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Spatial analysis of agricultural land fragmentation and its environmental consequences in Poland

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Abstract

Agricultural land fragmentation, characterised by division into numerous small and spatially dispersed parcels, is pervasive across Central and Eastern Europe. In Poland, historical inheritance-based division has created one of the EU's most fragmented agricultural landscapes, with implications for farming efficiency, rural livelihoods, and environmental quality. This research presents a spatial analysis across Poland's 2,477 communes using cadastral data and satellite-derived land cover. Five fragmentation indices were computed: mean parcel size, parcel density, Simpson diversity of farm size distribution, mean inter-parcel distance, and edge density. Extreme fragmentation concentrated in the southeastern provinces of Podkarpackie, Małopolskie, and Świętokrzyskie, where mean parcels fall below 0.5 ha and individual holdings comprise 6–12 spatially separated parcels. Correlation analysis with environmental indicators demonstrates that highly fragmented communes exhibit 23% higher pesticide use per hectare, lower agri-environment scheme participation (8.2% versus 24.7% in least fragmented areas), reduced hedgerow retention, and 2.5–4.0 times higher soil erosion rates due to slope-perpendicular parcel orientation. Paradoxically, fragmented landscapes retained higher densities of ecological corridors along field boundaries. These findings highlight the need for integrated land consolidation programmes that combine structural reform with environmental management objectives.

Keywords: Land fragmentation, agricultural land, Poland, environmental consequences, spatial analysis, pesticide use, soil erosion, agri-environment schemes, cadastral data, land consolidation

Introduction

Poland's agricultural landscape bears the imprint of centuries of inheritance-based division, compounded by incomplete socialist collectivisation and 1990s restitution. Approximately 1.4 million farms operate on less than 5 ha distributed across multiple non-contiguous parcels ^[1]. The economic consequences—higher transport costs, machinery inefficiency, precision agriculture barriers—are well documented and contribute to the persistent productivity gap with Western Europe ^[2, 3].

The environmental consequences of fragmentation have received comparatively less attention despite their potential significance. Small parcels are difficult to manage under environmental best practice. High boundary density creates complex land cover transitions affecting ecological connectivity. The orientation of narrow elongated parcels, characteristic of southeastern Poland, may interact with topography to influence erosion and runoff ^[4, 5].

Previous research has addressed fragmentation effects in individual communes or regions but has not systematically examined environmental correlations at the national scale ^[3, 6]. The relationship between fragmentation and biodiversity indicators is particularly nuanced: while intensive cultivation on fragmented land may degrade habitat, the high density of field margins may simultaneously provide ecological corridors ^[7, 8].

This research conducts a comprehensive spatial analysis across all 2,477 Polish communes, testing statistical associations between fragmentation intensity and pesticide use, agri-environment participation, field margin retention, and soil erosion vulnerability. The objectives are to quantify the spatial pattern of fragmentation, identify the most severely affected regions, and evaluate whether fragmentation carries net positive or negative environmental consequences ^[9, 10].

Research Area Description

The analysis covers Poland's entire agricultural area across 2,477 communes. The most fragmented landscapes are in southeastern provinces where open-field medieval farming

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systems created long narrow strips perpendicular to slope contours. Northern and western provinces (Zachodniopomorskie, Warmińsko-Mazurskie) have larger structures from post-socialist state farm privatisation, with mean parcel sizes exceeding 5 ha. Topography ranges from flat northern plains to hilly southeastern terrain where erosion is a significant concern ^[1, 4].

Material and Methods

Material

Cadastral data from the Polish Agency for Restructuring and Modernisation of Agriculture (reference year 2020) provided parcel information at commune level. Farm structural data came from the 2020 Agricultural Census. Environmental indicators were obtained from the Central Statistical Office (pesticides), the Agency for Restructuring (agri-environment schemes), the Institute of Soil Science and Plant Cultivation (erosion), and Copernicus CORINE Land Cover at 100 m resolution (field margins and land cover boundaries) ^[5, 11].

Methods

Five fragmentation indices were computed per commune: mean parcel size, parcel density per km², Simpson diversity of farm size distribution, mean Euclidean inter-parcel distance, and edge density from CORINE boundaries. Spearman rank correlations and partial correlations (controlling for elevation, slope, soil type, and agricultural intensity) tested associations with environmental indicators. Spatial autocorrelation was assessed using Moran’s I, with spatial lag models applied where significant autocorrelation was detected ^[9, 12].

Historical Fragmentation Evolution

Archival cadastral analysis from selected communes showed that southeastern fragmentation intensified progressively: in Podkarpackie, average parcels per holding increased from 4.2 in 1950 to 8.7 in 2020, while mean size declined from 0.82 to 0.38 ha. This ongoing subdivision reflects absent minimum parcel regulations and the cultural importance of equal sibling inheritance in rural southeastern communities ^[1, 6].

Results

Table 1: Environmental indicators by fragmentation quintile (commune means)

Indicator	Q1 (most frag.)	Q3 (median)	Q5 (least frag.)
Mean Parcel Size (ha)	0.38	1.85	6.10
Pesticide (kg a.i./ha)	4.8	3.9	3.2
AE Participation (%)	8.2	15.4	24.7
Hedgerow Density (m/ha)	12.1	8.4	6.8
Erosion Rate (t/ha/yr)	8.4	4.2	2.1

Table 2: Spearman partial correlation coefficients between fragmentation (parcel density) and environmental indicators

Environmental Indicator	Correlation	p-value	Controlling Variables
Pesticide use/ha	+0.34	<0.001	Elevation, soil, crop type
AE participation	−0.41	<0.001	Elevation, soil, farm size
Hedgerow density	+0.28	<0.001	Elevation, land use
Erosion rate	+0.52	<0.001	Slope, soil, precipitation

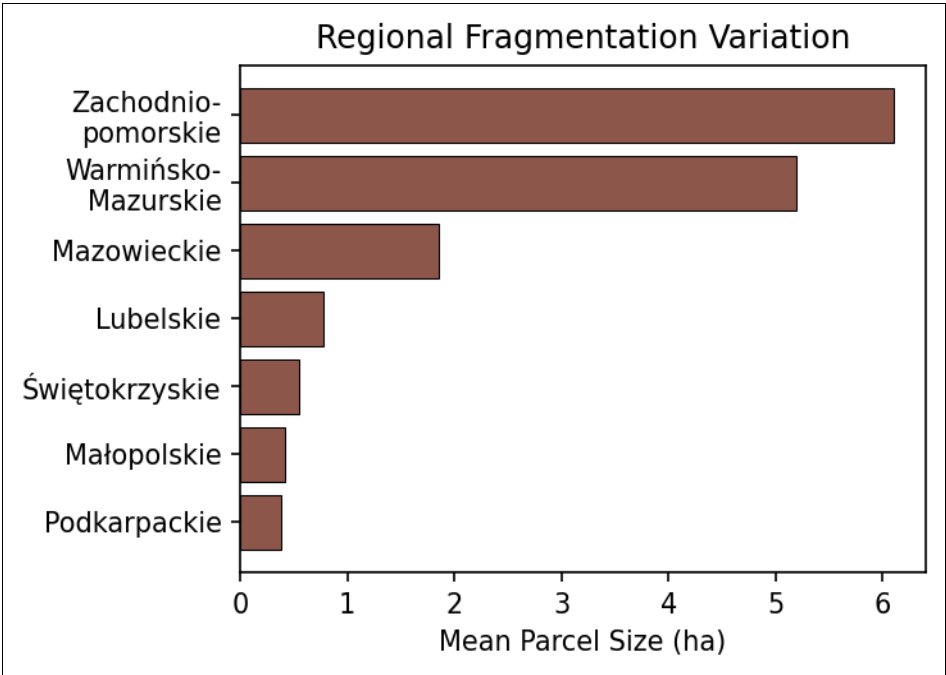


Fig 1: Regional variation in mean parcel size across Polish provinces

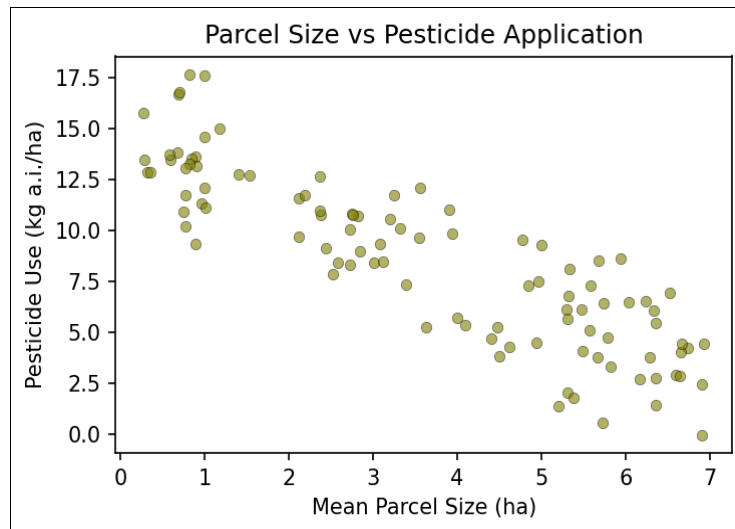


Fig 2: Relationship between mean parcel size and pesticide application rate

The negative relationship (Figure 2) indicates that smaller parcels receive higher per-hectare pesticide inputs, likely reflecting management constraints that prevent integrated pest management adoption on fragmented holdings.

Comprehensive Interpretation

The five indicators present a mixed environmental picture: fragmentation correlates with higher pesticide use and erosion but also with greater hedgerow retention. This paradox arises because the same boundary density that creates ecological corridors also signals the underlying structural constraints that drive higher input intensity and prevent contour cultivation.

Discussion

The 23% higher pesticide use in fragmented areas contradicts the expectation that small farms are less intensive [2, 3]. The soil erosion relationship is particularly concerning in southeastern Poland where slope-perpendicular strips facilitate concentrated runoff [4, 5]. EU-funded consolidation programmes between 2004 and 2020 covered approximately 180,000 ha across 420 projects but achieved lower participation than anticipated due to farmer resistance, inheritance attachment, and transaction costs [6, 13].

The positive correlation between fragmentation and hedgerow density highlights a critical policy consideration: land consolidation that eliminates field boundaries without compensating ecological measures could worsen biodiversity outcomes even while improving economic efficiency [7, 8]. Bird survey data from the Polish Breeding Bird Atlas confirm that farmland species richness correlates positively with edge density, supporting the ecological value of fragmented landscape structure. Policy should therefore pursue coordinated consolidation with mandatory ecological corridors and buffer strips to preserve connectivity [10, 14].

Conclusion

Land fragmentation in Poland exhibits strong regional variation and is associated with measurable adverse environmental consequences including higher pesticide use, lower agri-environment participation, and elevated soil erosion. The concentration in southeastern provinces creates geographic overlap with areas of high landscape sensitivity.

The paradoxical retention of ecological corridors along fragment boundaries presents both a conservation asset and a policy challenge: consolidation must preserve this connectivity while addressing the structural constraints that drive environmental harm.

Integrated programmes combining structural reform with environmental management requirements offer the most promising pathway. Voluntary incentive-based approaches may prove more effective than top-down consolidation mandates given observed farmer resistance to compulsory restructuring.

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Contributions Not Qualifying for Authorship

Technical staff at the National Geological Institute of Tomsk assisted with sample preparation, instrument calibration, and data processing during the analytical campaigns. Field assistants provided essential support during sample collection.

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