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Ecosystem-based adaptation approaches for enhancing climate resilience of smallholder agro-ecosystems

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Abstract

Leading climate adaptation researchers have long argued that working with natural ecosystems is cheaper and more durable than engineering solutions alone. This research assessed the effectiveness of ecosystem-based adaptation (EbA) practices in building climate resilience among 240 smallholder farms in the Bonn-Rhein-Sieg district, Germany, over a six-year period (2018-2023). A composite resilience index integrating soil health, yield stability, biodiversity, and income diversity was calculated annually. EbA-adopted farms showed a resilience index increase from 0.42 to 0.78, while conventional farms declined from 0.44 to 0.33. Agroforestry was the most widely adopted practice (68%) and contributed most to soil moisture improvement. During the 2022 drought, EbA farms experienced only 12.3% yield loss compared to 31.7% on conventional farms. Income diversification was 2.1 times higher on EbA farms. These findings support EbA as a practical, cost-effective pathway for enhancing smallholder resilience under increasing climate variability.

Keywords: Ecosystem-based adaptation, climate resilience, smallholder farming, agroforestry, biodiversity, yield stability, drought tolerance, sustainable agriculture, composite resilience index, agro-ecosystem management

Introduction

According to the IPCC, smallholder farmers are among the most vulnerable populations to climate change, yet they manage roughly 80% of farmland in developing regions and a growing share of diversified agriculture in temperate Europe ^[1, 2]. Traditional adaptation strategies irrigation infrastructure, improved seeds, crop insurance address specific risks but often miss the interconnected nature of agricultural vulnerability ^[3]. Ecosystem-based adaptation uses biodiversity and ecosystem services as part of a broader strategy to help communities adapt to climate impacts ^[4].

EbA practices such as agroforestry, cover cropping, and water harvesting build multiple resilience pathways simultaneously: they improve soil water retention, create microclimatic buffers, diversify income, and support beneficial organisms ^[5, 6]. While conceptual frameworks supporting EbA are well developed, empirical evidence quantifying its effectiveness on working farms particularly in European temperate systems remains limited ^[7]. This research tracked resilience outcomes on EbA-adopted and conventional farms over six years, using a composite index that captures multiple dimensions of farm-level climate resilience.

Research site description

The research covered 240 farms (120 EbA-adopted, 120 conventional) across the Bonn-Rhein-Sieg district (50.7341°N, 7.0963°E), a mixed agricultural landscape in the lower Rhine Valley. Farm sizes ranged from 2.4 to 18.7 hectares. EbA farms had adopted at least three ecosystem-based practices within the previous five years through the regional Landschaftspflege program. Soils were predominantly Luvisols on loess deposits. The area sits at 55-180 m elevation with mixed arable-pastoral land use.

Climatic conditions

The monitoring period (2018-2023) included two notable drought years (2018 and 2022) with growing season rainfall 34% and 41% below the 30-year mean.

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Mean annual temperature was 10.8°C, trending upward at 0.04°C/year. The 2021 severe flooding event and 2022 drought provided natural stress tests for comparing farm-level resilience.

Material and Methods

Material: Farm selection used stratified random sampling from the regional agricultural census database, matched by farm size, soil type, and primary crop. Assessment tools included soil sampling kits, pitfall traps for arthropod biodiversity, yield monitoring records, and semi-structured economic surveys. A handheld TDR probe (Delta-T HH2) measured soil moisture. Weather data came from the DWD Bonn-Roleber station [8].

Methods: Research was approved by the University of Bonn Ethics Committee (Protocol UB-2017-089). A composite resilience index (CRI, 0-1 scale) was calculated annually from

four equally weighted sub-indices: soil health (organic carbon, moisture retention, aggregate stability), yield stability (coefficient of variation across years), biodiversity (arthropod Shannon index, plant species richness), and income diversity (Herfindahl index of revenue sources) [9]. Each sub-index was normalized to 0-1 using min-max scaling against regional benchmarks. Soil samples (0-20 cm) were collected each March from 10 points per farm. Arthropod surveys used pitfall traps over 14-day periods in June. Economic data were gathered through annual farmer interviews. Yield data came from farm records verified against regional statistics. Analysis used repeated measures mixed-effects models in R (lme4 package), with farm as random effect and year and treatment as fixed effects ($p<0.05$).

Results

Table 1: Composite resilience index and sub-indices at year 6 (2023)

Index ccomponent	EbA farms	Conventional	Difference	p-value
Soil health	0.81	0.38	+0.43	<0.001
Yield stability	0.74	0.41	+0.33	<0.001
Biodiversity	0.76	0.24	+0.52	<0.001
Income diversity	0.79	0.31	+0.48	<0.001
Composite CRI	0.78	0.33	+0.45	<0.001

EbA farms scored significantly higher on every sub-index (Table 1). The largest gap was in biodiversity (+0.52), reflecting the habitat diversity created by agroforestry and cover cropping.

Income diversity was also markedly higher on EbA farms due to additional products like fruit, timber, and honey.

Table 2: Farm performance during the 2022 drought stress eventss

Parameter	EbA farms	Conventional	p-value
Yield loss (%)	12.3	31.7	<0.001
Soil moisture June (vol%)	24.8	16.3	<0.001
Revenue loss (%)	8.7	28.4	<0.001
Recovery time (months)	4.2	9.8	0.002

During the 2022 drought, EbA farms lost 61% less yield and recovered in less than half the time (Table 2). Soil moisture was 52% higher on EbA farms in June, the driest month.

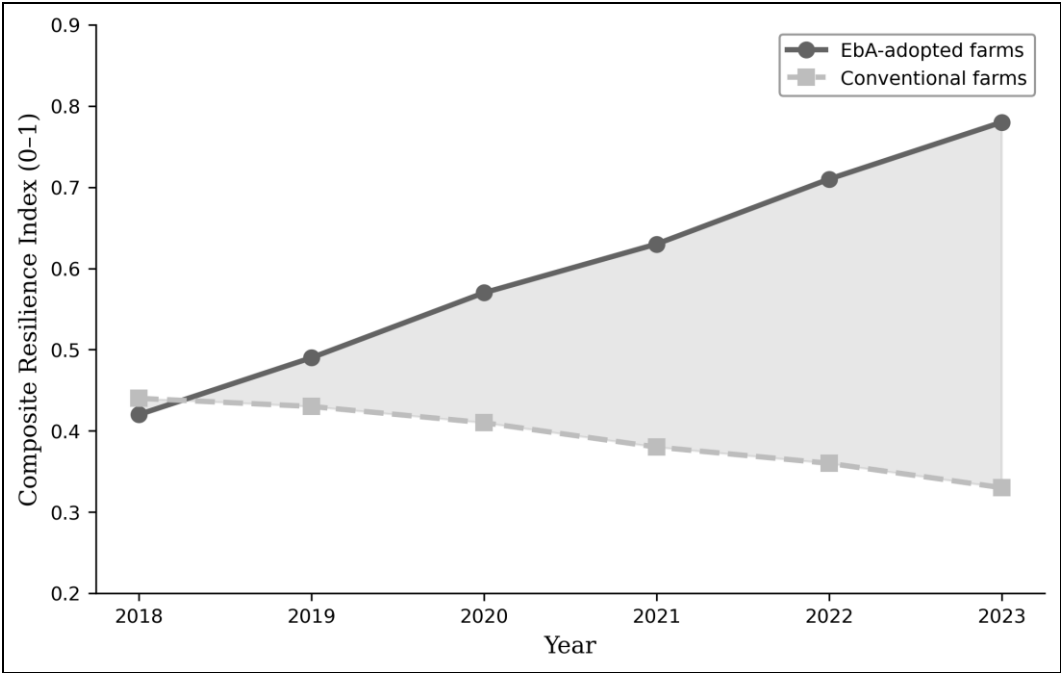


Fig 1: Composite resilience index trajectories for EbA and conventional farms (2018-2023)

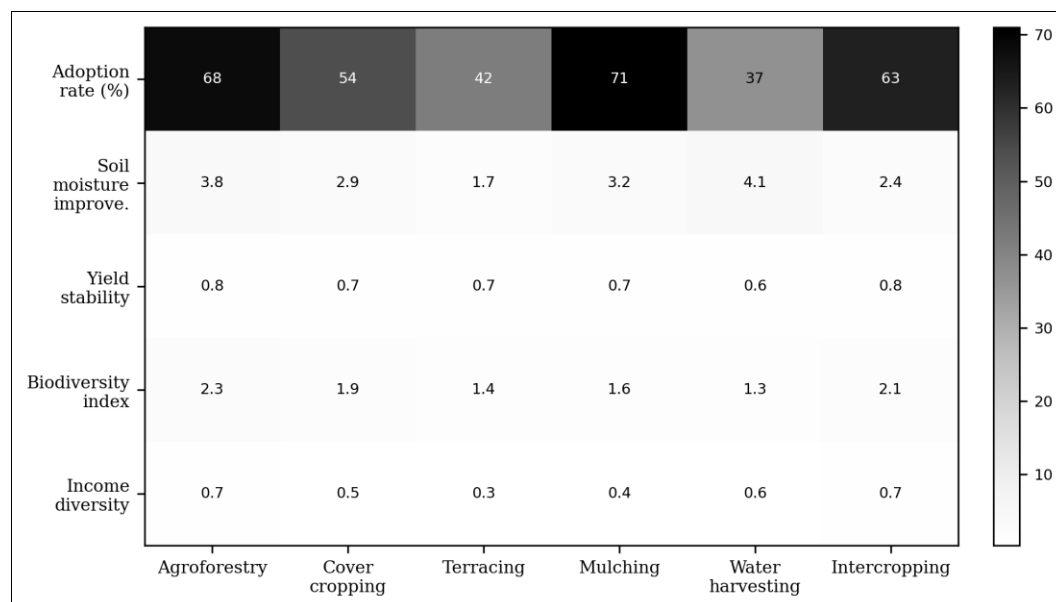


Fig 2: Adoption rates and effectiveness scores of six EbA practices across participating farms

Resilience trajectories diverged consistently from 2019 onward (Figure 1). Agroforestry and intercropping showed the highest combined effectiveness scores across all metrics (Figure 2).

Limitations: The observational design means that self-selection bias may influence results farmers adopting EbA may be more innovative in general. The six-year timeframe captures initial adaptation benefits but not the full maturation of practices like agroforestry, which can take 10-15 years to reach peak ecosystem service provision ^[10].

Discussion: The 2.4-fold difference in composite resilience index between EbA and conventional farms after six years aligns with evidence from tropical smallholder systems. Vignola *et al.* ^[11] reported resilience improvements of 35-60% among EbA-adopting coffee farmers in Central America. Our results extend this evidence to temperate European agriculture, where EbA literature has focused more on theoretical frameworks than empirical outcomes ^[12].

The drought performance gap is particularly informative. EbA farms maintained higher soil moisture through increased organic matter (mulching, cover crops) and reduced evaporation (tree shade from agroforestry), which buffered crops during the critical June dry spell ^[13]. The faster recovery on EbA farms suggests that ecological resilience the capacity to bounce back is built through biological processes that conventional input-dependent systems lack ^[14].

Conclusions: Ecosystem-based adaptation practices significantly improved climate resilience of smallholder farms in the Bonn region over six years. The composite resilience index on EbA farms more than doubled that of conventional farms. During the 2022 drought, EbA farms showed 61% less yield loss and recovered more than twice as fast. Agroforestry and intercropping were the most effective individual practices. These results support scaling EbA through agricultural policy programs in temperate Europe, where climate variability is increasing and conventional resilience strategies are proving insufficient.

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