Farming System 4 (2026) 100173

Contents lists available at ScienceDirect

Farming System

journal homepage: www.journals.elsevier.com/farming-system

# Geospatial and geostatistical analysis of land fragmentation and parcel shape indicators for sustainable farm structure in land consolidation

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ARTICLE INFO

*Keywords:*
Land consolidation
Land fragmentation
Geospatial analysis
Geostatistical analysis
Türkiye

ABSTRACT

Land consolidation (LC) is one of the key implementations to improve farm structure by enhancing parcel shape and reducing land fragmentation. Many researchers have developed indicators to measure parcel shape deformation and land fragmentation levels; however, these indicators often lack consistency for assessing land consolidation projects. In this study, we demonstrate that our newly developed New Parcel Shape Index (NSI) and New Land Fragmentation Index (NLFI) are more effective for assessing land consolidation projects. Geospatial and geostatistical analyses were applied to calculate the new indicators using ArcGIS-ArcMAP, with Excel utilised for calculating and comparing other indicators. To test these analyses, the cadastral data and reports of the Türkiye Malatya Province Arguvan District Tatkınlık Village Land Consolidation project were used as material.

As a result, it was observed that parcels with NSI values approaching 1 were close to a rectangular shape, while those deviating from an NSI value of 1 exhibited deformation. Other shape indices were found to perform poorly in parcel shape analysis. In measuring the level of land fragmentation, farms with small NLFI values were observed to be less fragmented than those with large NLFI values. Other land fragmentation indexes showed poor performance compared to NLFI. As a result, NSI is recommended for shape analysis, and NLFI is recommended for assessing land fragmentation. These indices can be utilised in before and after LC evaluations or in determining priority LC areas.

## 1. Introduction

Land consolidation is a key strategy for improving the efficiency and sustainability of agricultural production systems. It aims to reorganize fragmented agricultural lands into more functional and productive units, thereby facilitating the provision of essential rural infrastructure and services, including roads, irrigation, and drainage networks (Değirmenci et al., 2017). In Türkiye, land consolidation projects have been successfully implemented over an area of approximately 7.2 million hectares; meanwhile, studies on additional areas are ongoing, and further expansions are planned (Arslan et al., 2025). Given the increasing pressure on land resources and the growing demand for sustainable agricultural development, land consolidation has become a critical component of rural development policies.

Among the primary objectives of land consolidation is the reduction of land fragmentation and the improvement of parcel shapes, both of which have significant implications for agricultural productivity, mechanization efficiency, irrigation planning, and transportation systems (Hristov, 2009; Kirmikil and Arici, 2013). Consequently, the evaluation of parcel shapes and fragmentation levels plays an essential role in assessing the overall effectiveness and performance of land consolidation projects.

Over the years, numerous studies have proposed various shape and fragmentation indices to measure these parameters. Commonly applied shape indices include the shape index, fractal dimension index, area shape factor, and area-perimeter ratios, which have been utilised in several land consolidation studies (Demetriou et al., 2013; Aslan, 2018). Similarly, different fragmentation indices have been developed to assess land subdivision and parcel distribution (Looga et al., 2018). However, despite their widespread application, many of these indices suffer from notable limitations. Several shape indices fail to fully capture parcel geometry due to their dependence on simplified parameters such as perimeter and area alone (Demetriou et al., 2013). Likewise, many fragmentation indices are either computationally complex, difficult to

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https://doi.org/10.1016/j.farsys.2025.100173
Received 13 July 2025; Received in revised form 4 September 2025; Accepted 5 September 2025
Available online 9 September 2025

interpret, or ineffective in producing consistent measurements across different land consolidation contexts. These shortcomings underline the necessity of developing indices that can accurately represent parcel shape and fragmentation while remaining practical for large-scale implementation.

The present study addresses this gap by testing a newly developed shape index and a new fragmentation index designed to overcome the deficiencies of existing methods. Additionally, the study evaluates land consolidation using indicators to provide a comprehensive assessment of project performance. The analyses were conducted using geographical, spatial, and statistical datasets derived from GIS from the Tatkınlık Village land consolidation project, located in the Arguvan District of Malatya Province.

## 2. Materials and methods

### 2.1. Study area and data collection

Malatya province Arguvan District Tatkınlık Village land consolidation project was chosen as the material. Data and reports were obtained from the 9th Regional Directorate of DSI. Data in NetCAD format was converted to DWG and imported to the ArcMAP program for analysis.

Tatkınlık Village land consolidation project started in 2018 and was completed at the end of the same year. Tatkınlık Village data before and after LC are given in Table 1.

Both plant and animal production are carried out in Tatkınlık Village. The creek banks that dividing the village in two are used for gardens, while the remaining areas are utilised for barley and wheat cultivation. The agricultural lands in the project area are generally rough. The vast majority of enterprises have 0–0.5 ha areas. 78.92 % of the project area is private lands, 19.47 % is treasury lands (mountain, hill, rocky, streams), 10 % is pasture lands and 9 % is village legal entity lands. Before the land consolidation work in the project area, 82.62 % of the parcels were used by the enterprises themselves, and the remaining 17.38 % were leased out (Anonymous, 2020).

### 2.2. Statistical evaluation

The main population of this study consists of businesses located in the Tatkınlık Village. According to the data obtained from Land Consolidation Project report, the total number of enterprises is 270. During the analysis of land fragmentation and fractional ownership, a sample was deemed necessary, as applying calculations to all enterprises would be time-consuming. The "proportional sampling method" is commonly utilised by researchers for sample selection. Proportional sampling method is commonly utilised by researchers in the process of sample selection. The formula for the proportional sampling method is provided by Oğuz and Bayramoğlu (2004) and Newbold (2000). As a result, the sample size was determined to be 59.12 with a 90 % confidence interval and a margin of error of 9.5 %. Thus, 60 enterprises were included in the study.

The sample size has been proportionally distributed based on the sizes of businesses among the 270 businesses located in Tatkınlık Village. The enterprises included in the sample were selected from the AT-8 report using the quota sampling method, stratified by their sizes (Kılıç, 2013). The distribution and percentage values of the selected businesses based on their sizes are presented in Table 2.

**Table 1**
Tatkınlık Village data before and after land consolidation.

| | Before LC | After LC |
|---|---|---|
| Number of enterprises | 270 | 270 |
| Agricultural area (ha) | 498.1 | 478 |
| Number of parcels | 661 | 542 |
| Average parcel size (ha) | 0.754 | 0.882 |
| Average number of parcels belong enterprises | 2.45 | 2.00 |
| Average enterprise size (ha) | 1.845 | 1.771 |

*da: decare is equal to 1000 square meters.

#### 2.2.1. Method

*2.2.1.1. General assessment.* To describe the performance of the project, we conducted a general evaluation of the Tatkınlık Village land consolidation project using selected indicators. Data such as the before and after consolidation agricultural fields, the number and average size, the number of enterprises, and the size of the enterprises were utilised to calculate these indicators, and formulas are presented in Table 3.

*2.2.1.2. Calculation of parcel shape indices.* The new shape index was compared to shape indices commonly used by researchers. All shape indices have been calculated for the parcels before and after the land consolidation in Tatkınlık Village. The correlation between the new shape index and other shape indices has been examined in detail using a statistical package program, while graphical representations were analysed using GIS. The calculation methods for these indices are provided in Table 4.

*2.2.1.3. Calculation of land fragmentation indices.* The newly introduced fragmentation index has been compared with other widely employed indices by researchers. These comparisons have been conducted through statistical analyses and generated maps. Land fragmentation indices were applied to a total of 60 enterprises, selected according to the sampling methodology.

The calculation methods of the utilised land fragmentation indices and the necessary data are provided in Table 5.

## 3. Results

### 3.1. General assessment before and after land consolidation

The number of businesses before and after the land consolidation project in Tatkınlık Village remains at 270. The agricultural area, which measured 498.1 ha before land consolidation, decreased to 478 ha. Consequently, the participation share for common facilities was calculated as 4.04 % (Table 6).

In the research area, the participation share for joint facilities has been utilised for new road and canal routes. The road length, which was 23.4 km before land consolidation, increased to 42.13 km after the project. An irrigation project was planned alongside the land consolidation project to determine the routes. However, this irrigation project was not completed after the land consolidation project. The average farm size in Tatkınlık Village was 1.845 ha before land consolidation, which decreased to 1.771 ha after the project. Before the land consolidation project in Tatkınlık Village, the average parcel size was 0.754 ha, while after the project, it increased to 0.882 ha, resulting in an approximate 17 % change in average parcel size. In the study area, the average number of parcels per farm decreased from 2.45 to 2 after the land consolidation project.

**Table 2**
Distribution of sample size according to business sizes.

| Enterprise size (ha) | Number of enterprises | Number of selected enterprises | Sample size (%) |
|---|---|---|---|
| 0.00–0.50 | 103 | 24 | 38.15 |
| 0.501–1.00 | 66 | 15 | 24.44 |
| 1.001–2.00 | 46 | 10 | 17.04 |
| 2.001–5.00 | 47 | 10 | 17.41 |
| 5.001–10.00 | 6 | 1 | 2.22 |
| >10.00 | 2 | 0 | 0.74 |
| Total | 270 | 60 | 100 |

**Table 3**
Indicators used in the general evaluation before and after land consolidation.

| Indicators | Formula | Data requirement |
|---|---|---|
| Share of participation in common facilities (SoPiCF, %) | $SoPiCF = \frac{NAA - FAF}{FAF} \times 100$ | FAF: Former Agricultural Field, da<br>NAA: New Agricultural Area |
| Consolidation ratio (CR, %) (Arıcı, 1994; Akkaya et al., 2007) | $CR = \frac{NoNP - NoOP}{NoOP} \times 100$ | NoOP: Number of Old Parcels<br>NoNP: Number of New Parcels |
| Average parcel size change (APSC, %) | $APSC = \frac{NAPS - FAPS}{FAPS} \times 100$ | FAPS: Former Average Parcel Size<br>NAPS: New Average Parcel Size |
| Change in the average number of operating parcels (CiANoOP, %) | $CiANoOP = \frac{NoNEP - NoOEP}{NoOEP} \times 100$ | NoOEP: Number of Old Enterprises Parcels<br>NoNEP: Number of New Enterprises Parcels |

### 3.2. Evaluation of parcel shapes

The Table 7 shows descriptive statistics of the shapes indices in the study area. The shape indices analysis done by ArcMAP and the classification map are presented in Figs. 1 and 2. After land consolidation, the average NSI (New Shape Index) values decreased by 0.14, approaching 1. Additionally, the difference between the average NSI values before and after land consolidation was found to be statistically significant ($P < 0.05$). Consequently, this indicates an improvement in parcel shapes. The most suitable value for the new shape index is 1. The decrease in the average NSI value after land consolidation, approaching 1, and the *t*-test p-value being less than 0.05 indicate an improvement in parcel shapes.

A correlation analysis was conducted to explain the statistical relationship between the new shape index (NSI) and other shape indices. In the correlation analysis, all parcels before and after land consolidation were used. The correlation coefficients between shape indices are provided in Table 8.

While no significant correlation was found between the New Shape Index and APR2 ($P > 0.05$; r: 0.026), statistically significant correlations were observed among the other shape indices. However, the correlation levels between the shape indices vary. The correlation between the new shape index (NSI) and FD is weak ($P < 0.05$; r: 0.252); it is strong between SI ($P < 0.05$; r: 0.683), FORM ($P < 0.05$; r: 0.639), AFF ($P < 0.05$; r: 0.639), APR1 ($P < 0.05$; r: 0.683), and APR3 ($P < 0.05$; r: 0.683). Consequently, it can be understood that NSI can be used in place of shape indices with strong correlations (Table 8).

The other shape indices investigated in this study are calculated

**Table 6**
Indices used for general assessment.

| Indices | value (%) |
|---|---|
| Share of participation in common facilities | 4.04 |
| Consolidation ratio | 18 |
| Average parcel size change | 16.98 |
| Change in the average number of parcels | −18.36 |

**Table 4**
Other shape indices are commonly used by researchers and their calculation methods.

| Shape | Abr[a] | Formula | Range | Optimum value | Source |
|---|---|---|---|---|---|
| New shape index | NSI | $NSI = \frac{A_{min}}{A_i}$ | [1, +∞] | 1 | Arslan et al., 2018; Arslan et al., 2018; Arslan et al., 2020; Arslan and Değirmenci, 2016 |
| Fractal dimension | FD | $FD = \frac{2\ln(P_i)}{\ln(A_i)}$ | [1,2] | 1 | Krummel et al., 1987; Demetriou et al., 2013 |
| Shape index | SI | $SI = \frac{P_i}{2\sqrt{\pi A_i}}$ | [π/2,+∞) | 1 | Mcgarical and Marks, 1995; Akkaya Aslan et al., 2007 |
| FORM factor | FORM | $FORM = \frac{4\pi A_i}{P^2}$ | (0,1) | 1 | Russ, 2002; Lewis et al., 1997 |
| Areal Form Factor | AFF | $AFF = \frac{A_i}{P_i^2}$ | (0,+∞) | 1 | Witney, 1988; Gonzalez et al., 2004; 2007; Demetriou et al., 2013 |
| Area-Perimeter Ratio-1 | APR1 | $APR1 = \frac{P_i}{4\sqrt{A_i}}$ | (√π/2,+∞) | 1 | Arslan et al. (2018) |
| Area-Perimeter Ratio-2 | APR2 | $APR2 = \frac{A_i}{P_i}$ | (0,+∞) | 1 | Jiao et al. (2012) |
| Area-Perimeter Ratio-3 | APR3 | $APR3 = \frac{P_i}{\sqrt{A_i}}$ | (0,+∞) | 4 | Libecap and Lueck, 2009; Demetriou et al., 2013 |

[a] NSI: New shape indeks, FD: Fractal Dimension, SI: Shape Index, FORM: FORM factor, AFF: Areal Form Factor, APR: Area-Perimeter Ratio, NoP: Number of Parcels, $A_{min}$: Minimum bounding geometry area of $A_i$), $A_i$: Area of parcel *i*, $P_i$: *i* perimeter of parcel *i*.

**Table 5**
Fragmentation indices and calculation methods.

| Index | Formula | Source | Optimum value | Data requirement |
|---|---|---|---|---|
| New land fragmentation index | $NLFI = \frac{\sum_{i=1}^{n} l_i}{n}$ | Arslan et al., 2018; Arslan et al., 2020; Arslan et al., 2020 | 0 | **n:** number of parcels, |
| Simmons | $Simmons = \frac{\sum_{i=1}^{n} A_i^2}{A^2}$ | Simmons (1964) | 1 | **li:** i. parcel' distance to center of minimum bounding geometry |
| Januszewski | $Januszewski = \frac{\sqrt{A}}{\sum_{i=1}^{n}\sqrt{A_i}}$ | Januszewski (1968) | 1 | **$A_i$:** *i.* parcel area ($m^2$) |
| Number of parcels | Total number of parcels belong to the enterprise | – | 1 | **A:** total area of *i.* enterprises ($m^2$) |
| Schmook | $Schmook = \frac{A_{minbonarea}}{A}$ | Schmook (1976) | 0 | **$A_{minbonarea}$:** area of the smallest polygon surrounding all parcels of the enterprise |
| Ibgozurike | $Igbozurike = \frac{\frac{\sum_{i=1}^{n} A_i}{n} \times Dt}{100}$ | Igbozurike (1974) | 1 | **Dt:** It is accepted as the perimeter of the smallest polygon covering all the parcels of an enterprise. |

**Table 7**
Basic statistics of shape indices.

| | | NSI | FD | SI | FORM | AFF | APR1 | APR2 | APR3 |
|---|---|---|---|---|---|---|---|---|---|
| Before LC | Min | **1.02** | 1.26 | 1.05 | 0.10 | 0.01 | 0.93 | 1.68 | 3.71 |
| | Max | **4.66** | 1.73 | 3.12 | 0.91 | 0.07 | 2.76 | 70.61 | 11.3 |
| | Mean (std.s.) | **1.56 (0.42)** | 1.38 (0.07) | 1.38 (0.27) | 0.57 (0.16) | 0.045 (0.01) | 1.23 (0.24) | 15.57 (8.63) | 4.90 (0.96) |
| After LC | Min | **1.01** | 1.25 | 1.06 | 0.07 | 0.01 | 0.94 | 1.85 | 3.77 |
| | Max | **4.61** | 1.81 | 3.89 | 0.88 | 0.07 | 3.45 | 67.67 | 13.79 |
| | Mean (std.s.) | **1.41 (0.39)** | 1.37 (0.07) | 1.36 (0.26) | 0.58 (0.15) | 0.047 (0.01) | 1.20 (0.23) | 17.57 (9.71) | 4.80 (0.92) |
| p-value[a] | | **0.000** | 0.000 | 0.039 | 0.020 | 0.020 | 0.039 | 0.000 | 0.039 |

[a] When the p-value is less than 0.05, it indicates a significant difference between the mean values. On the other hand, when the p-value is greater than 0.05, it signifies that there is no significant difference among the means.

based on parcel area and perimeter. However, NSI is calculated using geographic information systems by utilising the parcel area and the area of the smallest surrounding rectangle. The strong correlation of the new shape index with commonly used shape indices by researchers is a positive indicator.

To determine the similarities and differences between the new shape index and other shape indices, classification maps were employed. The classification maps were analysed using before and after land consolidation cadastral data in ArcMAP 10.7.1 software. The classification map was created for each shape index. The classification maps were categorized into four classes, each representing 25 % of the total parcel count. The first class is shown in green. Parcels in green represent those with the best shape according to the respective shape index. The second class, shown in light green, and the third class, shown in orange, depict parcels that gradually deteriorate in shape. The fourth class, displayed in red, represents the parcels with the worst shape according to the respective shape index.

Shapes shown in green have NSI values ranging from 1.23 to 1.28. Parcels categorized in light green (NSI: 1.28–1.47) exhibited more deterioration compared to the green parcels. Parcels categorized in orange have NSI values ranging from 1.46 to 1.70. The class with the most distorted shape is represented by red, with NSI values ranging from 1.70 to 4.66.

Parcels classified in green have FD values ranging from 1.26 to 1.33. Parcels categorized in light green have FD values between 1.33 and 1.37. Parcels in orange fall within the FD range of 1.37–1.41, while those in red have FD values between 1.41 and 1.73. Upon examining this classification map, it is observed that both irregular and rectangular parcels are placed in the same classes.

Parcels in green have SI values ranging from 1.04 to 1.20, while those in light green fall within the range of 1.20–1.30. Parcels categorized in orange have SI values between 1.30 and 1.47, and those in red have SI values ranging from 1.47 to 3.11. When examining the SI values based on colours, it is evident that after land consolidation, parcels with a rectangular shape are categorized as light green, while some parcels with distorted shapes are placed in the best class.

Parcels classified in green have FORM values ranging from 0.68 to 0.91, while those in light green fall within the range of 0.58–0.68. Parcels categorized in orange have FORM values between 0.45 and 0.58, and those in red have FORM values ranging from 0.10 to 0.45.

Parcels classified in green have AFF values ranging from 0.054 to 0.072. Parcels categorized in light green have AFF values between 0.046 and 0.054. Parcels in orange fall within the AFF range of 0.036–0.046, while those in red have AFF values ranging from 0.008 to 0.036.

Parcels in green have APR1 values ranging from 0.92 to 1.06. Parcels categorized in light green fall within the range of 1.06–1.15. Parcels in orange have APR1 values between 1.15 and 1.30, and those in red have APR1 values ranging from 1.30 to 2.76. This classification map displays similar characteristics in terms of low performance in measuring parcel shapes, similar to the FD, SI, FORM, and AFF classification maps. When examining parcels resembling rectangles after land consolidation, they are found in the worst shape classification within the APR1 map.

Parcels in green have APR2 values ranging from 1.67 to 9.32, while those in light green fall within the range of 9.32–13.45. Parcels categorized in orange have APR2 values between 13.45 and 20.89, and those in red have APR2 values ranging from 20.89 to 70.61. Upon examining this classification map, it becomes apparent that APR2 is unsuccessful in measuring parcel shapes. Large-shaped parcels are clustered in the unfavourable classification colour, while smaller-shaped parcels are placed in the green class.

Parcels in green have APR3 values ranging from 3.71 to 4.26, while those in light green fall within the range of 4.26–4.63. Parcels categorized in orange have APR3 values between 4.63 and 5.22, and those in red have APR3 values ranging from 5.22 to 11.04. This classification map resembles APR1 and APR2 in defining rectangular shapes. It is observed that APR3 is inconsistent in measuring rectangular-shaped parcels.

In order to comprehensively examine the performance of the new Shape Index (NSI), parcels with varying shapes were grouped based on their values. For this purpose, before and after land consolidation cadastre data from Tatkın Village were utilised. These data were analysed using the ArcMAP program to create grouping maps, which were generated from parcels with different NSI values. The resulting classification map is presented in Fig. 3.

The first group consists of parcels with NSI values ranging from 1 to 1.10. The optimal value for the new shape index is 1. Parcels with the best shape are found within this group, and it is observed that these parcels closely resemble rectangular shapes. In the second group, parcels with NSI values between 1.10 and 1.20 are included. Upon comparison with the parcels in the first group, it is apparent that parcels in this group exhibit slightly more distorted shapes. The third group encompasses parcels with NSI values ranging from 1.20 to 1.30, and the shapes of parcels within this group are observed to be even more distorted than those in the second group. Upon examining the other shape groups, it is evident that as the NSI value increases, the shapes of parcels gradually deteriorate.

Upon examining all the groups.

- Parcels with NSI values between 1.00 and 1.10 exhibit a "rectangular" shape.
- Parcels with NSI values between 1.10 and 1.20 display a "partially rectangular" shape.
- Parcels with NSI values between 1.20 and 1.30 manifest a "partially distorted" shape.
- Parcels with NSI values between 1.30 and 1.50 present a "distorted" shape.
- Parcels with NSI values between 1.50 and 2.00 showcase a "poor" shape.
- Parcels with NSI values greater than 2 exhibit a "very poor" shape.

### 3.3. Evaluation of land fragmentation

To compare the new fragmentation index with other fragmentation indices, enterprises with increasing NLFI values were selected. The maps

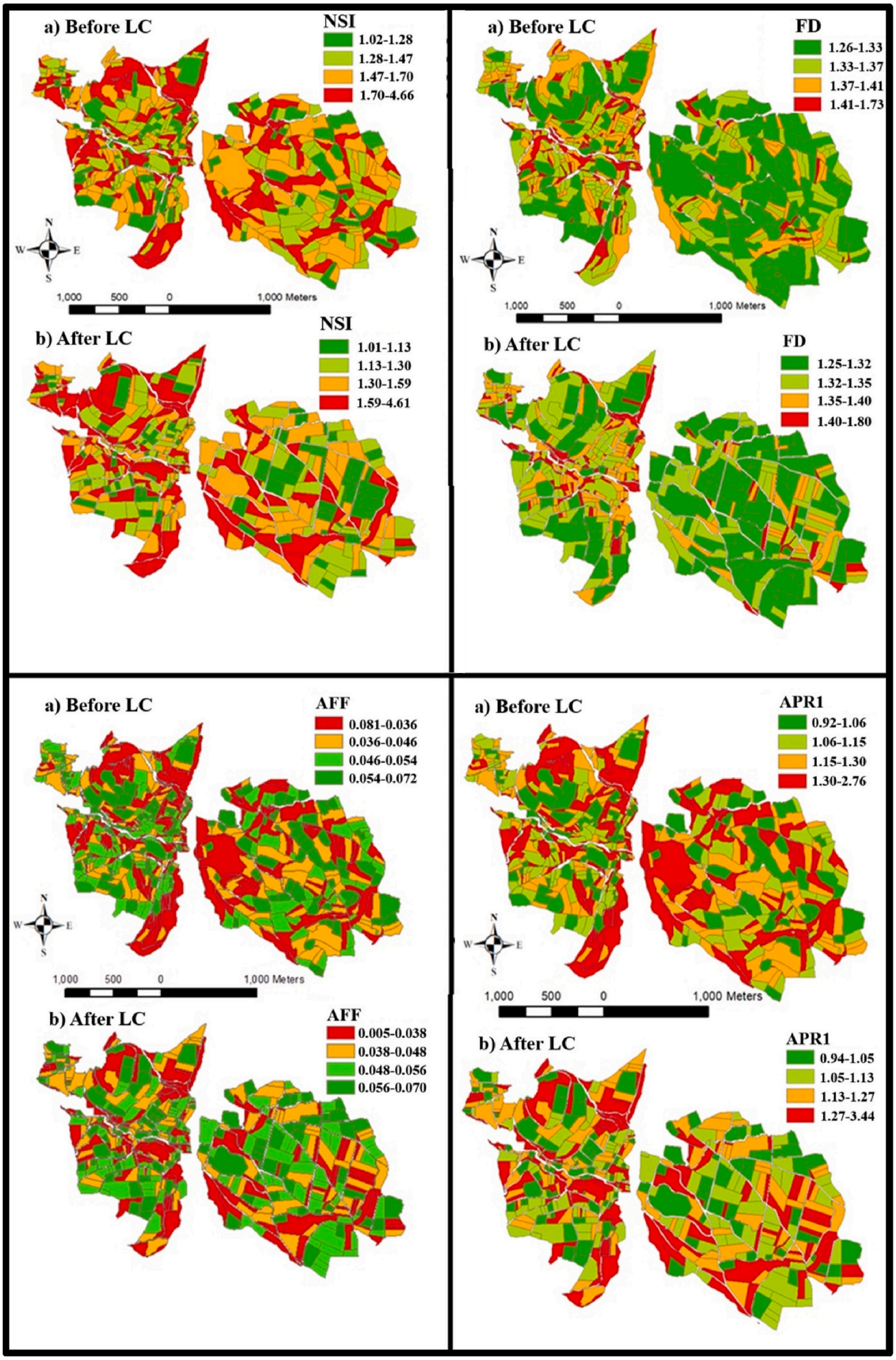


**Fig. 1.** Shape indices classification map (NSI, FD, AFF, APR1).

of these selected enterprises were generated using ArcMAP 10.7.1 software. The created maps are presented in Fig. 4, and the fragmentation index values of the enterprises are provided in Tables 9 and 10.

Upon examining Enterprise 14, it is observed that enterprises with a single parcel have fragmentation values that are equal to or close to the optimal value. In the case of Enterprise 12, since its parcels are contiguous, it can be inferred that this enterprise exhibits no fragmentation. However, when evaluated based on parcel count and the Simmons and Januszevski indices, this enterprise is considered fragmented.

Enterprise 2 consists of three contiguous parcels, and an additional

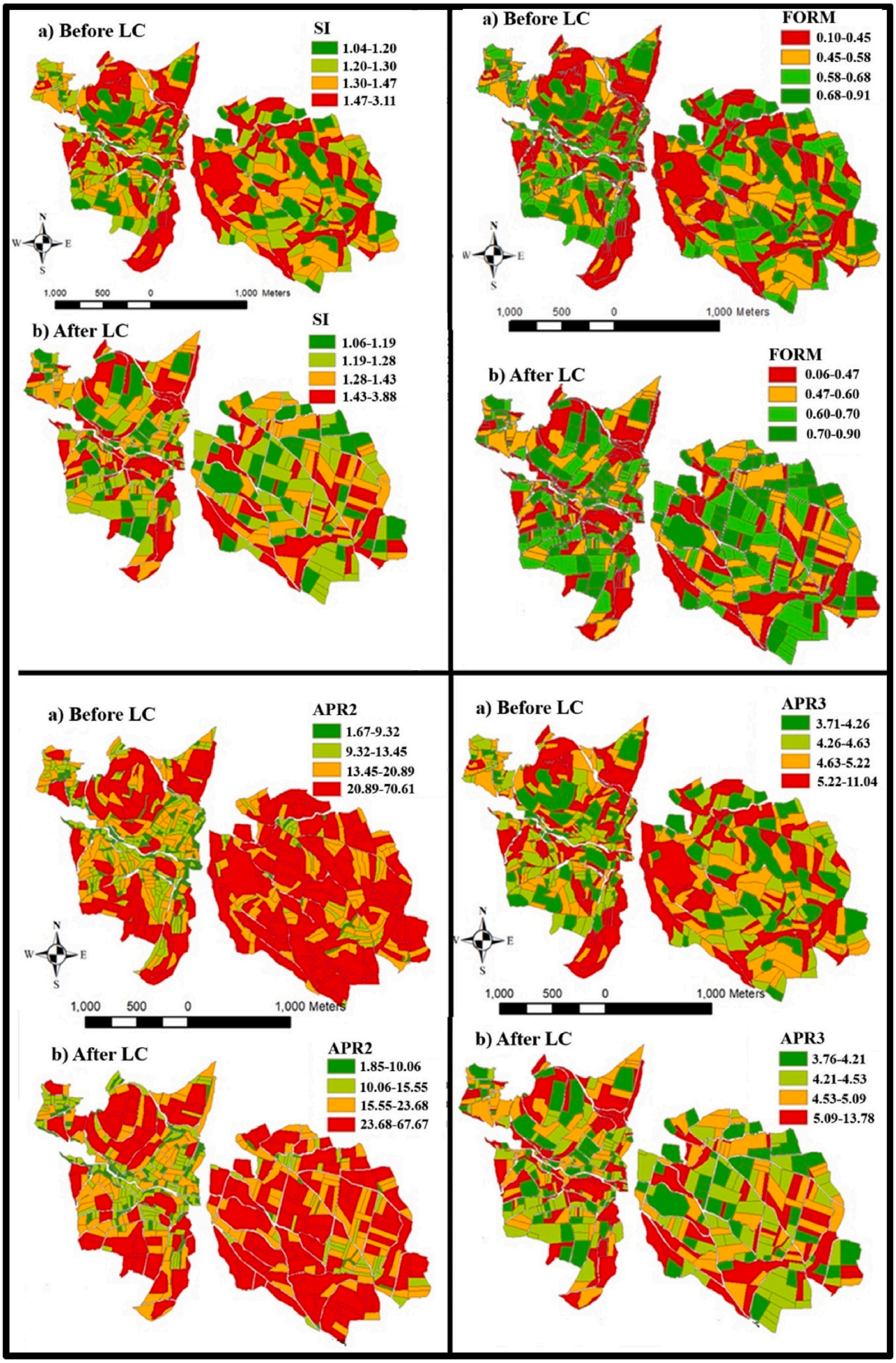


**Fig. 2.** Shape indices classification map (SI, FORM, APR2, APR3).

parcel located approximately 100 m away from them. The fragmentation level of this enterprise is low according to the NLFI, Schmook, and Ibgozurike indices.

Enterprise 50 comprises a total of four parcels situated at different locations. Two of these parcels are merged. The farthest distance between parcels is around 1 km. Despite having a large number of parcels, Enterprise 38 maintains a relatively close distance of about 500 m between its parcels. Consequently, the owner of Enterprise 38 would not

**Table 8**
Correlation among shape indices.

| | FD | SI | FORM | AFF | APR1 | APR2 | APR3 | NSI |
|---|---|---|---|---|---|---|---|---|
| **FD** | 1 | 0.492[a] | −0.476[a] | −0.476[a] | 0.492[a] | −0.803[a] | 0.492[a] | 0.252[a] |
| **SI** | | 1 | −0.918[a] | −0.918[a] | 1.000[a] | −0.157[a] | 1.000[a] | 0.683[a] |
| **FORM** | | | 1 | 1.000[a] | −0.918[a] | 0.163[a] | −0.918[a] | −0.639[a] |
| **AFF** | | | | 1 | −0.918[a] | 0.163[a] | −0.918[a] | −0.639[a] |
| **APR1** | | | | | 1 | −0.157[a] | 1.000[a] | 0.683[a] |
| **APR2** | | | | | | 1 | −0.157[a] | −0.026 |
| **APR3** | | | | | | | 1 | 0.683[a] |
| **NSI** | | | | | | | | 1 |

[a] A correlation is considered statistically significant at the 0.01 level.

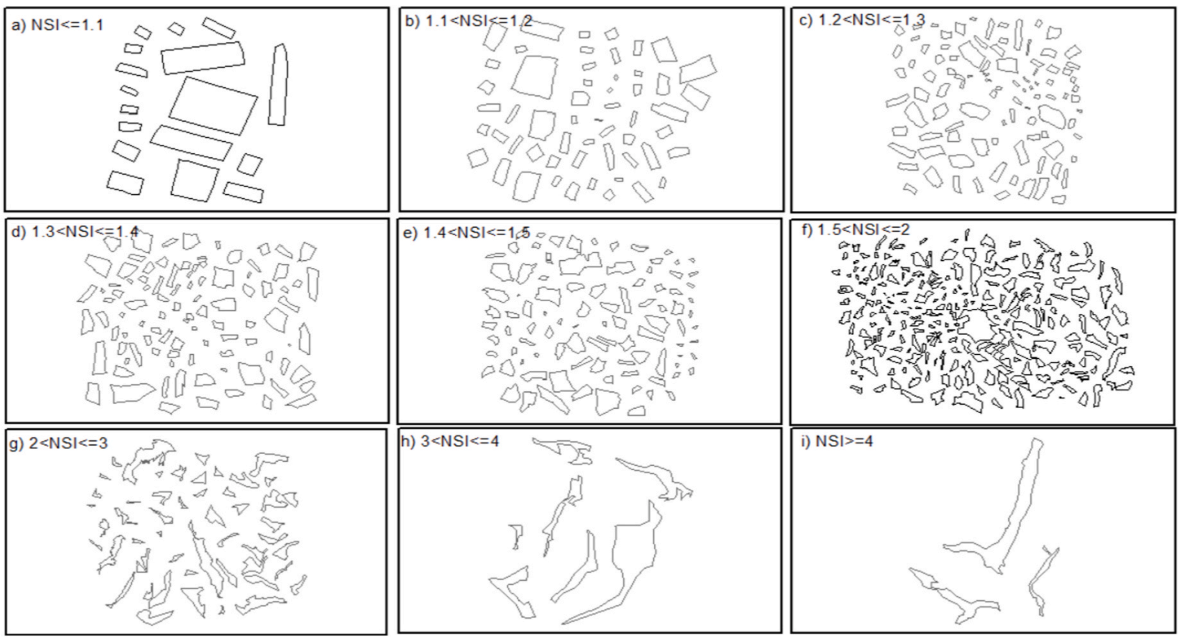


**Fig. 3.** New parcel shapes NSI classification map.

incur significant travel time accessing the parcels. In contrast to Enterprise 38, Enterprise 50's five parcels are spread across three distinct areas. It is evident that the distance between parcels is greater and more dispersed compared to Enterprise 38. Enterprise 8 has a maximum distance of approximately 2 km between its farthest parcels. Larger parcels in Enterprise 8 are positioned closer to each other. Therefore, the Ibgozurike index value of Enterprise 8 is smaller compared to Enterprise 30, attributable to the larger size of its parcels.

Enterprise 25 is composed of four separate parcels, with the greatest distance between these parcels being approximately 1.8 km. While Enterprise 17 has three times the number of parcels as Enterprise 25, its fragmentation level, as assessed by the NLFI, is lower. Despite the substantial number of parcels, their proximity to each other results in decreased fragmentation according to the NLFI.

For Enterprise 34, the NLFI value is high, indicating significant parcel fragmentation due to the considerable distance and dispersion between its parcels. However, the Ibgozurike index portrays a low fragmentation level for this enterprise. In this context, the Ibgozurike index displays reduced performance.

Enterprise 6 exhibits NLFI values similar to those of Enterprise 34. Upon examining the distribution of parcels in Enterprise 6, similarities with Enterprise 34 become evident.

The NLFI, Simmons, parcel count, Januszevski, Schmook, and Ibgozurike index values for Enterprise 41 are 1243.49, 0.08, 22, 0.24, 1296.36, and 164.83, respectively. Among the selected enterprises, Enterprise 41 exhibits the highest level of fragmentation. Upon examining the Ibgozurike index of this enterprise, it suggests a lower fragmentation level compared to Enterprise 50. However, upon closer examination of Enterprise 50, it becomes evident that it is significantly less fragmented than Enterprise 41.

The Simmons and Januszevski indices are the most used indices among researchers. Parcel count is frequently mentioned in reports depicting the before and after land consolidation situation in our country. Schmook and Ibgozurike indices have been less frequently utilised by researchers compared to other indices. The NLFI, however, has been proposed as an indicator of land fragmentation by Arslan and Değirmenci (2016). Upon examining the characteristics of all fragmentation indices, it becomes evident that they possess both strengths and weaknesses. Consequently, there is a need for improving the utilised fragmentation indices. Among the fragmentation indices, NLFI could be considered more successful. However, its weakness lies in not accounting for the size of the parcels within an enterprise.

To examine the statistical relationships between fragmentation indices, a correlation analysis was conducted. The correlation coefficients between fragmentation indices are presented in Table 11. Significant correlations were found among all fragmentation indices. The NLFI exhibits both negative and positive correlations with other fragmentation indices. An increase of one unit in NLFI is associated with a decrease of 0.621 units in the Simmons index, an increase of 0.575 units in parcel count, a decrease of 0.688 units in the Januszevski index, an increase of 0.287 units in the Schmook index, and an increase of 0.519 units in the Ibgozurike index. The NLFI's highest correlation is with the Januszevski index (Pearson correlation coefficient: 0.688). The fact that NLFI exhibits a high level of correlation with other

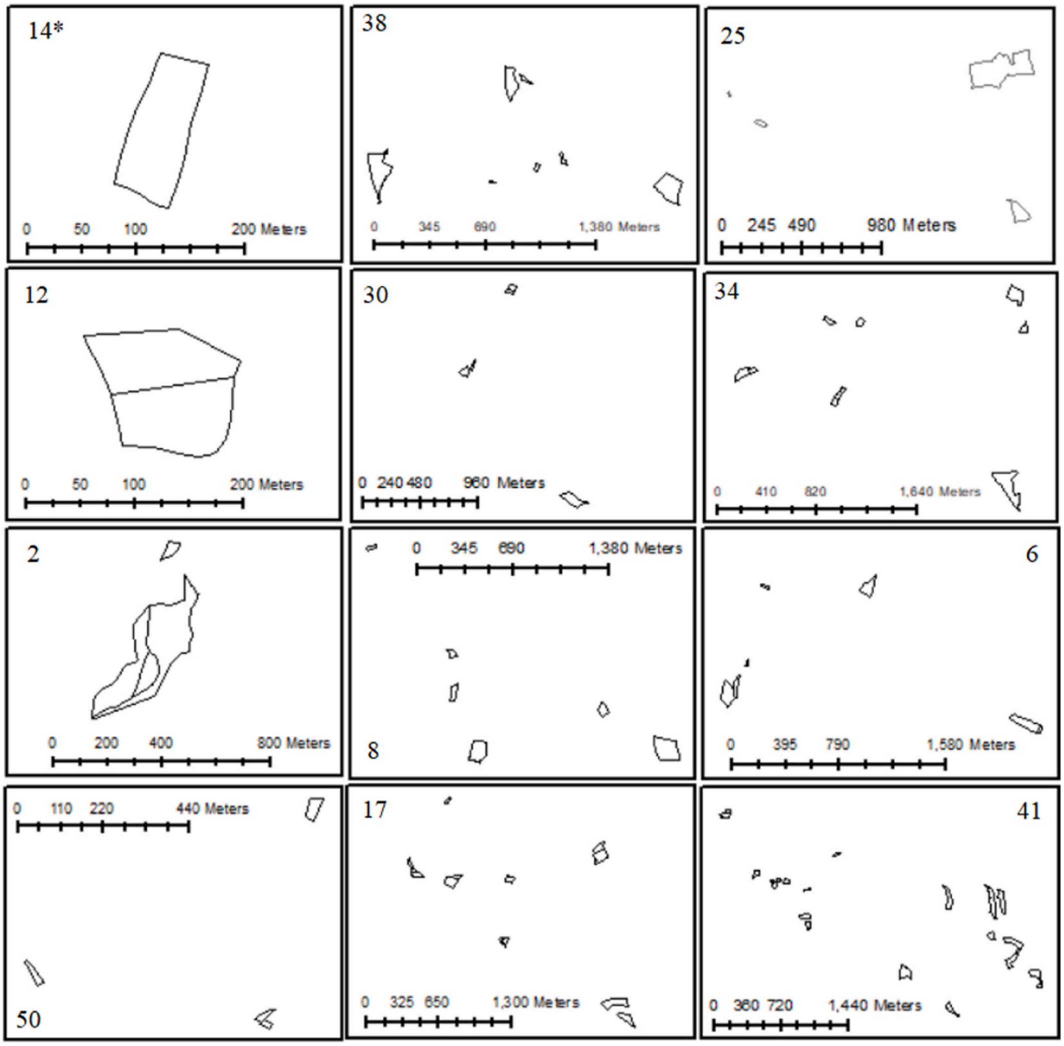


**Fig. 4.** Some selected enterprises evaluated prior to land consolidation.
*Enterprise no.

**Table 9**
Before and after land consolidation fragmentation index values.

| | | NLFI | Simmons | Januszevski | NoP | Schmook | Ibgozurike |
|---|---|---|---|---|---|---|---|
| Before LC | Min | **0** | 0.08 | 0.24 | 1 | 1.03 | 2.20 |
| | Max | **1359.13** | 1.00 | 1 | 22 | 2530.89 | 238.24 |
| | Mean | **769.31** | 0.31 | 0.46 | 7.62 | 546.52 | 93.81 |
| | Std. Dev. | **330.24** | 0.19 | 0.16 | 4.63 | 697.53 | 58.91 |
| After LC | Min | **0** | 0.09 | 0.26 | 1 | 1.10 | 3.31 |
| | Max | **1384.72** | 1 | 1 | 18 | 109.35 | 181.33 |
| | Mean | **768.64** | 0.34 | 0.50 | 6.07 | 32.54 | 78.53 |
| | Std. Dev. | **329.08** | 0.22 | 0.17 | 3.62 | 21.83 | 48.45 |

fragmentation indices ($p < 0.01$) suggests that NLFI could be used in lieu of other fragmentation indices.

The strengths and weaknesses of the new fragmentation index and other fragmentation indices are presented in Table 12. This table is based on the analysis and observations conducted.

## 4. Discussion

### 4.1. General assessment

Acar and Bengin (2018) calculated a participation share of 5.34 % in the land consolidation project in Başkent Village, Yozgat province. Dağdelen et al. (2017) reported a participation share of 5.31 % in their study conducted in Hamzabali Village, Yenipazar District, Aydın Province. According to land consolidation regulations, the maximum participation share for common facilities in Türkiye is 10 %. In comparison to these studies, the participation share for joint facilities in the Tatkınlık Village land consolidation project is lower.

Lök and Değirmenci (2019) examined land consolidation projects in Hasaköy and Bağlama Villages, Niğde Province. The average farm size change was 12.09 % in Hasaköy project and 6.10 % in Bağlama project. Arslan and Tunca (2013) evaluated land consolidation projects in Bafra

**Table 10**
Fragmentation index values of selected enterprises prior to land consolidation.

| Enterprise | NLFI | Simmons | NoP | Januszevskski | Schmook | Ibgozurike |
|---|---|---|---|---|---|---|
| 14 | 0 | 1 | 1 | 1 | 1.03 | 5.23 |
| 12 | 27.60 | 0.50 | 2 | 0.71 | 2.13 | 7.24 |
| 2 | 180.51 | 0.42 | 4 | 0.82 | 16.24 | 5.37 |
| 50 | 354.72 | 0.31 | 4 | 0.51 | 140.07 | 238.24 |
| 38 | 484.81 | 0.31 | 7 | 0.46 | 94.88 | 70.29 |
| 30 | 712.85 | 0.36 | 5 | 0.48 | 193.83 | 93.26 |
| 8 | 786.34 | 0.32 | 6 | 0.50 | 47.69 | 56.14 |
| 17 | 829.57 | 0.13 | 12 | 0.31 | 411.96 | 125.85 |
| 25 | 882.12 | 0.71 | 4 | 0.66 | 21.41 | 31.20 |
| 34 | 981.14 | 0.25 | 9 | 0.37 | 744.76 | 93.37 |
| 6 | 987.99 | 0.24 | 7 | 0.43 | 1765.47 | 93.83 |
| 41 | 1243.49 | 0.08 | 22 | 0.24 | 1296.36 | 164.83 |

**Table 11**
Correlation among fragmentation indices.

| | NLFI | Simmons | NoP | Januszevski | Schmook | Igbozurike |
|---|---|---|---|---|---|---|
| NLFI | 1 | −0.621[a] | 0.575[a] | −0.688[a] | 0.287[a] | 0.519[a] |
| Simmons | | 1 | −0.755[a] | 0.952[a] | −0.246[a] | −0.546[a] |
| NoP | | | 1 | −0.842[a] | 0.304[a] | 0.518[a] |
| Januszevski | | | | 1 | −0.291[a] | −0.594[a] |
| Schmook | | | | | 1 | 0.261[a] |
| Igbozurike | | | | | | 1 |

[a] A correlation is considered statistically significant at the 0.01 level.

Plain. The average farm size changes were 4.65 % in Dedeli project, 3.62 % in Örencik project, and 4.97 % in Yörgüç project. In comparison to Hasaköy and Bağlama Villages, the average farm size change in Tatkınlık Village land consolidation project is smaller. However, this indicator shows similarities with the land consolidation projects studied in the Bafra Plain. An increase in average farm size enhances the success of land consolidation projects. A decrease or no change in average farm size does not necessarily indicate the failure of land consolidation projects. This is because the resolution of fractional ownership issues can lead to a reduction in average farm size.

The average agricultural farm size in Türkiye is 5.9 ha (TÜİK, 2020). In Europe, the average farm size is 16.6 ha according to 2016 data (EUROSTAT, 2020), and in the United States, it was 44.3 ha as of 2018 (STATISTA, 2020). The average farm size in Tatkınlık Village is below the average farm sizes in Türkiye, Europe, and the United States. In the study area, the number of parcels, which was 661 before LC, decreased to 542 after LC, and the consolidation ratio was 18 %. Tunalı and Dağdelen (2018) examined 8 land consolidation projects carried out in the Tavas Plain of Denizli Province. These land consolidation projects calculated the average consolidation as 35.5 %. Kesici Bahar (2019) calculated the achievements and consolidation in Kesik Village of Kayseri Province Yenihisar District as 26.87 %.

Kuzu et al. (2018) conducted an examination of four land consolidation projects in the villages, namely Aşlama, Çarıklı, Çayırlı, and Karatlı, situated within the Misli Plain of Niğde Province. Within the ambit of these land consolidation projects, the respective consolidation rates were calculated as 54.18 %, 23.08 %, 35.72 %, and 37.70 %. This is in accordance with the findings of Başyiğit et al. (2016), who reported that among a comprehensive dataset of 507 land consolidation projects undertaken across 33 provinces in Türkiye, the average consolidation rate was determined to be 48 %. Comparatively, the land consolidation rate exhibited in the Tatkınlık Village project is noted to be comparatively lower than the rates indicated in the aforementioned studies. Evidently, the consolidation rate is directly correlated with the mitigation of land fragmentation and the diminution of parcelisation. Pertinently, as one traverses from the western to the eastern geographical extremities of Türkiye, the discernible upsurge in the number of familial constituents (Başkaya and Özkılıç, 2017) has engendered a concomitant predicament characterised by parcelisation. Consequently, both the numerical proliferation of parcels and the escalation of land fragmentation have been distinctly precipitated by the intricate predicaments associated with parcelization.

In comparison to other studies, the average parcel size change in the Tatkınlık Village land consolidation project is considerably lower. Sönmezyıldız and Çakmak (2013) reported a 30.79 % change in average parcel size in their study of the land consolidation area in Beyazaltın Village, Eskişehir Province. Peker and Dağdelen (2016) examined a land consolidation project in Yenipazar Plain, Aydın Province, and calculated a 70.15 % change in average parcel size. Consequently, the relatively low change in average parcel size in the Tatkınlık Village land consolidation project suggests that fragmentation has not decreased significantly after the land consolidation.

According to the 2016 Agricultural Farm Structure Survey in Türkiye, the average number of parcels per farm is 5.9 (TÜİK, 2020). The pre-consolidation parcel count of approximately 2.45 in Tatkınlık Village is below the Turkish average. According to the 2016 Agricultural Farm Structure Survey in Türkiye, 80.7 % of agricultural farms fall within the category of farms with sizes smaller than 100 da. The Tatkınlık Village land consolidation project calculated a change of 18.36 % in the average number of parcels per farm. Akkaya Aslan (2018) examined a land consolidation project in Pınarlar Village, Tavas District, Denizli Province, reporting a 62.4 % change in the average number of parcels per farm. Bayramoğlu and Oğuz (2004) studied a land consolidation project in Küçükköy Village, Çumra District, Konya Province, and reported a 50.68 % change in the average number of parcels per farm. The calculated change in the average number of parcels per farm in the Tatkınlık Village land consolidation project is smaller than that observed in other studies. This suggests a relatively low consolidation rate in the research area.

Land fragmentation is recognized as a global problem that significantly impacts the low profitability of farms and is often caused by inheritance, land subdivision, and socioeconomic factors. Despite significant investment and effort, land consolidation projects face numerous challenges in achieving their objectives (Janus and Markuszewska, 2017; Janus and Ertunç, 2020; Basista and Balawejder, 2020; Wojewodzic et al., 2021). For example, in Poland, despite significant funding, less land has been consolidated in recent years than in previous periods. A key challenge in assessing project effectiveness stems from

**Table 12**
Strengths and weaknesses of fragmentation indices.

| Fragmentation indices | Strengths | Weaknesses |
|---|---|---|
| **NLFI** | Geographic Information Systems (GIS) facilitate effortless calculations.<br>Assessing the proximity of parcels to one another.<br><br>Quantifying the dispersion.<br>Straightforward interpretation of results<br>Enhances clarity and comprehensibility of information | The system does not consider parcel sizes.<br><br>Assigns higher values to enterprises with small and sparsely distributed parcels. |
| **Simmons** | Effortless calculations. | Lacks the capability to detect merged parcels.<br>Incapable of determining distances between parcels.<br>Generates inconsistent indicator values. |
| **NoP** | The metric for assessing the success of land consolidation projects (mostly).<br>Straightforward interpretation of results<br>The application of this concept in land consolidation reports in Türkiye. | Inability to identify merged parcels.<br><br>Provide information at a superficial level. |
| **Januszevski** | Effortless calculations. | Inability to identify merged parcels.<br>Incapable of determining distances between parcels.<br>Generates inconsistent indicator values. |
| **Schmook** | Efficient calculations facilitated by GIS.<br><br>Obtaining an understanding of the combined area covered by all parcels based on the index value. | There is a potential for yielding inaccurate outcomes in measuring the fragmentation of enterprises possessing extensively scattered parcels.<br>The accurate measurement of parcels with a large number of parcels grouped together but dispersed small parcels may not be achieved using this index. |
| **Igbozurike** | Efficient calculations facilitated by GIS.<br><br>Capability to estimate the total distance covered in order to traverse all parcels belonging to a business. | A high fragmentation index value stemming from a multitude of parcels grouped together yet originating from a small number of individual parcels.<br>Challenges arising due to the consideration of average parcel size rather than individual parcel sizes, leading to disparities between some parcels being significantly larger while others are considerably smaller. |

the varying accuracy of the different methods used to measure fragmentation and parcel shape (Kontek et al., 2023). Simplified indices (e.g., Januszewski, Simmons), while easy to calculate, can often lead to inaccurate results because they often overlook critical spatial data such as actual parcel location, distance to farm buildings, or road networks. The organisation of cadastral data, particularly communal property information, can significantly impact fragmentation index calculations and interpretations, highlighting the need to modernise cadastral records. Furthermore, project objectives vary from country to country; in Türkiye, irrigation system improvement and parcel shape are the primary objectives, while in Poland, road access and parcel reduction are key objectives. These differing priorities, combined with social and legal factors, raise concerns that projects designed according to landowner preferences may not always result in economically optimal land arrangements and may even lead to further fragmentation in certain cases (e.g., divisions resulting from the dissolution of common property) (Leń et al., 2024). For these reasons, parcel shape and land fragmentation indicators have gained increased importance in land consolidation projects.

### 4.2. Evaluation of parcel shapes

In a study by Değirmenci and Arslan (2019), the NSI was evaluated for the Upper Karakoç Village land consolidation project. They indicated that parcels with NSI values between 1.04 and 1.20 had regular shapes. They also noted that as NSI values increased, parcel shapes became more distorted.

FD demonstrated poor performance, and this finding is consistent with the study by Demetriou et al. (2013), who showed that parcels with the same FD value can have different shapes, and parcels with different FD values can have the same shape. The created classification map supports these findings.

Comparing this classification map with the FD and SI classification maps, it displays similar characteristics.

These examples indicate that SI is unsuccessful in measuring parcel shapes. In the study by Akkaya Aslan et al. (2007), they noted that despite improvements in parcel shapes in the research area, SI deviates from the optimal value. The classification maps demonstrate better performance in measuring parcel shapes compared to the FD, SI, and FORM classification maps. Gonzalez et al. (2004) investigated the impact of parcel shapes on agricultural mechanization using this indicator in Spain. However, when examining parcel shapes resembling rectangles after land consolidation, it is observed that AFF's performance is lower compared to NSI.

The most comprehensive study regarding parcel shapes was conducted by Demetriou et al. (2013). In the study conducted in the Republic of Cyprus, they extensively examined the FD, SI, AFF, APR1, and APR3 shape indices. They demonstrated that parcels with the same shape index value could have different shapes, and parcels with different values could have the same shape, leading them to develop a novel parcel shape index formula. This shape index is calculated using six distinct factors: concave angles, convex angles, edge lengths, the number of points composing the parcel, area-perimeter ratio, and uniformity of all angles. The calculation of this shape index involves numerous factors, leading to complexity. Kwinta and Gniadek (2017a,b) carried out a study in Poland focusing on land fragmentation and parcel shapes. They introduced a novel method for measuring parcel shape, which involves measuring with a rectangle having an area equal to that of the parcel. However, the use of this shape index, which is calculated by aligning these two shapes at their center in a GIS environment, can lead to confusion.

Arslan et al. (2018) investigated the statistical relationships between FD, SI, AFF, FORM, APR1, APR2, and APR3 in their study conducted in Mersin Province. They found that, except for APR2, there was statistically significant correlation among all shape indices.

Bayram and Değirmenci (2018) examined FD, SI, and FORM shape indices in their study in Niğde Province. In the evaluation of pre- and post-consolidation parcel shapes, they stated that FD, SI, and FORM shape indices could be used, but added that these indices did not yield accurate results specifically for evaluating parcel shapes.

In their work in Şanlıurfa, Değirmenci et al. (2019a) evaluated an land consolidation project using FD, SI, FORM, AFF, and APR1 shape indices. They reported that these shape indices were unsuccessful in pre- and post-consolidation shape evaluations. Değirmenci and Arslan (2019) evaluated a land consolidation project in Yozgat Province using the NSI and concluded that it could be used for measuring parcel shapes. Their study revealed that parcels with rectangular shapes approached an NSI value of 1, while irregularly shaped parcels deviated from an NSI value of 1.

When analysing the calculated shape indices before and after land consolidation in Tatkın Village, it can be observed that FD, SI, FORM, AFF, APR1, APR2, and APR3 indices share a common point with previous studies, indicating that parcels with the same shape could have different values, and parcels with different shapes could share the same shape index value.

### *4.3. Evaluation of land fragmentation*

Van Hung et al. (2007) employed the Simpson index to measure land fragmentation. The Simpson index is calculated by subtracting the Simmons index from 1. Similarly, as with the Simmons index, we can make similar observations about the Simpson index. While the Simpson index is derived from the Simmons index, it may not be considered practical as it does not adequately incorporate spatial data such as parcel distances. Regardless of how far apart the parcels are or even if the center of operation is in another village or city, this index's result remains unaffected. Consequently, conducting studies using the Simpson index alongside the new fragmentation index and comparing the results could help evaluate any differences.

Factors such as parcel count, parcel sizes within an operation, parcel shapes, distribution of parcels, and other influencing variables contribute to land fragmentation (Platonova and Baumane, 2014; Demetriou et al., 2012; Aasmäe and Maasikamäe, 2014; Siik and Maasikamäe, 2015; Looga et al., 2018). Land fragmentation refers to the scattered distribution of parcels within an operation that might hinder agricultural production. When examining land consolidation studies conducted in Türkiye, it is evident that many enterprises consist of numerous contiguous parcels (Değirmenci et al., 2017; Bayram and Değirmenci, 2018; Lök and Değirmenci, 2019; Arslan et al., 2018). Conversely, there are also operations where parcels are close to each other, with only a road passing between them. Therefore, the mere presence of multiple parcels under a single operation does not necessarily indicate land fragmentation. Considering parcel count as a measure of land fragmentation could lead to similar issues. The impact of parcel sizes on land fragmentation is debatable. Primarily, the location of parcels within an operation should be conducive to agricultural production. Parcel locations should justify the operating costs. Optimal parcel size factors in variables such as crop pattern, transportation costs, equipment usage, maintenance, pesticide application, and fertilization. Optimal operation size and optimal parcel size should not be confused. Optimal operation size is a subject that lacks a clear consensus, with limited research conducted on the topic (Gökçe and Adanacıoğlu, 2002; Dernek and Aktaş, 2002; Arslan et al., 2020). Optimal operation and parcel sizes are influenced by the region's agricultural characteristics, soil type, climate, and type of agricultural production (Sağlam, 2005). In the end, an operation with an optimal size might not have parcels of optimal size. A small-scale operation cultivating low-value products might have a parcel located far from the operation's center, with expenses outweighing potential gains. In such a scenario, the importance of optimal parcel size becomes evident. Having parcels in close proximity reduces costs. The key parameter NLFI attempts to measure is the contiguity of plots or their distance to the midpoint of parcel locations. Ultimately, the high correlation between the new fragmentation index and other fragmentation indices is a significant finding, suggesting that it could be used in lieu of other indices.

## 5. Conclusion

The scientific findings of this study primarily focus on the development and effectiveness of new indicators for evaluating the success of land consolidation projects, namely the New Shape Index (NSI) and the New Land Fragmentation Index (NLFI). For parcel shape assessment, the NSI was found to successfully indicate improvements in parcel shapes; NSI values approaching 1 signified parcels becoming more rectangular. In contrast, other commonly used parcel shape indices (FD, SI, FORM, AFF, APR1, APR2, APR3) were found to perform poorly in evaluating parcel shapes, often yielding different values for identically shaped parcels or identical values for differently shaped parcels. It was concluded that these indices, calculated based on area and perimeter, could not fully describe parcel shapes. Therefore, the use of NSI is strongly recommended for evaluating parcel shapes both before and after land consolidation projects.

Regarding the measurement of land fragmentation levels, the New Land Fragmentation Index (NLFI) was shown to accurately measure the decrease or increase in fragmentation based on the number and location of parcels within farms; smaller NLFI values indicated less fragmented farms. Other existing fragmentation indices (Januszewski, Simmons, Schmook, Ibgozurike) were found to be less effective in measuring the level of fragmentation. A noted weakness of NLFI is that it does not account for the size of parcels within an enterprise, potentially assigning higher values to enterprises with small and sparsely distributed parcels. Nevertheless, a statistically significant correlation found between NLFI and other fragmentation indices suggests that NLFI could be used in place of these other indices. NLFI can also be effectively utilised for assessing land fragmentation and identifying priority areas for land consolidation.

## CRediT authorship contribution statement

**Fırat Arslan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hasan Değirmenci:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization.

## Statement

This manuscript has been produced from P. hD. theises conducted by Fırat Arslan under supervisor Hasan Değirmenci from Kahramanmaras Sutcu Imam University, Türkiye.

## Declaration competing interest

Declarations of interest: none.

## Acknowledgment

This paper is based on a doctoral thesis titled "Geospatial and geostatistical analysis of land consolidation projects" completed at Kahramanmaraş Sütçü İmam University in 2020.

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