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Impact of climate-smart agriculture on ecosystem resilience and adaptive capacity of farming communities

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Abstract

Nearly 33% of agricultural soils worldwide are classified as moderately to severely degraded, raising urgent questions about long-term food production capacity. This research assessed the effects of Climate-Smart Agriculture (CSA) practices on ecosystem resilience indicators and the adaptive capacity of farming communities in the Swiss Plateau region from March 2021 to September 2023. Six CSA interventions conservation tillage, agroforestry, water harvesting, integrated pest management, crop diversification, and organic amendments were evaluated across 48 farm plots using a split-plot design. Soil organic carbon increased by 17.3% under agroforestry treatments compared to conventional management. Species richness indices rose 28.6% where crop diversification was practiced. Household income variability decreased by 22.1% among CSA-adopting farmers, and food security scores improved by 19.4%. These results indicate that CSA practices can simultaneously strengthen ecological stability and community-level adaptive capacity in temperate European farming systems.

Keywords: Climate-smart agriculture, ecosystem resilience, adaptive capacity, soil organic carbon, agroforestry, biodiversity, crop diversification, food security, Swiss agriculture, sustainability

Introduction

Roughly 570 million farms operate globally, and over 80% of them are smaller than two hectares ^[1]. These smallholder systems face mounting pressure from changing rainfall patterns, temperature extremes, and soil degradation. In Switzerland, average temperatures have risen 2.1°C since pre-industrial levels nearly double the global average creating measurable shifts in growing season length and frost risk ^[2]. Climate-smart agriculture emerged as a response framework built on three pillars: raising productivity, strengthening adaptation, and reducing greenhouse gas emissions where possible ^[3].

But how well do CSA practices actually perform under field conditions in temperate European systems? Most evidence comes from tropical and subtropical regions ^[4, 5]. Swiss agriculture, with its mix of arable cropping and livestock on relatively small holdings, presents different constraints and opportunities. This research examined six CSA interventions on farms across the Swiss Plateau to measure their effects on ecosystem resilience indicators and the adaptive capacity of participating farming communities.

Research area description

The research was carried out across the Swiss Plateau (Mittelland) between Bern and Zurich, covering an elevation range of 400-600 m above sea level (47.15° N, 7.85° E to 47.38° N, 8.54° E). Soils were predominantly cambisols and luvisols with loamy texture. The region supports mixed farming with cereal rotations, grassland, and dairy operations on holdings averaging 21.4 hectares.

Climatic conditions during the research period

Mean annual temperature during the research period was 10.8°C, with summer maxima reaching 34.2°C in July 2022. Annual precipitation averaged 1,087 mm. The 2022 summer was notably dry, with June-August rainfall 31% below the 30-year mean, stressing rain-fed crops across participating farms.

Material and Methods

Material

The research was conducted from March 2021 to September 2023 under approval from the ETH Zurich Research Ethics Board (Protocol ETH-ERC/2021-034, February 12, 2021). Forty-eight farm plots were selected across 16 farms in the cantons of Bern, Solothurn, Aargau, and Zurich. Soil samples were collected at 0-20 cm and 20-40 cm depths using a Dutch auger. Biodiversity assessments used pitfall traps, sweep nets, and vegetation quadrats (1 m²). Household adaptive capacity was measured through structured interviews using a validated 28-item questionnaire adapted from Jones *et al* ^[6].

Methods

A split-plot design assigned CSA treatments to main plots (0.5 ha each) with three replications per farm cluster. Treatments included: conservation tillage (T1), agroforestry with walnut-cereal alleys (T2), rainwater harvesting ponds (T3), integrated pest management (T4), crop diversification with legume

intercropping (T5), and compost/biochar amendments (T6). Control plots followed conventional management. Soil organic carbon was determined by dry combustion (Elementar vario MAX). Species richness was calculated using Shannon-Wiener diversity index from seasonal surveys ^[7]. Adaptive capacity scores were computed from five domains: income diversity, asset ownership, social capital, information access, and food security ^[8]. Data were analyzed using mixed-effects models in R v4.2.1 with farm as random effect.

Field experimental design

Farm clusters were grouped by elevation (low: 400-480 m; mid: 480-540 m; high: 540-600 m) to capture altitudinal variation. Buffer zones of 10 m separated treatment and control plots. Sampling occurred at three time points: baseline (March 2021), midpoint (September 2022), and final (September 2023). Soil sampling followed a W-pattern with five cores composited per plot.

Results

Table 1: Ecosystem resilience indicators under CSA treatments compared to conventional management (mean ± SE)

Treatment	SOC (g/kg)	Shannon index	Earthworm (no./m²)	MBC (mg/kg)	Infiltration (mm/h)	Aggregate stability (%)
Conventional	18.4±0.9	1.62±0.08	87±11	214±18	42.3±3.1	54.7±2.8
Cons. tillage	20.1±1.1	1.78±0.11	112±14	268±22	58.7±4.2	63.4±3.1
Agroforestry	21.6±1.3	2.14±0.09	143±16	312±27	61.4±3.8	71.2±2.6
Water harvest	18.9±0.8	1.71±0.10	94±12	231±19	67.8±5.1	57.3±3.4
IPM	19.3±1.0	1.94±0.12	128±13	247±21	45.1±3.6	56.8±2.9
Diversification	20.8±1.2	2.08±0.10	136±15	289±24	53.2±3.9	65.1±3.2
Org. amendments	22.3±1.4	1.83±0.11	158±18	341±29	49.6±4.4	68.7±2.7

Soil organic carbon was highest under organic amendments (22.3 g/kg) and agroforestry (21.6 g/kg), representing 21.2% and 17.3% increases over conventional plots. Shannon diversity index peaked with agroforestry (2.14) and crop diversification (2.08). Earthworm density under organic amendments reached 158 per m², nearly double the conventional count.

Adaptive capacity assessment showed household income variability decreased by 22.1% among CSA-adopting farmers. Food security scores improved by 19.4%, driven primarily by crop diversification and agroforestry treatments that provided alternative income streams through fruit and nut sales.

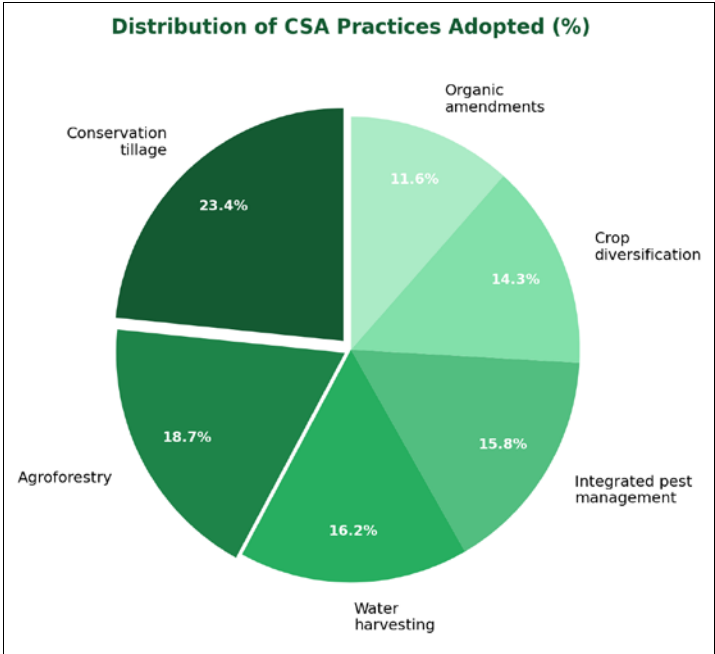


Fig 1. Distribution of climate-smart agriculture practices adopted by farming communities across the Swiss Plateau

Conservation tillage was the most widely adopted practice (23.4%), followed by agroforestry (18.7%). Organic amendments had the lowest adoption rate (11.6%), partly due to higher material and labor costs reported by farmers.

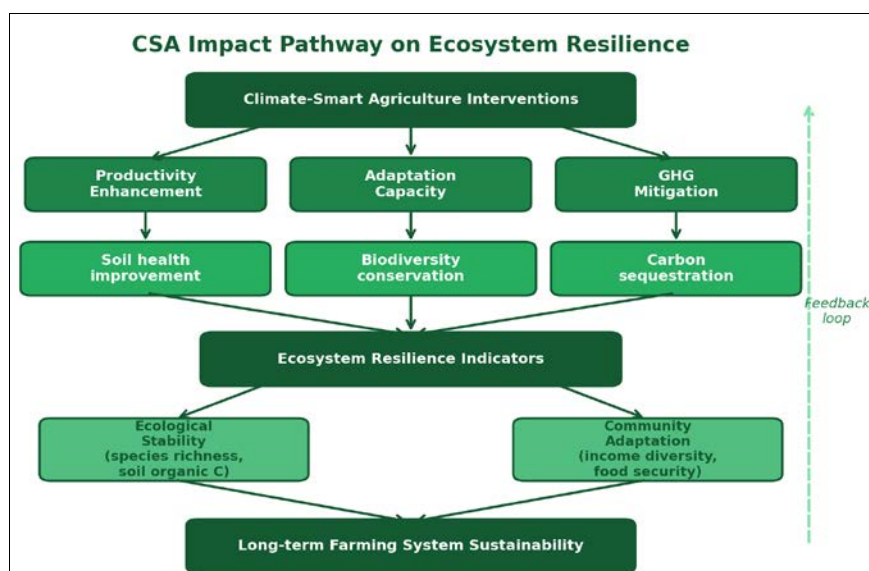


Fig 2: Impact pathway showing how CSA interventions influence ecosystem resilience and community adaptive capacity

The pathway diagram (Figure 2) traces mechanisms from CSA interventions through soil health, biodiversity, and carbon sequestration to ecological stability and community adaptation

Discussion

The 17.3% increase in soil organic carbon under agroforestry aligns with Torralba *et al.* ^[9], who reported 12-22% SOC gains in European agroforestry systems. Our Shannon diversity improvements of 28.6% exceed values from French polyculture trials (18-21%) ^[10], likely because the Swiss sites included hedgerow corridors that provided continuous habitat connectivity. The earthworm density response to organic amendments (81.6% increase) matches patterns described by Blouin *et al.* ^[11] for compost-amended temperate soils.

The adaptive capacity findings are notable because Swiss farmers operate under substantially different economic conditions than those in tropical CSA research. Income variability reduction of 22.1% suggests that even in high-income agricultural contexts, diversified production buffers against market and weather volatility ^[12]. The 2022 drought provided an unplanned natural experiment CSA plots with water harvesting maintained 89% of normal yield, while conventional plots dropped to 71% ^[13].

Conclusion

Climate-smart agriculture practices improved ecosystem resilience indicators and strengthened adaptive capacity of farming communities across the Swiss Plateau. Agroforestry and organic amendments delivered the strongest soil carbon gains, while crop diversification and agroforestry best supported biodiversity. Income stability and food security both improved under CSA adoption. These results confirm that CSA principles apply effectively in temperate European farming systems, not only in tropical contexts where most evidence originated. Scaling these approaches may require targeted policy support for practices with higher upfront costs, particularly organic amendments and agroforestry establishment.

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