land

MDPI

Article

Using Cadastral Information to Support Forest Owner Aggregation in Small-Scale and Fragmented Forest Ownerships: A Network Analysis Approach in the Forest Sharing® Platform

Giuliano Secchi [1], Ilaria Zorzi [2,3], Alessandro Errico [2,3], Yamuna Giambastiani [2,3], Jessica Scriva [2], Irene Fattoretto [1], Guido Milazzo [2,3], Niccolò Fani [2], Lorenzo Massai [2,3], Cristiano Guadagnino [2], Willy Reggioni [4], Tommaso Tognetti [2], Ilaria Incollu [1], Livia Passarino [1], Bianca Rompato [1], Giacomo Pinzani [2], Hervè Corti [2], Reicht Prince Destin Batomene [2], Andrea Laschi [5], Cristiano Foderi [1] and Francesca Giannetti [1,3,*]

1 Department of Agriculture, Food, Environment and Forestry, University of Florence, 50145 Florence, Italy; giuliano.secchi@unifi.it (G.S.); irene.fattoretto@unifi.it (I.F.); ilaria.incollu@unifi.it (I.I.); livia.passarino@unifi.it (L.P.); bianca.rompato@unifi.it (B.R.); cristiano.foderi@unifi.it (C.F.)

2 Bluebiloba Startup Innovativa s.r.l., Via C. Salutati 78, 50126 Florence, Italy; ilaria.zorzi@bluebiloba.com (I.Z.); alessandro.errico@bluebiloba.com (A.E.); yamuna.giambastiani@bluebiloba.com (Y.G.); jessica.scriva@bluebiloba.com (J.S.); guido.milazzo@bluebiloba.com (G.M.); niccolo.fani@bluebiloba.com (N.F.); admin@bluebiloba.com (L.M.); cristiano.guadagnino@bluebiloba.com (C.G.); tommaso.tognetti@bluebiloba.com (T.T.); giacomo.pinzani@bluebiloba.com (G.P.); princebatomene@gmail.com (R.P.D.B.)

3 ForTech Laboratorio Congiunto, University of Florence, 50145 Florence, Italy

4 Parco Nazionale Dell'Appennino Tosco-Emiliano, Via Enzo Bagnoli, 30, 42032 Ligonchio, Italy; willy.reggioni@parcoappennino.it

5 Department of Agricultural, Food and Forest Sciences—SAAF, University of Palermo, Viale Delle Scienze ed 4, 90128 Palermo, Italy; andrea.laschi@unipa.it

* Correspondence: francesca.giannetti@unifi.it; Tel.: +39-389-6831656

Abstract

Forest ownership fragmentation represents a major constraint to sustainable forest management in many European countries, particularly in Italy, where private forests are often divided into small and spatially dispersed holdings. This study evaluates the potential of cadastral data to support forest-owner aggregation through graph-based spatial network analysis implemented within the Forest Sharing® platform. Its novelty lies in the operational integration of voluntary cadastral parcel data with a comparative network framework that quantifies how parcel representation and spatial thresholds alter the identification of candidate multi-owner management units. The analysis included 29,549 cadastral forest parcels voluntarily registered by 910 private forest owners across Italy. Parcels were treated as network nodes, and three spatial relationship models were compared: strict topological adjacency, minimum polygon-to-polygon distance, and distance between internal representative points. Distance-based networks were evaluated at 50-m increments from 50 to 1000 m, while cluster eligibility was defined by a minimum area of 30 ha and at least two owners. Strict adjacency identified six eligible clusters covering 465.7 ha. The minimum polygon-distance method identified 31 eligible clusters and 7297.2 ha at 100 m, increasing to 44 clusters and 14,204.8 ha at 1000 m. The point-on-surface method was substantially more conservative at short thresholds but progressively converged with the polygon method; edge recall increased from 0.479 at 100 m to 0.916 at 1000 m, while precision remained equal to 1.0. Median ownership complexity remained limited to two or three owners per eligible cluster, although the largest components included substantially more owners at high thresholds. The results demonstrate that parcel geometry and threshold selection materially influence estimated aggregation opportunities and support the use of

Academic Editors: Anita Kwartnik-Pruc, Agnieszka Pęska-Siwik and Monika Mika

Received: 25 June 2026
Revised: 3 August 2026
Accepted: 5 August 2026
Published: 18 August 2026

polygon-based proximity combined with sensitivity analysis as a transparent screening framework for collective forest management.

Keywords: forest ownership fragmentation; forest owner aggregation; forest owner associations; land information systems; collective forest management; spatial network analysis

1. Introduction

Sustainable forest management increasingly depends on accurate and up-to-date spatial information [1–4]. Within this information framework, cadastral data provide the parcel-level geometry and administrative reference needed to connect forest resources, land tenure, planning, and territorial management [5–8]. Approximately 60% of European forests are privately owned [9], and in many countries this ownership is divided among numerous small and spatially dispersed holdings [10–14]. Schmithüsen and Hirsch (2010) [15] estimated that 61% of private forest holdings in Europe are smaller than 1 ha, whereas only 1% exceed 50 ha. Although larger private estates are more common in parts of Northern Europe, particularly Sweden and Finland [14], small-scale and fragmented ownership is especially relevant in Southern European countries, including Italy and Spain [16,17].

At the Italian national level, forest ownership is strongly fragmented. Giannetti et al. (2023) [10] reported an average forest holding of 8.2 ha per owner, which is below the European average of 12.7 ha [18,19]. Fragmentation can be even more pronounced at the parcel level: in the north-eastern Italian Alps, Alberti et al. (2016) [20] found that 95% of cadastral forest parcels covered less than 1 ha. These figures indicate that the operational problem is not only limited to the small total area owned by individual landholders but also concerns the subdivision of holdings into multiple non-contiguous parcels.

Forest ownership fragmentation results from inheritance, repeated land subdivision, demographic change, rural depopulation, and land abandonment [10,17,21–25]. It constrains timber mobilisation, coordinated silviculture, forest planning, investment, and the provision of ecosystem services [14,26]. Fragmented ownership also increases transaction and operational costs, limits participation in certification schemes, and complicates timber traceability and transparency along forest-based value chains [14,27,28]. Põllumäe et al. (2016) [29] identified the small size of individual holdings as a persistent barrier to cooperation: owners may regard their properties as too limited to justify active management, even though these are precisely the holdings that could benefit most from collective arrangements.

European and national policies increasingly promote forest-owner cooperation through associations, cooperatives, producer organisations, and landscape-scale management initiatives [29]. In Italy, the National Forest Law (Legislative Decree No. 34/2018) and the National Forest Strategy [30] explicitly support forest-owner aggregation and coordinated management as instruments for sustainable forest management, wood mobilisation, carbon-stock enhancement, and improved competitiveness of the forest sector. These policy objectives require methods capable of identifying where spatially coherent groups of parcels and owners could constitute feasible starting units for joint management.

Cadastral information is essential for this purpose because it provides the primary spatial reference for parcel boundaries, registered holders, and the territorial organisation of land [31]. Its legal and administrative meaning, however, differs among European land-administration systems. European cadastral and land-registration systems can be broadly grouped into Central European, Nordic integrated, Latin, and mixed or transitional models (Table 1).

Table 1. Main cadastral and land-registration models in the European Union and their implications for the legal status and operational use of ownership information.

Land Administration Model	Legal Status of Ownership Information	EU Member States
Central European (Grundbuch-based systems)	Ownership rights are recorded in legally authoritative land registers with strong evidentiary or constitutive effect. Cadastral and registry information are closely integrated.	Austria, Germany, Czech Republic, Slovakia, Slovenia, Croatia, Hungary, Poland, Italy (Autonomous Provinces of Trento and Bolzano)
Nordic Integrated Systems	Integrated cadastral and land registration systems providing high legal certainty and comprehensive digital land information infrastructures.	Sweden, Finland, Denmark, Estonia, Latvia, Lithuania
Latin Cadastre Systems	Cadastre primarily serves fiscal and technical purposes, while ownership rights are established through separate land registry systems and registered deeds.	Italy, France, Spain, Belgium, Luxembourg
Mixed or Transitional Systems	Ongoing integration of cadastral and land registration functions, with varying degrees of legal effectiveness and institutional coordination.	Portugal, Greece, Malta, Cyprus, Romania

Central European and Nordic systems generally show stronger legal and institutional integration between cadastral geometry and property registration, facilitating ownership verification, land governance, aggregation initiatives, and supply-chain traceability. In Latin cadastral systems, including most of Italy, cadastre primarily has fiscal and technical functions and does not itself constitute legal proof of ownership; property rights are established through separate land-register records and registered deeds. Table 1 provides a concise institutional synthesis relevant to the interpretation and operational use of cadastral data in forest-owner aggregation.

Although the Italian cadastre provides a comprehensive spatial framework for identifying parcels and registered holders, cadastral records generally do not constitute legal proof of ownership. The correspondence between registered and actual ownership may weaken over time because of unregistered successions, informal transfers, incomplete administrative updates, demographic change, and prolonged land abandonment [25,32]. Identifying the current rights holder may therefore require the reconstruction of ownership histories through historical cadastral records, land-register archives, notarial deeds, and succession documents. In forest areas, this may produce both parcels with unknown or difficult-to-trace ownership [33] and the progressive fragmentation of otherwise documented properties [5,10]. Cadastral information is consequently suitable for spatial screening and preliminary aggregation analysis, whereas formal collective-management arrangements require subsequent legal verification of property rights.

An important Italian exception is represented by the Autonomous Provinces of Trento and Bolzano, where the Austro-Hungarian land-registration system (Libro Fondiario/Grundbuch) remains in force and provides legal certainty through the registration of real-estate rights.

This institutional setting may contribute to conditions favourable to long-term forest governance and planning. According to the National Forest Information System (SINFor), the Autonomous Province of Bolzano has the highest proportion of forest area covered by forest management plans in Italy (87.3%), followed by the Autonomous Province of Trento (approximately 68%), compared with a national average of 18.4%. These differences cannot be attributed to the land-registration system alone because they also reflect established forestry traditions, strong local institutions, and the economic importance of forest resources.

https://doi.org/10.3390/land15081497

Nevertheless, clearly identifiable rights holders can reduce information and transaction costs and facilitate long-term planning. Across Italy, regardless of the legal regime, cadastral databases remain the main operational spatial source for identifying contiguous or nearby properties and supporting cooperative management, owner associations, forest planning, land-consolidation initiatives, and timber traceability.

Within the Italian National Forest Strategy, reactivating the management of forests owned by small private proprietors also requires identifying and reconnecting with owners, many of whom live far from their properties or have limited knowledge of their exact location [10]. Forest Sharing® was developed as a digital platform to facilitate this process. Landowners voluntarily register their properties using basic cadastral identifiers; the corresponding parcel geometries can then be linked to forest, environmental, and management information. Several functions of the platform have been described by Giannetti et al. (2023) [10].

Beyond the extraction of forest inventory and environmental information [5,34,35], cadastral geometries can support the identification of neighbouring owners and spatially coherent groups of properties. Coordinated management among adjacent or nearby holdings may reduce search and coordination costs, facilitate shared silvicultural operations and infrastructure planning, and provide an evidence base for participatory processes and forest-owner associations. This study addresses management aggregation rather than physical land consolidation: parcel boundaries and ownership remain unchanged, while spatial analysis is used to identify candidate units for coordinated management.

Graph-based methods are well established in landscape ecology, land administration, and spatial planning [36,37]. Accordingly, this study does not claim novelty in the graph-theoretical methods themselves. The research gap lies in the limited evidence on how alternative parcel-connection rules perform when applied to large cadastral forest datasets from a voluntary digital platform, and on how sensitive the resulting candidate management units are to distance and minimum-area assumptions. Accordingly, this study aims to (i) identify potential multi-owner forest management clusters using strict parcel adjacency, minimum polygon-to-polygon distance, and point-on-surface distance; (ii) quantify the sensitivity of cluster number, area, ownership composition, and network structure to distance and minimum-area thresholds; (iii) evaluate the agreement among the three spatial representations; and (iv) assess the extent to which cadastral network analysis can provide a transparent screening tool for forest-owner aggregation under the Italian and European policy context described above.

The remainder of this paper is organised as follows. Section 2 describes the study area, datasets, spatial network construction, cluster eligibility criteria, and agreement metrics. Section 3 presents the sensitivity and comparison results for the alternative parcel-connection rules. Section 4 discusses the methodological contribution, policy relevance, limitations, and transferability of the approach. Section 5 summarises the main conclusions and priorities for further research.

2. Materials and Methods

2.1. Study Area and Dataset

The study area comprised the national territory of Italy, as shown in Figure 1. Its outer boundary corresponds to the Italian national boundary, while the analysed parcels are distributed across multiple municipalities and regions and therefore do not belong to a single administrative area. The dataset included 29,549 cadastral forest parcels, representing approximately 25,917 ha registered by 910 owners through the Forest Sharing® platform (Bluebiloba, Florence, Italy) [10].

Figure 1. National distribution of the 29,549 cadastral forest parcels registered by 910 owners in the Forest Sharing® platform (Bluebiloba, Florence, Italy). The map shows the Italian national boundary, geographic coordinate grid, north arrow, and parcel legend; cadastre parcels subscribed in the Forest Sharing platform are reported as green dots distributed across multiple Italian administrative regions.

Figure 2 characterises the ownership and parcel-size structure of the dataset before the spatial network analysis.

Participation in the platform is voluntary; therefore, the dataset should not be interpreted as a statistically representative sample of all Italian private forest owners. It constitutes a large operational dataset of owners who have already expressed an interest in locating, understanding, or managing their forest properties. Forest ownership within the dataset was strongly skewed toward small holdings: approximately 67% of owners held less than 5 ha, about 11% held 5–10 ha, and 6.5% held 10–20 ha, whereas ownerships larger than 100 ha accounted for approximately 6% of owners (Figure 2).

Each record consisted of a georeferenced cadastral polygon associated with an owner identifier. The cadastral parcel was retained as the basic spatial and network unit. Owner identifiers were generated from the available platform fields, and records lacking a usable identifier were treated as distinct unknown owners to avoid artificial aggregation of unrelated parcels.

All geometries were transformed to WGS84/UTM Zone 32N (EPSG:32632), validated, and restricted to non-empty polygonal components. Parcel area was calculated directly from the cleaned geometry and expressed in hectares. A unique parcel identifier and an internal point generated with the point-on-surface operation were also derived for each polygon.

For each parcel, the analysis retained the following attributes: (i) a unique parcel identifier; (ii) an owner identifier; (iii) polygon area in hectares; and (iv) polygon-geometry; and (v) the coordinates of an internal point used in the point-based comparison and network visualisation.

The distribution of individual parcel areas and the total area held by each owner were summarised to characterise the initial fragmentation structure and to assess how parcel size may influence cluster formation.

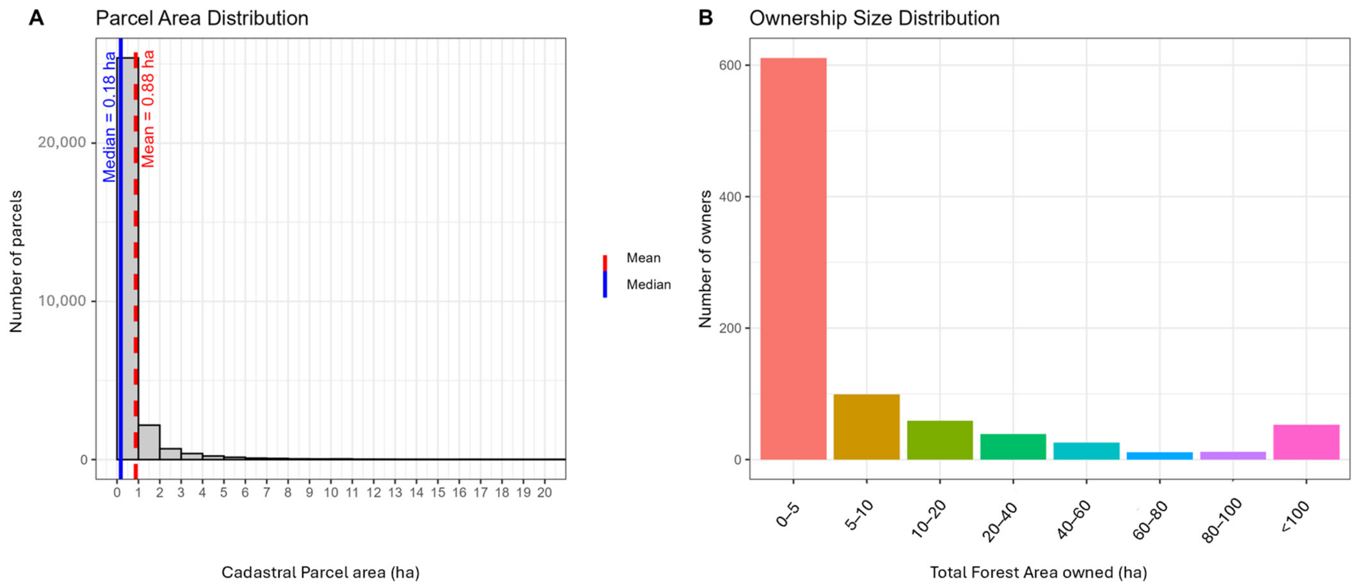

Figure 2. Forest ownership and parcel-size structure. (**A**) Distribution of cadaster parcel areas, with mean and median parcel size indicated by vertical lines (**B**). Distribution of forest owners according to the total forest area owned. Bars represent the number of forest owners within each class of total forest area owned (ha), calculated as the sum of all parcels belonging to the same owner.

2.2. Spatial Network Construction and Alternative Parcel-Connection Rules

A graph-based approach was used to identify candidate units for coordinated forest management. In every scenario, cadastral parcels were represented as nodes and spatial relationships between pairs of parcels were represented as undirected edges. Connected components of the resulting graph were interpreted as potential management clusters. Three connection rules were analysed separately to quantify the consequences of alternative spatial representations.

The first rule, strict adjacency, connected two parcel polygons only when their boundaries touched, as identified with the st_touches operation. This scenario represents the most restrictive topological definition of spatial continuity and does not require a distance threshold.

The second rule, minimum polygon distance, connected two parcels when the minimum Euclidean distance between their polygon geometries was equal to or lower than a specified threshold. Unlike a centroid-based representation, this rule accounts for parcel shape, size, and the location of the nearest boundaries.

The third rule, point-on-surface distance, represented each polygon by an internal point and connected parcels when the Euclidean distance between these points was equal to or lower than the threshold. Point-on-surface was used instead of a geometric centroid because it guarantees that the representative point lies within the parcel. This computationally efficient representation was retained as a methodological comparator, while recognising that it compresses parcel geometry into one location and may therefore misrepresent proximity for large or elongated parcels.

For the two distance-based rules, candidate edges were first generated up to a maximum distance of 1000 m and their exact Euclidean distances were stored. Scenarios were subsequently obtained by filtering this common edge set, thereby ensuring computational consistency across thresholds and avoiding repeated all-pairs distance calculations.

Euclidean distance was selected as a transparent and reproducible measure of geometric separation between cadastral units. It is appropriate for a national-scale screening analysis, but it is not a measure of travel time, road accessibility, extraction distance, terrain difficulty, or management cost. Rivers, ridges, infrastructure, slope, administrative boundaries, and other barriers were not incorporated and must be evaluated in subsequent operational assessments.

Distance sensitivity was assessed from 50 to 1000 m at 50-m intervals. The 100, 250, 500, and 1000 m scenarios were retained as principal reporting thresholds because they span four readily interpretable levels of connection: very local proximity, neighbourhood-scale proximity, broader local coordination, and landscape-scale association. They are analytical scenarios rather than universally prescriptive forestry standards; their interpretation was therefore supported by the full sensitivity curves and by network and compactness metrics.

Spatial processing was performed in R (v. 4.6.1) using the sf (v. 1.1-1) package, while graph construction and connected-component analysis were conducted with igraph (v. 2.3.3). All parcels, including isolated nodes, were retained in each graph.

For each method and threshold, connected components were identified from graph membership. The connected-component definition allows indirect links: parcels A and C may belong to the same cluster when A is linked to B and B is linked to C, even if A and C are farther apart than the edge threshold. This chaining property is intrinsic to connected-component clustering and was explicitly evaluated through cluster spatial extent, graph diameter, and spatial compactness. Consequently, the selected edge threshold constrains only direct parcel-to-parcel links and does not impose a maximum end-to-end distance on the complete component; successive short links can therefore produce a cluster whose overall span is substantially larger than the threshold.

2.3. Cluster Eligibility and Sensitivity to Minimum Area

A connected component was classified as an eligible candidate for collaborative management when it contained at least 30 ha of forest and at least two distinct owners. The ownership criterion ensures that retained components represent a potential cooperative arrangement rather than the internal organisation of a single holding.

The 30-ha threshold was used as a pragmatic minimum management scale for the primary analysis, not as a legal or universally optimal requirement. It excludes very small components while retaining units large enough to support preliminary consideration of shared planning and operations. Because operational and policy requirements vary among regions and instruments, the robustness of the findings was tested using alternative minimum cluster areas of 10, 20, 30, 50, and 100 ha.

For each minimum-area threshold, the number of eligible clusters, their total forest area, the number of included owners, and median cluster characteristics were recalculated without rebuilding the spatial graph.

2.4. Cluster, Ownership, Geometric, and Network Indicators

For every scenario, cluster-level indicators described structural composition, ownership complexity, spatial form, and graph structure. Structural indicators included the number of parcels, total cluster area, mean and median parcel area, minimum and maximum parcel area, and variation in parcel size. Ownership indicators included the number of owners, area per owner, parcels per owner, and owner and parcel densities per 100 ha.

Network indicators included the number of edges, mean and maximum edge distances, average node degree, graph density, and graph diameter. Spatial extent was measured from the diagonal of the bounding box of parcel internal points. For eligible clusters at the principal thresholds, polygon union and convex-hull area were calculated, and spatial compactness was expressed as the ratio between union area and convex-hull area. Lower compactness, large spatial extent, and a high graph diameter relative to the connection threshold were interpreted as evidence of a stronger chaining effect.

The influence of individual parcel size was evaluated through parcel-area distributions within clusters, cluster-level mean and median parcel area, coefficients of variation, and relationships between parcel number, owner number, and total cluster area. These indicators allow the analysis to distinguish aggregation driven by many very small parcels from aggregation involving fewer and larger units.

2.5. Agreement Among Spatial Representations

The three network constructions were compared at common thresholds. Edge-set agreement between minimum polygon distance and point-on-surface distance was quantified using Jaccard similarity. Treating the polygon-distance relation as the geometric reference, precision, recall, and F1 score were calculated for point-derived edges; this reference indicates geometric fidelity and should not be interpreted as validation against observed cooperation. Agreement was also measured for the sets of eligible parcels, eligible forest area, and included owners. Area-weighted Jaccard similarity accounted for differences in parcel size. Cluster correspondence was evaluated by matching each eligible cluster to the cluster in the alternative representation with the greatest parcel and area overlap. Strict-adjacency results were compared with both distance-based methods to show how moving from topological continuity to progressively broader proximity changes candidate management units.

3. Results

3.1. Effects of Spatial Relationship Model and Distance Threshold

The three spatial relationship models produced markedly different estimates of parcel connectivity and potential forest-owner aggregation. Strict topological adjacency represented the most conservative scenario, identifying six eligible multi-owner clusters. These clusters included 77 cadastral parcels belonging to 13 owners and covered 465.7 ha, corresponding to 1.8% of the forest area represented in the dataset.

The minimum polygon-distance method identified substantially more aggregation opportunities, including at short distance thresholds. At 100 m, 31 eligible clusters were detected, encompassing 2582 parcels, 87 owners, and 7297.2 ha of forest area (28.2% of the dataset area). At 250 m, 41 clusters included 5460 parcels, 140 owners, and 8550.1 ha. The number of eligible clusters reached 46 at 500 m, while the eligible area increased to 10,689.3 ha and involved 224 owners. At 1000 m, the number of clusters declined slightly to 44 because previously separate components merged, but eligible forest area continued to increase to 14,204.8 ha (54.8% of the dataset area), involving 331 owners (Figure 3).

https://doi.org/10.3390/land15081497

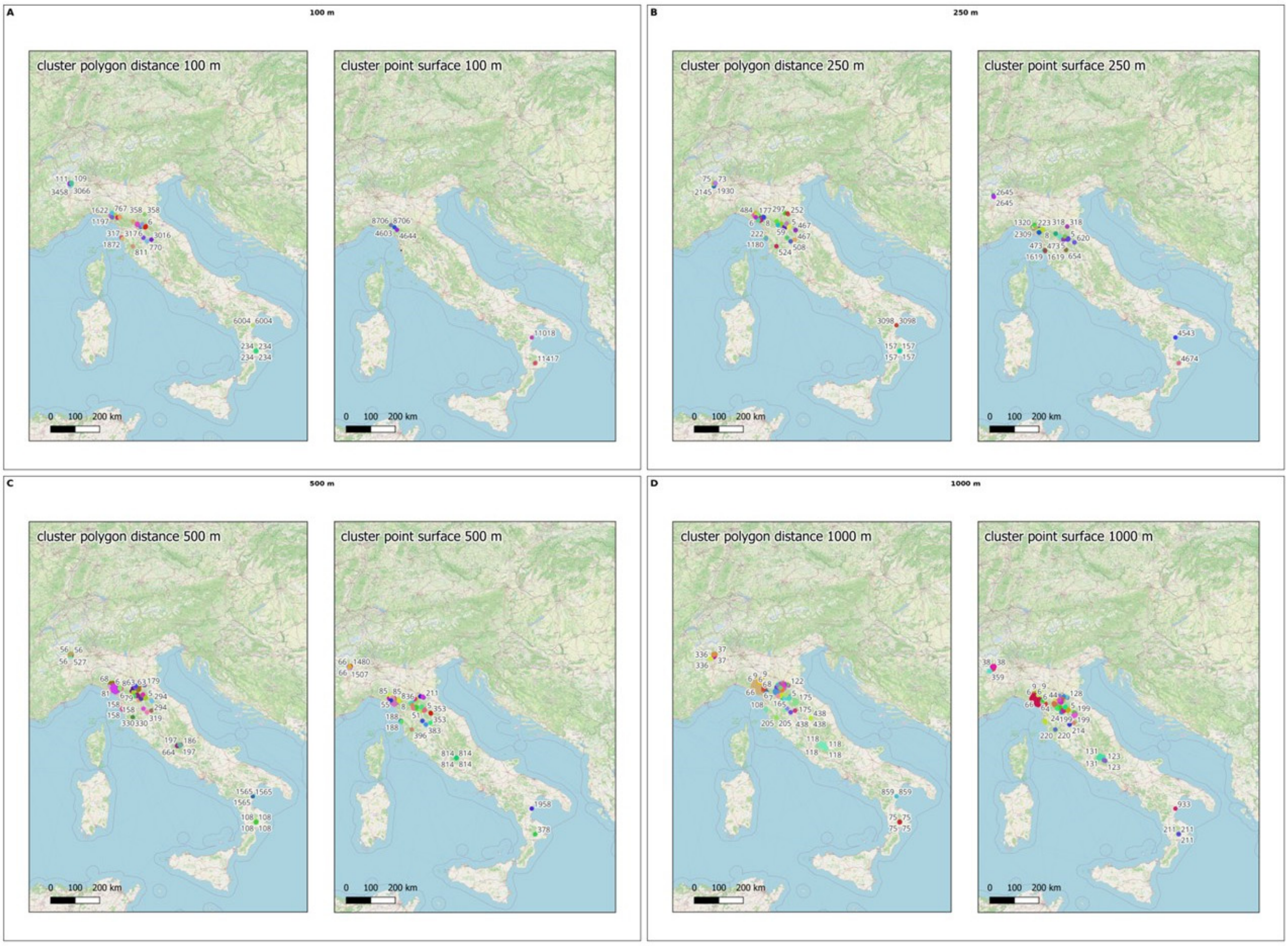

Figure 3. Spatial distribution of eligible forest-management clusters identified using the minimum polygon-distance method at increasing distance thresholds: (**A**) 100 m, (**B**) 250 m, (**C**) 500 m, and (**D**) 1000 m. coloured dot separate clusters satisfying the eligibility criteria of at least 30 ha of total forest area and at least two distinct forest owners.

The point-on-surface method was considerably more restrictive at short distances. At 100 m, it identified only five eligible clusters, comprising 11 parcels, 10 owners, and 697.5 ha. The number of eligible clusters then increased to 30 at 250 m and 48 at 500 m. At 1000 m, 47 eligible clusters covered 12,967.4 ha and included 322 owners. Differences between the two proximity methods were therefore largest at short thresholds and progressively decreased as the distance threshold increased (Figure 3).

The continuous sensitivity analysis also showed that the number of eligible clusters did not increase monotonically with distance. For both proximity models, cluster numbers initially increased as isolated parcels became connected, stabilised around 45–50 clusters at intermediate thresholds, and then fluctuated or declined slightly as connected components merged. In contrast, total eligible forest area increased consistently with distance. Median ownership complexity remained between two and three owners per cluster across the threshold range, whereas median spatial extent increased, indicating a trade-off between the amount of forest area incorporated and the spatial compactness of the resulting management units (Figure 4).

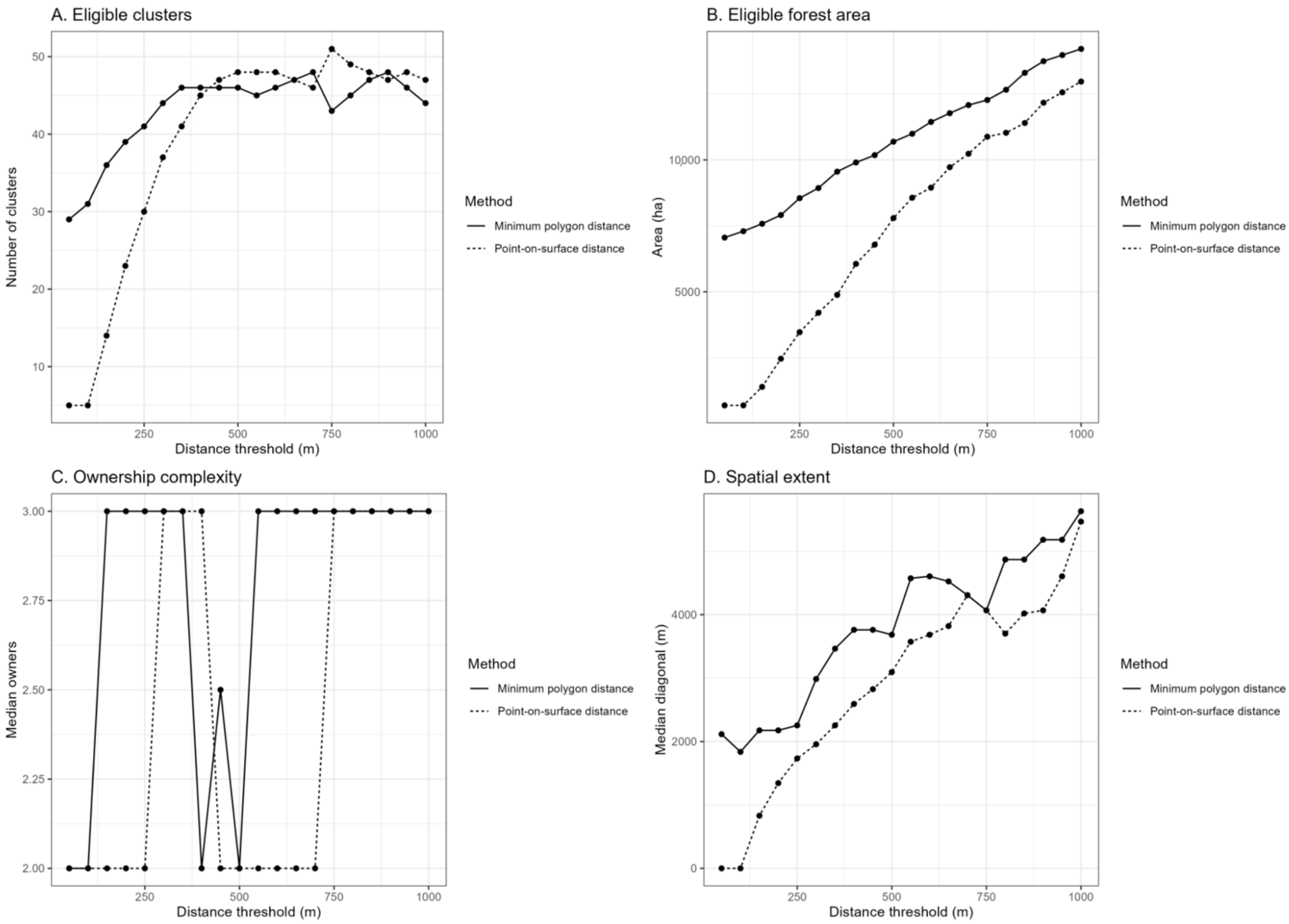

Figure 4. Sensitivity of potential forest-owner aggregation to the distance threshold. (**A**) Number of eligible clusters; (**B**) total eligible forest area; (**C**) median number of owners per cluster; and (**D**) median spatial extent of eligible clusters, expressed as the diagonal of their bounding box, which approximates the maximum spatial span between the outermost parts of each cluster. Solid lines represent the minimum polygon-distance method and dotted lines the point-on-surface method. Eligible clusters included at least 30 ha and at least two owners.

3.2. Cluster Size, Ownership Complexity, and Spatial Configuration

Eligible cluster characteristics varied with both the spatial relationship model and the distance threshold (Table 2). Under strict adjacency, clusters had a median area of 66.4 ha and included a median of 2.5 owners and 4.5 parcels. Under the polygon-distance method, the median cluster area was 75.7 ha at 100 m, 61.6 ha at 250 m, 68.2 ha at 500 m, and 92.9 ha at 1000 m. This non-monotonic pattern resulted from the simultaneous formation of new eligible components and the progressive merging of existing components.

Median ownership complexity remained relatively limited: two owners at 100 and 500 m and three owners at 250 and 1000 m under the polygon-distance method. However, the upper tail expanded markedly with threshold. The maximum number of owners in a single polygon-distance cluster increased from 14 at 100 m to 21 at 250 m, 87 at 500 m, and 178 at 1000 m. The point-on-surface method showed a similar pattern at larger thresholds, reaching a maximum of 171 owners at 1000 m. Thus, the typical eligible cluster retained a relatively simple ownership structure, while a limited number of very large components would require more complex governance arrangements.

Table 2. Summary of eligible forest-management clusters for strict adjacency and the four principal distance thresholds.

Method	Threshold (m)	Eligible Clusters	Eligible Area (ha)	Area (%)	Parcels	Owners	Median Owners	Max Owners
Adjacency	0	6	465.7	1.8	77	13	2.5	3
Polygon distance	100	31	7297.2	28.2	2582	87	2.0	14
Point-on-surface	100	5	697.5	2.7	11	10	2.0	3
Polygon distance	250	41	8550.1	33.0	5460	140	3.0	21
Point-on-surface	250	30	3472.0	13.4	3224	82	2.0	15
Polygon distance	500	46	10,689.3	41.2	11,577	224	2.0	87
Point-on-surface	500	48	7793.3	30.1	10,160	198	2.0	63
Polygon distance	1000	44	14,204.8	54.8	18,583	331	3.0	178
Point-on-surface	1000	47	12,967.4	50.0	18,022	322	3.0	171

Note: eligible clusters contained at least 30 ha of forest land and at least two distinct owners. Area (%) is calculated relative to the total forest area represented in the dataset.

3.3. Agreement Between Polygon-Distance and Point-on-Surface Methods

Agreement between the two proximity-based methods increased consistently with the threshold (Figure 5). Edge-set Jaccard similarity rose from 0.479 at 100 m to 0.718 at 250 m, 0.844 at 500 m, and 0.916 at 1000 m. Similarity of parcels included in eligible clusters increased from 0.004 at 100 m to 0.590 at 250 m, 0.878 at 500 m, and 0.970 at 1000 m. The area-weighted Jaccard index increased from 0.096 to 0.406, 0.729, and 0.913 at the same thresholds, while owner-set similarity increased from 0.115 to 0.586, 0.884, and 0.973.

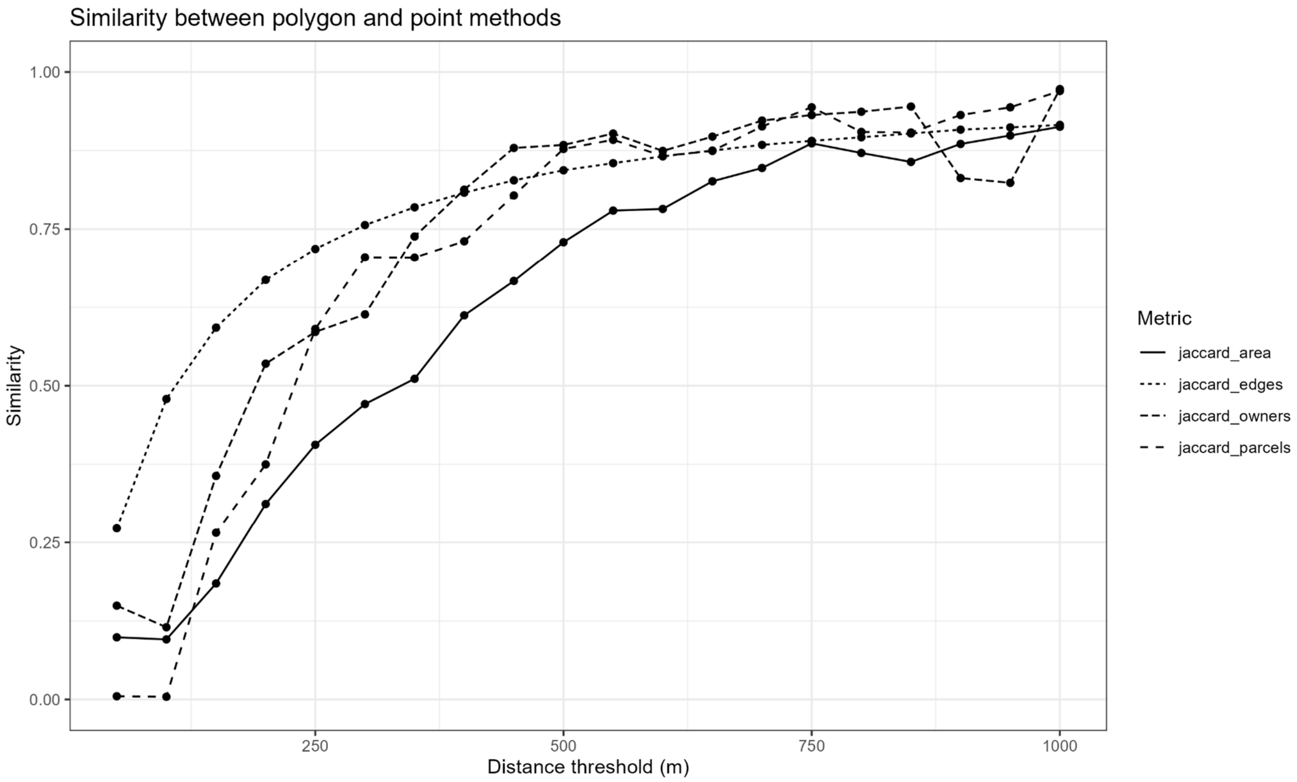

Figure 5. Similarity between the minimum polygon-distance and point-on-surface methods across distance thresholds. Jaccard indices were calculated for network edges, parcels included in eligible clusters, eligible forest area, and forest owners represented in eligible clusters.

These results demonstrate that simplifying parcel polygons to internal representative points has its strongest influence at short and intermediate spatial scales. At larger thresholds, the two methods progressively converge because differences between parcel-boundary distance and representative-point distance become smaller relative to the selected connection threshold.

3.4. Edge-Based Performance of the Point-on-Surface Approximation

Using the minimum polygon-distance network as the geometric reference, the point-on-surface method showed precision equal to 1.00 at every threshold (Figure 6). Therefore, every edge detected from representative points was also present in the corresponding polygon-distance network. The main difference was omission rather than commission: parcels whose boundaries were close were not always connected because their internal representative points were farther apart.

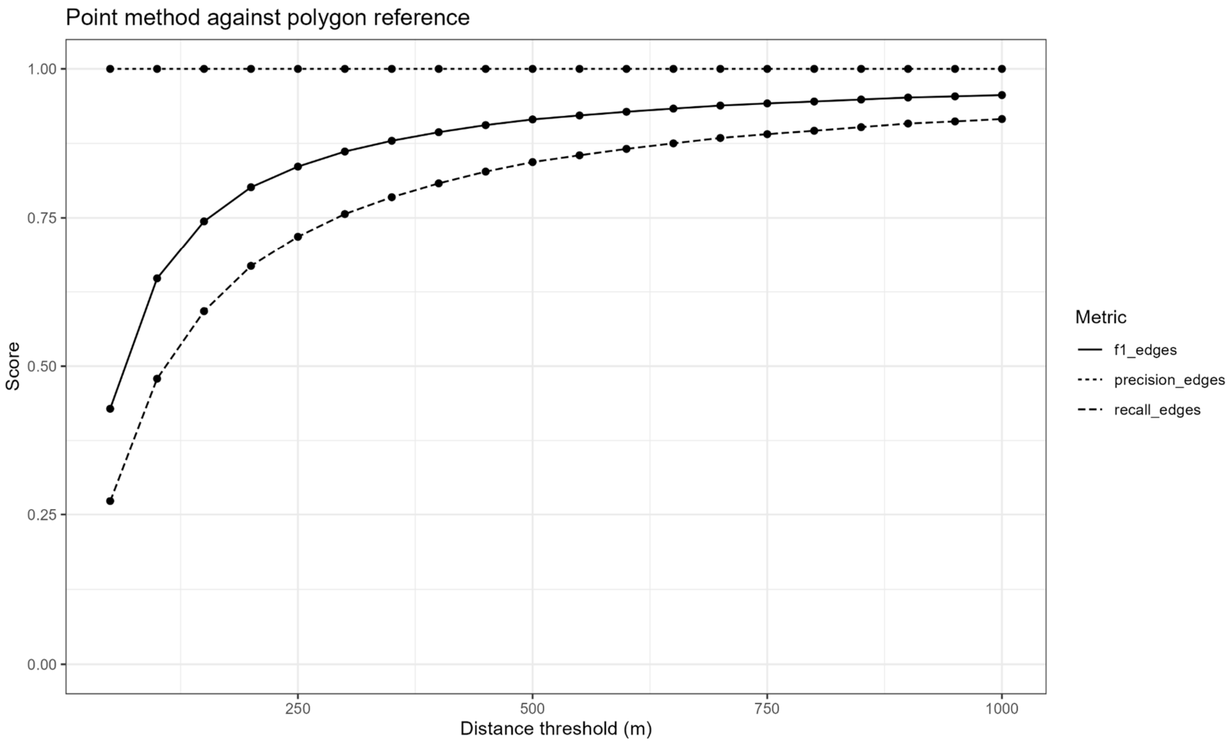

Figure 6. Edge-based agreement of the point-on-surface method relative to the minimum polygon-distance network. Precision, recall, and F1 scores were calculated for thresholds from 50 to 1000 m. The polygon-distance method is used as a geometric reference for method comparison, not as an independent validation of operational aggregation feasibility.

Recall increased from 0.479 at 100 m to 0.718 at 250 m, 0.844 at 500 m, and 0.916 at 1000 m. The corresponding F1 score increased from 0.648 to 0.836, 0.915, and 0.956. At the lowest tested threshold of 50 m, recall was only 0.273 and the F1 score was 0.428. These patterns confirm that the point-on-surface method is a conservative approximation of polygon proximity and can markedly underestimate local connectivity for large, elongated, or irregular parcels.

3.5. Sensitivity to the Minimum Eligible Cluster Area

The number of eligible clusters was sensitive to the minimum-area requirement, whereas the total eligible forest area was comparatively more stable. Under the polygon-distance method at 250 m, reducing the minimum cluster area from 30 to 10 ha increased the number of eligible clusters from 41 to 87 and the eligible area from 8550.1 to 9422.8 ha.

Increasing the minimum area to 50 ha reduced the number of clusters to 29 while retaining 8096.2 ha; at 100 ha, 14 clusters remained eligible and covered 7085.6 ha.

A comparable pattern occurred at 500 m, where eligible cluster numbers declined from 87 at a 10-ha minimum to 46 at 30 ha, 31 at 50 ha, and 14 at 100 ha, while the eligible area declined more gradually from 11,441.1 to 10,689.3, 10,133.5, and 8928.0 ha, respectively. At 1000 m, increasing the minimum area from 10 to 30 ha reduced cluster numbers from 66 to 44, but the total eligible area decreased only from 14,608.9 to 14,204.8 ha. Even at 100 ha, 20 clusters remained eligible and covered 12,846.5 ha. The 30-ha criterion therefore removed numerous small components while retaining most of the area concentrated in larger clusters, supporting its use as an intermediate screening threshold rather than as a universal optimum.

3.6. Strict Adjacency as a Conservative Baseline

Strict adjacency captured a distinct and substantially narrower form of spatial association than either proximity method. All adjacency edges were included in the polygon-distance networks because touching parcels have a minimum geometric distance of zero. However, adjacency represented a progressively smaller subset of the proximity network as threshold increased: edge-set Jaccard similarity with polygon distance was 0.120 at 100 m, 0.052 at 250 m, 0.024 at 500 m, and 0.011 at 1000 m. Parcel-level Jaccard similarity declined from 0.030 at 100 m to 0.004 at 1000 m. These low values reflect conceptual difference rather than inconsistency: strict adjacency identifies compact cores of directly contiguous parcels, whereas distance-based approaches include parcels separated by limited gaps or landscape discontinuities.

4. Discussion

4.1. Methodological Contribution and Robustness of the Spatial-Network Approach

Graph-based methods are well established in landscape ecology, land administration, and spatial planning [36–38]. Accordingly, the contribution of this study does not lie in proposing a new graph-theoretical algorithm. Rather, it lies in using cadastral parcels as operational units for identifying potential multi-owner management configurations, embedding this analysis within the Forest Sharing® platform, and explicitly testing how alternative spatial representations affect the inferred aggregation opportunities. The comparison among strict adjacency, minimum polygon-to-polygon distance, and point-on-surface distance provides a more transparent basis for interpreting the results than reliance on a single spatial model.

The sensitivity analysis demonstrates that the inferred aggregation potential depends materially on both the definition of an edge and the selected threshold. Strict adjacency identified only six eligible clusters covering 465.7 ha, whereas the minimum polygon-distance model identified 31 eligible clusters and 7297.2 ha at 100 m. This large difference confirms that direct boundary contiguity and short-range functional proximity represent distinct planning concepts. Adjacency is useful for identifying the most compact cores of immediately contiguous holdings, while distance-based models can include parcels separated by roads, clearings, agricultural land, or other limited discontinuities that do not necessarily prevent coordinated management.

The comparison between polygon and point representations also quantifies the consequences of simplifying parcel geometry. Precision of the point-on-surface method was equal to 1.00 at all thresholds, meaning that every point-based edge was also identified by the polygon-distance model. Its limitation was therefore omission rather than the creation of additional connections. Edge recall increased from 0.479 at 100 m to 0.916 at 1000 m, while area-weighted Jaccard similarity increased from 0.096 to 0.913. Representative points therefore provide a conservative approximation, particularly at short distances, because the internal extent, elongation, and irregularity of parcels collapsed into a single location. The increasing agreement at larger thresholds indicates that this geometric simplification becomes less influential as the connection distance grows relative to parcel dimensions.

4.2. Interpreting Distance Thresholds and the Trade-Off Between Inclusion and Spatial Coherence

The continuous 50-m sensitivity assessment shows that no single distance can be interpreted as a universally optimal threshold. The number of eligible clusters initially increased as isolated parcels became connected, then stabilised at approximately 45–50 clusters and fluctuated as previously separate components merged. In contrast, eligible forest area increased continuously. Under the polygon-distance model, eligible area rose from 7297.2 ha at 100 m to 8550.1 ha at 250 m, 10,689.3 ha at 500 m, and 14,204.8 ha at 1000 m. This pattern reflects a fundamental planning trade-off: larger thresholds include more forest area and owners, but also generate spatially broader and potentially less compact management units.

The 250-m scenario should therefore be regarded as a policy-relevant intermediate case rather than an optimum established independently of context. It identified 41 eligible polygon-distance clusters covering 8550.1 ha and involving 140 owners, with a median of three owners per cluster. Compared with 100 m, it substantially increased the number of opportunities and eligible area; compared with 500 and 1000 m, it limited the spatial expansion and ownership complexity of the largest components. Its practical suitability would nevertheless depend on local topography, road accessibility, forest type, management objectives, and administrative boundaries. Consequently, the proposed workflow is better understood as a threshold-screening framework that allows planners to examine alternative spatial scenarios rather than as a procedure that prescribes one fixed distance.

The sensitivity to the minimum cluster-area requirement leads to a similar conclusion. At 250 m, reducing the minimum area from 30 to 10 ha increased the number of eligible clusters from 41 to 87, but the eligible area increased more modestly, from 8550.1 to 9422.8 ha. Conversely, increasing the threshold to 100 ha retained only 14 clusters but still included 7085.6 ha. At 1000 m, raising the minimum area from 10 to 30 ha reduced the number of clusters from 66 to 44 while retaining 97% of the eligible area. The 30-ha criterion therefore functions as a pragmatic screening value that excludes many small components while preserving most of the area concentrated in larger aggregations; it should not be interpreted as a legal or universally efficient management standard.

4.3. Parcel Size, Ownership Complexity, and the Economics of Coordinated Management

The results also address the role of individual parcel size, which is important because parcels constitute the nodes of the network. Parcel area was retained in all cluster summaries, and the polygon-distance model preserved parcel shape and extent when constructing edges. The marked divergence between polygon and point results at short thresholds shows that parcel geometry is not a secondary issue: large or elongated parcels may have nearby boundaries even when their representative points are relatively distant. Thus, analyses based only on representative points can understate the connectivity of fragmented holdings, especially where parcel morphology is heterogeneous.

Despite the substantial increase in eligible area at larger thresholds, the typical ownership structure remained relatively simple. Median ownership complexity ranged from two to three owners per eligible cluster under the principal polygon-distance scenarios. This is a practically important result because many candidate aggregation initiatives would not initially require coordination among a very large number of actors. However, the upper tail changed considerably: the maximum number of owners increased from

14 at 100 m to 21 at 250 m, 87 at 500 m, and 178 at 1000 m. The distinction between the median cluster and a small number of very large components is therefore essential. Larger components may provide greater economies of scale, but they also entail higher negotiation, coordination, monitoring, and governance costs.

Transaction-cost economics provides a useful interpretation of this trade-off [28,39]. In fragmented ownership systems, the fixed costs of identifying neighbouring owners, organising agreements, preparing management plans, and coordinating forest operations can be disproportionate to the area of an individual holding [40–44]. The spatial clusters identified here can reduce information asymmetry and the search costs associated with locating potential partners. Nevertheless, the analysis does not demonstrate actual cost savings, harvesting efficiency, or economic viability. These outcomes depend on stand conditions, timber value, accessibility, infrastructure, and the institutional arrangements used to distribute costs and benefits [40–44]. The clusters should therefore be treated as candidate units for subsequent technical and economic assessment rather than as automatically viable associations.

4.4. From Spatial Proximity to Collective Action and Forest Policy

Spatial proximity is a necessary but insufficient condition for collective forest management. Cooperation is also shaped by trust, previous experience, owner objectives, time constraints, perceived fairness, and confidence in intermediary organisations [27,29,45,46]. The owners represented in Forest Sharing® voluntarily registered their properties and may therefore be more receptive to information exchange or collective initiatives than the general population of private forest owners. This self-selection increases the operational relevance of the platform but limits the extent to which participation behaviour can be generalised to all Italian forest owners.

The practical contribution of the cadastral network is to support the first stage of an aggregation process: identifying where cooperation could plausibly be initiated, which owners and parcels are involved, and how much forest area could be managed jointly. A second stage is then required to verify ownership, contact landholders, assess willingness to cooperate, evaluate forest resources and accessibility, and establish governance rules. In this sense, Forest Sharing® can reduce informational and organisational barriers, but it cannot replace facilitation, trust-building, legal verification, or participatory planning.

The results are directly relevant to the Italian policy context. The Consolidated Forest Law (Legislative Decree No. 34/2018) and the National Forest Strategy promote forest-owner aggregation and coordinated management [30]. Regional measures, such as the Tuscany Regional Forest Fund, also require minimum aggregated areas and support cadastral investigations, mapping, planning, and the establishment of associative structures. The proposed method can inform these preliminary activities by identifying spatially coherent candidate units and quantifying their area and ownership composition. However, clusters that cross regional boundaries may face different planning rules and administrative procedures, illustrating how spatial efficiency can be constrained by regulatory fragmentation.

Management aggregation should also be distinguished from physical land consolidation. The present approach does not modify cadastral boundaries or transfer ownership rights. It identifies opportunities for coordinated planning and operations while properties remain legally distinct. Nevertheless, the same spatial evidence could help identify areas where voluntary exchanges, boundary adjustment, or formal consolidation might be considered through separate legal and participatory procedures. Such interventions would require explicit evaluation of property values, owner consent, legal rights, and distributive effects and cannot be inferred from spatial connectivity alone.

4.5. Limitations, Validation, and Transferability

Several limitations define the appropriate interpretation of the findings. First, Euclidean distance is a geometric screening measure and does not represent travel time, extraction distance, slope, road-network accessibility, rivers, ridges, protected areas, or other physical barriers. Polygon-distance analysis improves the representation of parcel geometry but does not establish operational connectivity. Future analyses should integrate digital terrain models, forest-road networks, hydrography, administrative boundaries, and cost-distance or network-distance measures. Second, connected components are susceptible to a chaining effect: a sequence of locally close parcels may generate a component whose overall spatial extent is much larger than the edge threshold. The increase in median spatial extent and decline in median compactness at higher thresholds indicate that this effect is relevant, particularly for the largest components. Graph diameter, compactness, and spatial extent should therefore be examined alongside total area and owner counts when candidate clusters are prioritised.

Third, the cadastral identifiers supplied through the platform support parcel retrieval but do not by themselves constitute definitive legal proof of ownership in most of Italy. Unregistered inheritances, incomplete updates, and discrepancies between cadastral records and land-registry documentation may affect the transition from identified clusters to formal agreements [32]. Ownership verification remains a required implementation step.

Finally, the comparison among the three network models constitutes internal methodological validation, not external validation against functioning forest-owner associations. The point and polygon methods converge strongly at larger thresholds, and the adjacency analysis provides a conservative baseline, but these comparisons do not establish which clusters will lead to successful cooperation. External validation should examine whether existing associations, joint management plans, or funded aggregation projects correspond to the spatial opportunities identified by the model. Because the underlying data consist of voluntarily registered properties, replication in other national or regional cadastral datasets will also be necessary to assess transferability.

5. Conclusions

This study demonstrates that cadastral information and spatial network analysis can provide a transparent screening framework for identifying potential forest-owner aggregation opportunities in highly fragmented ownership contexts. The comparison among strict adjacency, minimum polygon distance, and point-on-surface distance shows that the representation of parcel geometry has a substantial influence on results, particularly at short thresholds. Strict adjacency captured only a small core of directly contiguous opportunities, while polygon-based proximity identified a much larger set of potentially coordinated management units. The point-on-surface method was consistently conservative: it introduced no additional edges relative to polygon distance but omitted many short-range connections, with agreement increasing progressively at larger thresholds.

The sensitivity analyses further show that neither distance nor minimum cluster area should be treated as a universal optimum. Increasing distance consistently expanded the forest area and number of owners included and also enlarged spatial extent and generated increasingly complex components through network merging and chaining. The 30-ha eligibility criterion removed many small components while retaining most of the area contained in larger clusters, supporting its use as a pragmatic screening threshold. Across the principal scenarios, median ownership complexity remained limited to two or three owners per cluster, suggesting that many candidate initiatives could begin with a manageable number of participants, although the largest components would require substantially more demanding governance arrangements.

The findings support the use of cadastral data and digital platforms such as Forest Sharing® to reduce the information and search costs involved in identifying neighbouring owners and spatially coherent areas for collective planning. However, the identified clusters represent potential management configurations rather than confirmed associations. Their implementation requires verification of legal ownership, assessment of accessibility and forest resources, economic appraisal, owner engagement, and the development of equitable governance mechanisms. The method is therefore most appropriately positioned as the first stage of a broader participatory and technical process supporting forest-owner associations and policy measures aimed at coordinated management.

Future research should integrate terrain, road networks, physical barriers, forest attributes, and administrative boundaries; assess transaction and harvesting costs; and validate model outputs against existing associations or collective management projects. Replication with broader cadastral datasets and non-voluntary owner samples will be important for evaluating transferability. Within these limits, the proposed approach offers a replicable basis for prioritising where institutional support and stakeholder facilitation may most effectively transform fragmented ownership patterns into coordinated forest management opportunities.

Author Contributions: Conceptualization, F.G., Y.G. and A.E.; methodology, F.G., Y.G. and A.E.; software, C.G., L.M., H.C., G.P. and R.P.D.B.; formal analysis, F.G. and G.S.; investigation, F.G., G.S., J.S., A.E. and Y.G.; resources, F.G., G.M., Y.G. and W.R.; data curation, F.G., Y.G., I.F., A.E., J.S. and T.T.; writing—original draft preparation, G.S. and F.G.; writing—review and editing, I.Z., A.E., Y.G., T.T., J.S., I.F., G.M., C.G., N.F., L.M., L.P., W.R., I.I., B.R., A.L. and C.F.; visualization, F.G.; supervision, F.G.; Project administration, F.G., N.F., G.M. and W.R.; funding acquisition, F.G., W.R. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the European Union's Horizon Europe Research and Innovation Programme under: (i) the project "SMURF—Sustainable Management Models and Value Chains for Small Forests" (Grant Agreement No. 101135516), (ii) the project "SINTETIC—Single Item Identification for Forest Production, Protection and Management" (Grant Agreement No. 101082051), (iii) For.CO.2—"*Sviluppo di un sistema di supporto decisionale per migliorare l'assorbimento del carbonio nelle foreste della Riserva della Biosfera Appennino Tosco Emiliano*" financed by Reg. UE 2021/2115, Art. 77—CSR 2023/2027 della Regione Toscana—Approvazione del Bando attuativo dell'intervento SRG01—Sostegno ai Gruppi Operativi del Partenariato Europeo per l'Innovazione in Agricoltura (PEI Agri) —Annualità 2024.

Data Availability Statement: The data presented in this study are not publicly available because they are proprietary and contain information subject to privacy and confidentiality constraints under the General Data Protection Regulation (GDPR, Regulation (EU) 2016/679). Therefore, raw data cannot be shared or distributed. However, the authors are willing to provide aggregated and processed data, upon reasonable request, for the purposes of future research and scientific collaboration, provided that such sharing complies with applicable legal and confidentiality obligations.

Acknowledgments: The authors would like to sincerely thank all forest owners participating in the Forest Sharing® platform. Their willingness to engage in innovative forms of collaboration and their commitment to exploring collective forest management solutions represent an important contribution towards addressing forest ownership fragmentation and fostering more sustainable forest management in Italy. The authors are also grateful for the patience, trust, and continued engagement of participating landowners throughout the aggregation process, which often requires considerable time, effort, and coordination before tangible results can be achieved. The authors further acknowledge the mayors, local administrators, and active stakeholders of the Garfagnana Green Community for their commitment to promoting sustainable rural and forest development.

Their efforts to reverse long-term trends of land abandonment and forest fragmentation in one of Italy's most heavily forested area provide an important foundation for the development of innovative and collaborative forest management approaches.

Conflicts of Interest: Authors Ilaria Zorzi, Alessandro Errico, Yamuna Giambastiani, Jessica Scriva, Guido Milazzo, Niccolò Fani, Lorenzo Massai, Cristiano Guadagnino, Tommaso Tognetti, Giacomo Pinzani, Hervè Corti and Reicht Prince Destin Batomene were employed by the company Bluebiloba Startup Innovativa s.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. D'amico, G.; Vangi, E.; Francini, S.; Giannetti, F.; Nicolaci, A.; Travaglini, D.; Massai, L.; Giambastiani, Y.; Terranova, C.; Chirici, G. Are We Ready for a National Forest Information System? State of the Art of Forest Maps and Airborne Laser Scanning Data Availability in Italy. *IForest* **2021**, *14*, 144–154. [CrossRef]
2. Taylor, C.; Id, D.B.L. The Use of Spatial Data and Satellite Information in Legal Compliance and Planning in Forest Management. *PLoS ONE* **2022**, *17*, e0267959. [CrossRef] [PubMed]
3. Baskent, E.Z.; Guilherme, J.; Jan, B. An Updated Review of Spatial Forest Planning: Approaches, Techniques, Challenges, and Future Directions. *Curr. For. Rep.* **2024**, *10*, 299–321. [CrossRef]
4. Meddens, A.J.H.; Steen-adams, M.M.; Hudak, A.T.; Mauro, F.; Byassee, P.M. Specifying Geospatial Data Product Characteristics for Forest and Fuel Management Applications. *Environ. Res. Lett.* **2022**, *17*, 045025. [CrossRef]
5. Cadez, L.; Giannetti, F.; de Luca, A.; Tomao, A.; Chirici, G.; Alberti, G. A WebGIS Tool to Support Forest Management at Regional and Local Scale. *IForest* **2023**, *16*, 361–367. [CrossRef]
6. Iryna, K.; Ivan, S.; Arkadii, S.; Sisenis, L.; Luksa, J.; Sciences, L.; Jelgava, T. USE OF LAND MANAGEMENT AND CADASTRE DATA FOR. *J. Balt. Surv.* **2024**, *20*, 33–41. [CrossRef]
7. Kumar, K.E.M.; Singh, S.; Attri, P.; Kumar, R.; Kumar, A.; Hooda, R.S. Gis Based Cadastral Level Forest Information System Using World View-Ii Data in Bir Hisar (Haryana). In *Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-8, 2014 ISPRS Technical Commission VIII Symposium, Hyderabad, India, 9–12 December 2014*; ISPRS: Saint-Mandé, France, 2014; Volume XL, pp. 9–12.
8. Cienciała, A.; Sobolewska-mikulska, K.; Sobura, S. Land Use Policy Credibility of the Cadastral Data on Land Use and the Methodology for Their Verification and Update. *Land Use Policy* **2021**, *102*, 105204. [CrossRef]
9. Živojinović, I.; Weiss, G.; Lidestav, G.; Feliciano, D.; Hujala, T.; Dobšinská, Z.; Lawrence, A.; Nybakk, E.; Quiroga, S.; Schraml, U. (Eds.) *Forest Land Ownership Change in Europe: COST Action FP1201 FACESMAP Country Reports Joint Volume*; European Forest Institute Central-East and South-East European Regional Office: Vienna, Austria, 2015.
10. Giannetti, F.; Laschi, A.; Zorzi, I.; Foderi, C.; Cenni, E.; Guadagnino, C.; Pinzani, G.; Ermini, F.; Bottalico, F.; Milazzo, G.; et al. Forest Sharing ® as an Innovative Facility for Sustainable Forest Management of Fragmented Forest Properties: First Results of Its Implementation. *Land* **2023**, *12*, 521. [CrossRef]
11. Kumer, P.; Slavic, I.P. Heterogeneous Small-Scale Forest Ownership: Complexity of Management and Conflicts of Interest. *Belgeo* **2016**, *2016*, 21. [CrossRef]
12. Niroula, G.S.; Thapa, G.B. Impacts and Causes of Land Fragmentation, and Lessons Learned from Land Consolidation in South Asia. *Land Use Policy* **2005**, *22*, 358–372. [CrossRef]
13. Weiss, G.; Gudurić, I.; Wolfslehner, B. *Review of Forest Owner Organisations in Selected Eastern European Countries*; Forestry Policy and Institutions Working Paper 30; FAO: Rome, Italy, 2012.
14. Weiss, G.; Lawrence, A.; Hujala, T.; Lidestav, G.; Nichiforel, L.; Nybakk, E.; Quiroga, S.; Sarvašová, Z.; Suarez, C.; Živojinović, I. Forest Policy and Economics Forest Ownership Changes in Europe: State of Knowledge and Conceptual. *For. Policy Econ.* **2019**, *99*, 9–20. [CrossRef]
15. Schmithüsen, F.; Hirsch, F. *Geneva Timber and Forest Study Paper 26- Private Forest Ownership in Europe*; United Nations: Geneva, Switzerland, 2010.
16. Loreggian, F.; Pettenella, D.; Secco, L.; Andrighetto, N.; Bottaros, G. Associative Organisational Models in Italian Forests for Addressing Land Abandonment. *Acta Silvae Ligni* **2024**, *134*, 27–38. [CrossRef]
17. Loreggian, F.; Andrighetto, N.; Masiero, M.; Storti, G. *Analisi Dello Stato Dell'arte Dell'associazionismo Forestale in Italia*; Università degli Studi di Padova: Padova, Italy, 2024.
18. Ficko, A.; Lidestav, G.; Ní Dhubháin, Á.; Karppinen, H.; Zivojinovic, I.; Westin, K. European Private Forest Owner Typologies: A Review of Methods and Use. *For. Policy Econ.* **2019**, *99*, 21–31. [CrossRef]

19. Mantero, G.; Morresi, D.; Marzano, R.; Motta, R.; Mladenoff, D.J.; Garbarino, M. The Influence of Land Abandonment on Forest Disturbance Regimes: A Global Review. *Landsc. Ecol.* **2020**, *35*, 2723–2744. [CrossRef]
20. Alberti, G.; Danelon, M.; De Simon, G.; Florean, M.; Francescatto, N.; Muzzolini, V.; Pergher, G.; Piussi, P.; Sbrizzi, N.; Chiabà, D.; et al. *Linee Guida per La Gestione Selvicolturale Di Boschi Misti Di Acero e Frassino Di Origine Secondaria: Aspetti Economici, Selvicolturali e Tecnologici*; Regione Autonoma Friuli Venezia Giulia—Direzione Centrale Risorse Agricole, Forestali e Ittiche: Udine, Italy, 2016.
21. Cadez, L.; Tomao, A.; Giannetti, F.; Chirici, G.; Alberti, G. Mapping Forest Growing Stock and Its Current Annual Increment Using Random Forest and Remote Sensing Data in Northeast Italy. *Forests* **2024**, *15*, 1356. [CrossRef]
22. Agnoletti, M.; Piras, F.; Venturi, M.; Santoro, A. Cultural Values and Forest Dynamics: The Italian Forests in the Last 150 Years. *For. Ecol. Manag.* **2022**, *503*, 119655. [CrossRef]
23. Weiss, G.; Emery, M.; Miina, J.; Kurttila, M.; Corradini, G.; Huber, P.; Vacik, H. Value Creation and Innovation with Non-Wood Forest Products in a Family Forestry Context. In *Services in Family Forestry*; Springer: Berlin/Heidelberg, Germany, 2019. [CrossRef]
24. Secco, L.; Paletto, A.; Romano, R.; Masiero, M.; Pettenella, D.; Carbone, F.; De Meo, I. Orchestrating Forest Policy in Italy: Mission Impossible ? *Forests* **2018**, *9*, 468. [CrossRef]
25. Pawlewicz, A.; Pawlewicz, K. The Risk of Agricultural Land Abandonment as a Socioeconomic Challenge for the Development of Agriculture in the European Union. *Sustainability* **2023**, *15*, 3233. [CrossRef]
26. Stern, T.; Schwarzbauer, P.; Huber, W.; Weiss, G.; Aggestam, F.; Wippel, B.; Petereit, A.; Navarro, P.; Rodriguez, J.; Boström, C.; et al. *Prospects for the Market Supply of Wood and Other Forest Products from Areas with Fragmented Forest-Ownership Structures*; European Commission: Brussels, Belgium, 2010.
27. Górriz-Mifsud, E.; Donazar, L.O.; Eseverri, E.M.; Govigli, V.M. The Challenges of Coordinating Forest Owners for Joint Management ☆. *For. Policy Econ.* **2019**, *99*, 100–109. [CrossRef]
28. Ji, Y.; Wan, S. The Impact of the Governance Fragmentation of Forestry Communities on the Economic Performance of State-Owned Forest Enterprises in Northeast China: An Empirical Analysis Based on the Transaction Cost Perspective. *Forests* **2024**, *15*, 1035. [CrossRef]
29. Põllumäe, P.; Lilleleht, A.; Korjus, H. Forest Policy and Economics Institutional Barriers in Forest Owners' Cooperation: The Case of Estonia. *For. Policy Econ.* **2016**, *65*, 9–16. [CrossRef]
30. Ministero delle politiche Agricole; Ministero della cultura; Ministero della transizione ecologica; Ministero dello Sviluppo Economico. *Strategia Forestale Nazionale*; Gazzetta Ufficiale della Repubblica Italiana: Rome, Italy, 2021; pp. 1–8.
31. Belém, M.D.; Freitas, C.; Teixeira, M.D.; Antunes, C.R.; Ribeiro, H.C.; Partidário, R. Beyond Cadaster: Landowners and Land Fragmentation—Insights from a Case Study. *Geographies* **2026**, *6*, 57. [CrossRef]
32. Ruggeri, L.; Winkler, S. *Family Property and Succession in EU Member States National Reports on the Collected Data*; University of Rijeka: Rijeka, Croatia, 2020; ISBN 9789538034251.
33. Iovino, G. *Recupero Dei Terreni Incolti e Il Ripopolamento Delle Aree Rurali*; Federazione ASITA: Milan, Italy, 2018; pp. 595–608.
34. Marto, M.; Reynolds, K.M.; Borges, J.G.; Bushenkov, V.A.; Marques, S.; Marques, M.; Barreiro, S.; Botequim, B.; Tomé, M. Web-Based Forest Resources Management Decision Support System. *Forests* **2019**, *10*, 1079. [CrossRef]
35. Sacchelli, S. A Decision Support System for Trade-off Analysis and Dynamic Evaluation of Forest Ecosystem Services. *IForest* **2018**, *11*, 171–180. [CrossRef]
36. Uşak, B.; Çağdaş, V.; Kara, A. Current Cadastral Trends—A Literature Review of the Last Decade. *Land* **2024**, *13*, 2100. [CrossRef]
37. Urban, D.; Keitt, T. Landscape Connectivity: A Graph-Theoretical Perspective. *Ecology* **2001**, *82*, 1205–1218. [CrossRef]
38. Juricev-martincev, F.; Giuffrida, B.; Thompson, H. A Novel Hierarchical Aggregation Algorithm for Optimal Repartitioning of Statistical Regions. *Int. J. Geogr. Inf. Sci.* **2023**, *37*, 1640–1666. [CrossRef]
39. Zhang, Y. Economics of Transaction Costs Saving Forestry. *Ecol. Econ.* **2001**, *36*, 197–204. [CrossRef]
40. Holm, S.; Frutig, F.; Lemm, R.; Thees, O.; Schweier, J. HeProMo: A Decision Support Tool to Estimate Wood Harvesting Productivities. *PLoS ONE* **2020**, *15*, e0244289. [CrossRef] [PubMed]
41. Borz, S.A.; Mari, A.; Kaakkurivaara, N. Performance of Skidding Operations in Low-Access and Low-Intensity Timber Removals: A Simulation of Productivity and Fuel Consumption in Mature Forests. *Forests* **2023**, *14*, 265. [CrossRef]
42. Simões, D.; Cavalcante, F.S.; Lima, A.; Rocha, Q.S.; Pereira, G.; Miyajima, R.H. Optimal Forest Road Density as Decision-Making Factor in Wood Extraction. *Forests* **2022**, *13*, 1703. [CrossRef]
43. Werder, M.; Gallus, L.; Id, B.; Id, J.S.; Id, O.T. A Comprehensive Analysis of Time Investment in Skid Trail Planning for Forest Access. *PLoS ONE* **2025**, *20*, e0317963. [CrossRef] [PubMed]
44. Cerveny, L.; Mclain, R.; Banis, D. The Use of Socio-Spatial Data for Sustainable Roads Planning: A National Forest Case Study The Use of Socio-Spatial Data for Sustainable Roads Planning: A National Forest Case Study. *J. Environ. Plan. Manag.* **2022**, *65*, 2190–2213. [CrossRef]

45. Carter, J.; Gronow, J. *Recent Experience in Collaborative Forest Management A Review Paper*; Center for International Forestry Research: Bogor, Indonesia, 2005; ISBN 0854-9818.
46. Sarvašová, Z.; Zivojinovic, I.; Weiss, G.; Dobšinská, Z.; Drăgoi, M.; Gál, J.; Jarský, V.; Mizaraite, D.; Põllumäe, P.; Šálka, J.; et al. Forest Owners Associations in the Central and Eastern European Region. *Small-Scale For.* **2015**, *14*, 217–232. [CrossRef]