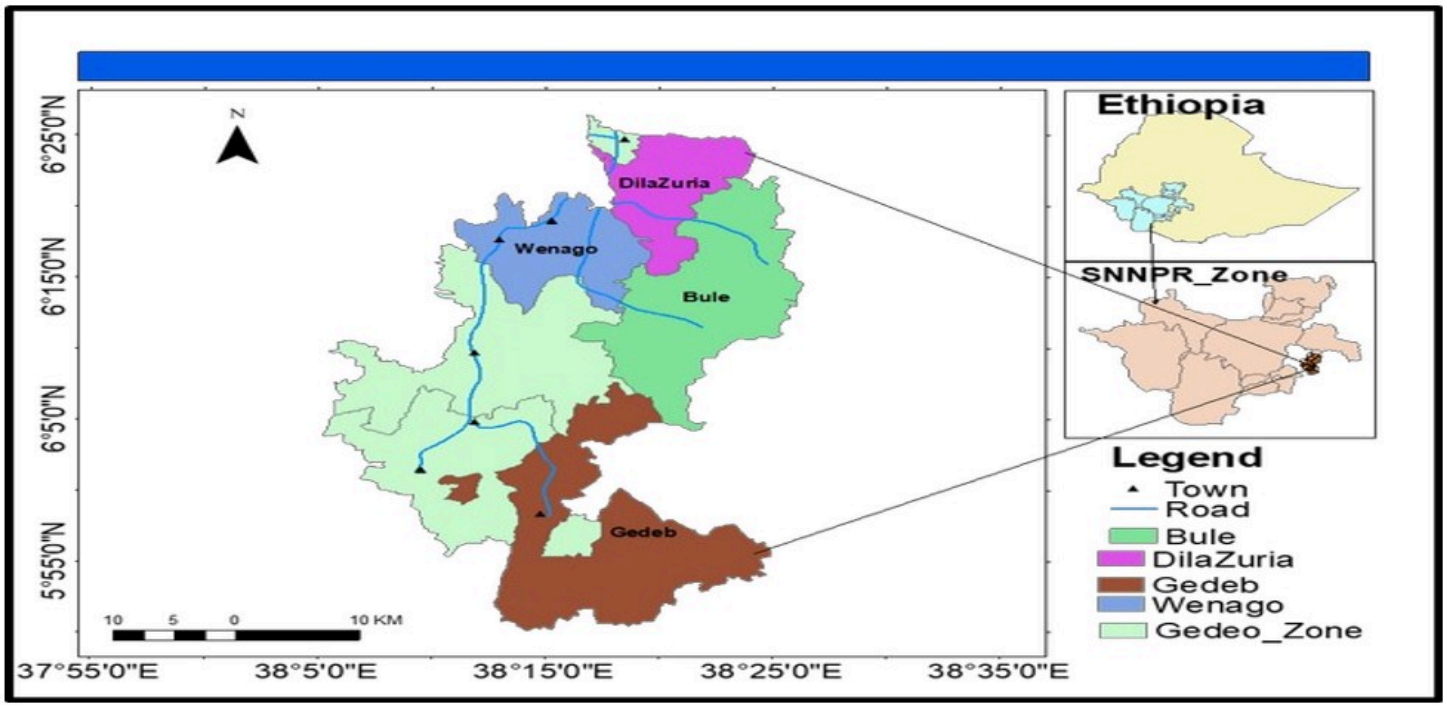


Figure 1

Location map of the study area (Gedeo Zone, Southern Ethiopia).Base map data sourced from the Ethiopian Geospatial Information Agency (EGIA, 2023). Administrative boundaries, elevation contours, and settlement locations were overlaid using ArcGIS 10.8 based on field validation during 2024-2025. The map was created by the first author for this study