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Geospatial Analysis of Forest Plantation Extent Stand Structure and Condition in Kosovo

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Abstract

This study presents a geospatial and statistical assessment of forest plantations in Kosovo based on GIS digitization, orthophoto and satellite image interpretation, field inventory, and historical forest management plans. The objective was to evaluate plantation extent, structure, productivity, species composition, and condition at the national scale. The results showed that forest plantations occupy a substantial but spatially uneven area, with the largest concentrations located in Mitrovica, Gjilan, and Prishtina. Marked regional variation was also observed in plantation productivity, and the highest mean growing stock per hectare was recorded in Prishtina and Peja. Species composition was strongly dominated by conifers, particularly Pinus nigra and Pinus sylvestris, whereas broadleaved species represented only a minor component of the plantation resource. Plantation condition emerged as a major constraint, with a considerable share of conifer growing stock affected by damage and fire identified as the principal disturbance factor. The assessment also identified extensive land suitable for both reforestation and afforestation, indicating substantial potential for future forest establishment. Overall, the findings show that forest plantations in Kosovo constitute a significant but structurally simplified and spatially uneven resource, highlighting the need for ecologically differentiated rehabilitation, improved protection measures, and greater species diversification in future plantation planning.

1. Introduction

Forest plantations are an important component of contemporary forest management because they contribute to land restoration, erosion control, timber production, and climate change mitigation (Brockerhoff et al. 2008; Carnus et al. 2006; Paquette and Messier 2010; Payn et al. 2015). In regions where natural forests have been degraded by overexploitation, fire, grazing, or land use change, plantations are often established to accelerate vegetation recovery, stabilize vulnerable landscapes, and restore ecosystem functions (Chazdon 2008; Evans 2009; Lamb 2011; Sedjo 1999). Their role is therefore both ecological and economic, particularly in territories where pressure on forest resources remains high and where degraded land requires active intervention.

At the global scale, planted forests have expanded substantially in recent decades and now represent an increasingly important share of the forest resource base (FAO 2020; Payn et al. 2015). At the same time, the ecological performance of plantation systems remains a subject of considerable discussion. Compared with natural forests, plantations often show lower species diversity, simpler stand structure, and greater dependence on silvicultural intervention (Brockerhoff et al. 2008; Carnus et al. 2006; Hartley 2002). Where plantations are dominated by a narrow range of species, their resistance and resilience may be reduced, particularly under increasing pressure from drought, fire, pests, and disease (Allen et al. 2010; Felton et al. 2010; Jactel and Brockerhoff 2007; Seidl et al. 2014; Turner 2010). Recent literature has emphasized that plantation sustainability depends not only on area expansion, but also on structural diversity, ecological suitability, and disturbance resilience (Bastin et al. 2019; Chazdon and Brancalion 2019; Griscom et al. 2017; Pretzsch et al. 2013).

In this context, accurate assessment of plantation extent, structure, productivity, and condition is essential for evidence-based forest planning. National forest inventories and geospatial methods are now widely used to support large area forest assessment and monitoring (Chirici et al. 2012; Corona 2016; McRoberts and Tomppo 2007; Tomppo et al. 2010). The integration of GIS analysis, orthophoto interpretation, satellite imagery, and field inventory has substantially improved the capacity to delineate forest resources, quantify growing stock, and evaluate structural attributes across broad spatial scales (Fassnacht et al. 2016; Hansen et al. 2013; Köhl et al. 2006; White et al. 2016; Wulder et al. 2008). When combined with historical forest management plans, these approaches allow both reconstruction of plantation development and assessment of current plantation status.

In Kosovo, forest plantations have been established over several decades under different management objectives, including erosion control, rehabilitation of degraded sites, protective forest functions, and wood production. However, despite their importance, information on their actual extent, growing stock, species composition, productivity, and condition has remained fragmented among historical management plans, cartographic records, and partial inventory sources. As a result, a consistent national scale evaluation of plantation resources has been lacking.

A comprehensive assessment of forest plantations in Kosovo is therefore necessary not only to quantify the plantation estate, but also to evaluate its functional condition and future management potential. Such an assessment is particularly relevant in view of current interest in afforestation, reforestation, forest landscape restoration, and climate change adaptation. A stronger empirical basis is required to determine where plantations are concentrated, how productive they are, which species dominate, how much damage is present, and where suitable land exists for future establishment.

The present study addresses this need through an integrated geospatial and statistical assessment of forest plantations in Kosovo. The specific objectives were to quantify the spatial extent of forest plantations, assess their structure and productivity, analyze their species composition, evaluate plantation condition and dominant damage factors, and identify areas suitable for afforestation and reforestation. By combining geospatial interpretation, field inventory, and historical forest management documentation, the study provides a national scale evidence base for future plantation rehabilitation, diversification, and planning.

2. Materials and Methods

2.1. Study Area and Analytical Framework

The study was conducted in Kosovo and focused on the national estate of forest plantations. The analytical framework was designed to produce a spatially explicit and statistically consistent assessment of plantation extent, structure, productivity, species composition, and condition. This approach was necessary because existing information on forest plantations was dispersed across historical management plans, cartographic records, image-based interpretation, and field observations

rather than contained in a single harmonized database. The study therefore adopted an integrated design in which geospatial delineation, historical reconstruction, field inventory, and statistical synthesis were combined into a unified assessment procedure.

Kosovo exhibits pronounced variation in relief, climate, and site conditions, which strongly influence plantation establishment, stand development, and disturbance exposure. This heterogeneity is particularly important for evaluating the suitability of plantation species, the spatial concentration of growing stock, and the distribution of damage. For that reason, the assessment was structured to capture both national totals and regional differences in plantation characteristics.

2.2. Data Sources

The analysis was based on four principal sources of information: historical forest management plans, thematic and non-thematic cartographic materials, orthophotos and high-resolution satellite imagery, and field inventory data. Historical management plans and associated maps were used to reconstruct plantation distribution and to identify previously recorded plantation units. Orthophotos and satellite imagery were used to delineate current plantation boundaries and to evaluate their spatial expression in the landscape. Field inventory data provided the quantitative basis for the estimation of growing stock, annual increment, diameter structure, species composition, and damage status.

This combination of documentary, geospatial, and inventory evidence is consistent with contemporary approaches to large-area forest assessment, in which national forest inventory principles provide statistical robustness, while remotely sensed data improve spatial completeness, spatial consistency, and boundary interpretation (Chirici et al. 2012; Corona 2016; McRoberts and Tomppo 2007; Tomppo et al. 2010; White et al. 2016; Wulder et al. 2008).

2.3. Geospatial Delineation of Forest Plantations

Plantation areas were delineated in a GIS environment through the combined interpretation of orthophotos, satellite imagery, and georeferenced historical maps. Historical cartographic materials were first scanned and georeferenced, after which plantation surfaces were digitized and compared with current image evidence. Plantation polygons were accepted with greater confidence where historical plan records, image interpretation, and field observations converged. Where inconsistencies occurred, final delineation relied on the integrated evaluation of all available sources.

Visual interpretation was based on spatial indicators commonly associated with plantation stands, including relatively regular stand geometry, homogeneous crown texture, distinct stand boundaries, and contrast with adjacent forest or non forest land. This procedure enabled identification of both current plantation extent and plantation areas recorded historically but still recognizable in the contemporary landscape. Such integration of image interpretation and GIS digitization is consistent with current practice in forest resource mapping, where spatial data are used to improve wall to wall representation of forest cover and stand pattern (Fassnacht et al. 2016; Hansen et al. 2013; Köhl et al. 2006; White et al. 2016; Wulder et al. 2008).

In addition to the delineation of existing plantations, land suitable for future forest establishment was identified and separated into areas suitable for afforestation and reforestation. Reforestation was considered in relation to degraded or insufficiently stocked forest land, whereas afforestation referred to non-forest land interpreted as suitable for tree establishment. Because the uploaded material does not fully specify the complete suitability rule set, the final submitted manuscript should state the operative criteria explicitly, including any land use exclusions, slope thresholds, ownership or legal constraints, and ecological suitability filters.

2.4. Field Inventory and Estimation of Stand Variables

The field inventory followed the general methodological principles of the National Forest Inventory of Kosovo, but used a denser sampling design for plantation assessment. A grid spacing of 1 × 1 km was applied in order to increase the probability of capturing plantation stands and to improve the representativeness of plantation related observations at the national scale. This denser grid was especially important because plantation stands are spatially clustered and may be insufficiently represented in coarser national sampling schemes.

Within sampled plantation stands, measurements and observations were used to characterize dominant species, diameter structure, growing stock, annual increment, and visible damage. These variables formed the basis for the statistical assessment of plantation structure and condition. Growing stock was aggregated at municipal, regional, and national levels, and mean growing stock per hectare was derived by relating total growing stock to plantation area within each territorial unit. Annual increment was expressed in cubic meters per year. To provide an integrated indicator of productive performance, the increment to stock ratio was calculated as:

$$ISR = \frac{I}{GS} * 100$$

where ISR is the increment to stock ratio, I is annual increment, and GS is total growing stock. Using the reported national values, the ratio was derived from an annual increment of 46,064.3 m^3 $year^{-1}$ and a growing stock of 966,326 m^3, resulting in a value of 4.8%.

Species composition was evaluated on the basis of growing stock and summarized by major species and species groups. Conifers and broadleaves were distinguished in order to assess the degree of compositional concentration within the plantation estate. Plantation condition was assessed through the analysis of damaged growing stock recorded during the inventory. Damage was classified into four principal categories: fire, disease, weather, and other causes. The damaged conifer share was calculated as:

$$DCS = \frac{DGV}{TCGS} * 100$$

where DCS is the damaged conifer share, DGV is damaged conifer growing stock, and TCGS is total conifer growing stock. Based on the reported data, damaged conifer growing stock amounted to 285,972 m^3 out of a total conifer growing stock of 846,288 m^3, corresponding to 33.8%.

2.5. Statistical Processing and Methodological Considerations

All spatial and field inventory information was compiled into a unified analytical database containing plantation area, growing stock, annual increment, diameter class structure, species composition, and damage variables. Descriptive statistics were generated for municipalities, regions, and the national total. Results were then presented through summary tables, thematic figures, and comparative graphs in order to evaluate spatial concentration, productive performance, compositional dominance, and damage intensity.

Several methodological limitations should be acknowledged. Historical management plans and older cartographic materials vary in scale, temporal relevance, and positional precision. Minor inconsistencies also occur between some reported regional totals and summed category values, indicating probable rounding or aggregation effects in the source material. In addition, the exact operational rules used to classify suitability for afforestation and reforestation are not fully described in the available documents and should therefore be clarified in the final version of the manuscript. Nevertheless, the integration of historical documentation, GIS-based delineation, image interpretation, and field inventory provides a more robust and spatially consistent basis for plantation assessment than reliance on any single data source in isolation (Chirici et al. 2012; Corona 2016; McRoberts and Tomppo 2007; Tomppo et al. 2010; White et al. 2016; Wulder et al. 2008).

3. Results

3.1. Potential for Afforestation and Reforestation

As shown in Table 1 and Fig. 1, the analysis identified a large spatial reserve for future forest establishment. The total area suitable for reforestation was estimated at 8068.36 ha, whereas the area suitable for afforestation reached 87,035.99 ha, indicating that the potential for expanding forest cover substantially exceeds the area requiring restorative intervention within already forest related land categories. The regional distribution was highly uneven. The greatest afforestation potential was recorded in Mitrovica (26,133.55 ha), followed by Prishtina (15,712.36 ha), Prizren (14,711.42 ha), and Gjilan (13,676.33 ha), while reforestation potential was highest in Prizren (3530.83 ha).

Table 1
Potential areas suitable for afforestation and reforestation by region.

Region	Reforestation (ha)	Afforestation (ha)
Ferizaj	536.70	6,217.49
Gjilan	765.95	13,676.33
Mitrovica	1,200.02	26,133.55
Peja	1474.15	10,584.85
Prishtina	560.71	15,712.36
Prizren	3,530.83	14,711.42
Total	8,068.36	87,035.99

This pattern is significant because it indicates that future plantation policy in Kosovo cannot be framed solely in terms of restoring degraded forest land. Rather, the spatial evidence suggests a broader land use opportunity in which afforestation may become a major instrument of landscape rehabilitation and climate-oriented forest expansion. Similar conclusions have been reported in broader afforestation and restoration literature, where the strategic value of identifying suitable non forest land is emphasized as a prerequisite for efficient and ecologically sound forest expansion (Bastin et al. 2019; Chazdon 2008; Chazdon and Brancalion 2019; Griscom et al. 2017; Lamb 2011). In this context, the dominance of afforestation potential over reforestation potential implies that future interventions could have a strong territorial planning dimension, particularly in regions where large contiguous areas are available for new establishment (Chazdon and Brancalion 2019; Griscom et al. 2017; Lamb 2011).

From a management perspective, the concentration of potential land in a limited number of regions also suggests that future investment priorities will not be spatially neutral. Regions such as Mitrovica and Prishtina are likely to become central to future plantation expansion strategies, whereas other regions may require more targeted restorative action. As illustrated in Fig. 1, the imbalance between afforestation and reforestation is evident across all regions, confirming that the future plantation agenda is likely to be driven more by expansion potential than by replacement alone. This territorial unevenness is consistent with broader findings showing that afforestation opportunities are often spatially concentrated rather than uniformly distributed across landscapes (Chazdon and Brancalion 2019; Griscom et al. 2017; Lamb 2011).

3.2. Spatial Extent and Territorial Concentration of Forest Plantations

The total area of forest plantations was estimated at 7803 ha. At the regional level, plantation area was concentrated predominantly in Mitrovica (1763 ha), Gjilan (1639 ha), Prishtina (1342 ha), and Peja (1294

ha), whereas Prizren (979 ha) and Ferizaj (786 ha) contributed comparatively smaller shares to the plantation estate (Table 2), indicating a marked spatial concentration of plantation resources across the regional structure of the country.

Table 2
Plantation area by region

Region	Plantation area (ha)
Ferizaj	786
Gjilan	1,639
Mitrovica	1,763
Peja	1,294
Prishtina	1,342
Prizren	979
Total	7,803

Table 2 refines the regional analysis by showing that plantation concentration is not only regional but also localized within a relatively small number of municipalities. In analytical terms, this means that the plantation estate is spatially clustered at more than one level of aggregation. Such clustering is relevant for planning because it identifies where plantation management is likely to have the greatest territorial impact. (Allen et al. 2010; Felton et al. 2010; Jactel and Brockerhoff 2007; Paquette and Messier 2010; Pretzsch et al. 2013; Seidl et al. 2014).

Figure 2 confirms that plantation resources are spatially concentrated at the regional level. This result strengthens the interpretation that the plantation estate in Kosovo is territorially clustered rather than evenly distributed, which in turn suggests that future monitoring, rehabilitation, and protection measures can be geographically prioritized.

3.3. Volume, Stand Structure, and Annual Increment

The total growing stock of forest plantations was estimated at 966,326 m^3, whereas total annual increment was estimated at 46,064.3 $m^3\ year^{-1}$. At the regional level, the highest growing stock was recorded in Gjilan (214,709 m^3), followed by Prishtina (198,616 m^3) and Peja (190,218 m^3). However, regional differences in plantation productivity were not proportional to plantation area. Mean growing stock per hectare was highest in Prishtina (148 $m^3\ ha^{-1}$) and Peja (147 $m^3\ ha^{-1}$), despite these regions not having the largest plantation extent. By contrast, Mitrovica, which had the largest plantation area, recorded a substantially lower mean value of 86 $m^3\ ha^{-1}$ (Table 3).

Table 3
Main plantation statistics by region.

Region	Area (ha)	Volume (m^3)	Average volume (m^3/ha)	Annual increment (m^3/year)
Ferizaj	786	80,958	103	5,344.8
Mitrovica	1,763	151,618	86	8,286.1
Peja	1,294	190,218	147	8,928.6
Prizren	979	130,207	133	4,992.9
Prishtina	1,342	198,616	148	8,186.2
Gjilan	1,639	214,709	131	10,325.7

As shown in Fig. 3, Gjilan recorded the highest total growing stock and annual increment, whereas the relationship between standing stock and current growth differed among the other regions. This result indicates that plantation extent alone does not determine productive performance and that regional productivity reflects the combined influence of stocking intensity, stand development, and site conditions.

A different perspective emerges when growing stock is expressed per unit area. As illustrated in Fig. 4, Prishtina and Peja exhibited the highest mean growing stock per hectare, despite not having the largest plantation area. This confirms that plantation area is not a reliable proxy for productivity. Regions with extensive plantation surfaces, such as Mitrovica, may still support lower average stocking than regions with smaller but denser stands.

Further evidence of stand condition is provided by the diameter structure of plantation growing stock. The distribution by diameter class is summarized in Table 4. Plantation growing stock was concentrated predominantly in the 7–30 cm and 30–50 cm classes, whereas the 50–70 cm and 70–90 cm classes contributed only a minor proportion of total stock.

Table 4
Volume distribution by diameter class and region

Region	7–30 cm	30–50 cm	50–70 cm	70–90 cm	Volume (m³)	Annual increment
Ferizaj	50,640	29,954	324	40	80,958	5,344.8
Mitrovica	114,493	34,266	2,832	0	151,591	8,286.1
Peja	142,665	43,750	2,663	1,141	190,219	8,928.6
Prizren	92,447	36,458	1,302	0	130,207	4,992.9
Prishtina	123,106	70,043	4,750	717	198,616	8,186.2
Gjilan	181,467	30,721	2,521	0	214,709	10,325.7

This structural pattern is shown in Fig. 5, which indicates that smaller and medium diameter classes dominate across all regions. The diameter profile therefore suggests that much of the plantation estate remains structurally immature and is dominated by young to middle aged stands rather than mature stands with large diameter timber.

Taken together, Table 3, Table 4, and Figs. 3–5 demonstrate that the spatial distribution of plantation area does not correspond directly to the spatial distribution of plantation performance. Regions with extensive plantation area do not necessarily exhibit the highest stocking intensity, while the dominance of lower diameter classes indicates that a substantial proportion of the plantation estate remains in relatively early stages of stand development and has not yet reached structural maturity.

3.4. Species Composition of Forest Plantations

The plantation resource was strongly dominated by conifers. As shown in Table 5, total conifer growing stock was 846,288 m³, representing 88% of total plantation growing stock, whereas native broadleaves contributed 112,833 m³, equivalent to 12%. The dominant species was Pinus nigra, with 516,236 m³ (61%), followed by Pinus sylvestris, with 186,184 m³ (22%). Together, these two species accounted for approximately 83% of total plantation growing stock. Other conifers included Pseudotsuga menziesii (8%), Picea abies (7%), and a residual group of other conifers (2%).

Table 5
Species participation in total plantation volume.

Species group	Volume (m³)	Share (%)
Pinus nigra	516,236	61
Pinus sylvestris	186,184	22
Pseudotsuga menziesii	67,703	8
Picea abies	59,240	7
Other conifers	16,925	2
Native broadleaves	112,833	12

This compositional structure indicates a pronounced degree of biological simplification. The overwhelming dominance of a small number of conifer species suggests that plantation establishment historically relied on a narrow silvicultural model, likely oriented toward rapid establishment and protective cover. The ecological implications of such a pattern are substantial because strong species concentration may reduce resilience and increase sensitivity to fire, pests, and disease (Brockerhoff et al. 2008; Carnus et al. 2006; Allen et al. 2010; Felton et al. 2010; Jactel and Brockerhoff 2007; Seidl et al. 2014; Forrester 2014; Forrester and Bauhus 2016; Liang et al. 2016; Paquette and Messier 2011; Pretzsch and Schütze 2009).

The same pattern is illustrated in Fig. 7, which shows the dominant contribution of Pinus nigra and Pinus sylvestris to plantation growing stock. A broader compositional contrast between conifers and broadleaves is emphasized in Fig. 8, together confirming that the plantation estate is organized around a narrow conifer base.

3.5. Health Status and Plantation Damage

The field inventory found substantial damage within plantation stands. Total conifer volume amounted to 846,288 m³, of which 285,972 m³ was classified as damaged (see Table 6). This corresponds to approximately 33.8% of total conifer volume. Damage causes include fire (151,664 m³), diseases (92,895 m³), weather (32,740 m³), and other causes (8,673 m³). By species, the highest damaged volume was recorded in Pinus nigra (184,296 m³), followed by Pinus sylvestris (61,067 m³), Pseudotsuga duglasii (25,766 m³), and Picea abies (7,938 m³).

Table 6
Plantation health status by tree species and damage type

Species	Volume	Fire	Diseases	Weather	Other	Total damaged
Pinus nigra	516,236	94,988	61,948	24,779	2,581	184,296
Pinus sylvestris	186,184	38,354	18,990	3,351	372	61,067
Pseudotsuga duglasii	67,703	14,421	5,754	243	5,348	25,766
Picea abies	59,240	2,073	3,732	2,133	0	7,938
Other conifers	16,925	1,828	2,471	2,234	372	6,905
Total conifers	846,288	151,664	92,895	32,740	8,673	285,972

The magnitude of damaged growing stock indicates that plantation impairment is not marginal but structural. Fire was the dominant damage category, which is ecologically significant because it suggests that current plantation composition and stand continuity may contribute to elevated disturbance exposure. Fire is widely recognized as a major risk factor in conifer dominated plantation landscapes, particularly where structural homogeneity and biomass continuity facilitate disturbance spread (Bowman et al. 2009; Reyer et al. 2017; Seidl et al. 2014; Stephens et al. 2013; Turner 2010).

This damage structure is illustrated in Fig. 8, which shows that fire is the dominant damage factor across the major conifer species. Together with the damaged share reported in the table, this confirms that plantation condition must be treated as a central component of plantation assessment rather than as a secondary issue.

3.6 Cross-source comparison of plantation statistics

The source material also includes comparative statistics derived from Inventory 2014, old management plans, and new plans. As shown in Table 7, these comparisons indicate that reported plantation area and growing stock depend strongly on the source used. At the national level, the inventory-based estimate was substantially higher than the value derived from old plans for both area and growing stock, whereas the values from new plans occupied an intermediate position. Comparable discrepancies were also observed for Ferizaj, Gjilan, and Prishtina.

Table 7
Cross-source comparison of plantation area and volume

Territory	Metric	Inventory 2014	Old Plans / New Plans pair
Kosovo	Area (ha)	7,803	Old Plans 3,743; New Plans 3,338
Kosovo	Volume (100 m³)	9,663	Old Plans 1,424; New Plans 4,636
Ferizaj	Area (ha)	786	Old Plans 784; New Plans 668
Ferizaj	Volume (100 m³)	809	Old Plans 52; New Plans 781
Gjilan	Area (ha)	1,639	Old Plans 1,087; New Plans 970
Gjilan	Volume (100 m³)	2,147	Old Plans 876; New Plans 1,424
Prishtina	Area (ha)	1,342	Old Plans 318; New Plans 626
Prishtina	Volume (100 m³)	1,986	Old Plans 90; New Plans 993

This comparison is important because it demonstrates that plantation statistics are strongly influenced by source provenance and that administrative records cannot be treated as interchangeable with inventory-based evidence. The comparison therefore supports the use of integrated GIS and field-based synthesis rather than reliance on a single legacy source.

The same conclusion is reinforced by Fig. 9 which shows consistent differences among the three data sources at both national and regional levels.

4. Discussion

The results of this study provide the first integrated geospatial and statistical assessment of forest plantations in Kosovo, revealing a plantation estate that is spatially concentrated, structurally simplified, and partially affected by disturbance. The combination of GIS analysis, field inventory, and historical forest management documentation made it possible to evaluate plantation extent, structure, productivity, and condition at a national scale.

One of the most prominent findings concerns the spatial distribution of plantation resources. Plantation area is strongly concentrated in a limited number of regions, particularly Mitrovica and Gjilan. Similar spatial concentration patterns have been reported in other plantation landscapes where afforestation programs historically followed land availability, erosion control priorities, or restoration initiatives rather than evenly distributed planning frameworks (Allen et al. 2010; Felton et al. 2010; Jactel and Brockerhoff 2007; Paquette and Messier 2010; Pretzsch et al. 2013; Seidl et al. 2014). While such clustering may improve operational efficiency in plantation management, it may also increase spatial exposure to disturbance where large plantation blocks share similar species composition and stand structure.

The analysis also revealed substantial potential for future forest expansion. The area suitable for afforestation was considerably larger than the area suitable for reforestation, indicating that the future development of forest plantations in Kosovo will likely depend more on the establishment of new forests on currently non forest land than on the restoration of degraded forest stands. This pattern is consistent with broader restoration research, which highlights the importance of identifying suitable land for afforestation as a key component of landscape restoration strategies and climate mitigation policies (Bastin et al. 2019; Chazdon 2008; Chazdon and Brancalion 2019; Griscom et al. 2017; Lamb 2011).

The structural characteristics of the plantation estate provide additional insight into plantation development. The dominance of lower diameter classes indicates that much of the plantation resource is composed of young to middle aged stands that have not yet reached structural maturity. Similar age and diameter distributions have been reported in plantation systems established during large scale afforestation programs, where stand development often reflects relatively recent establishment phases and limited thinning or tending interventions (Forrester 2014; Forrester and Bauhus 2016; Liang et al. 2016; Paquette and Messier 2011; Pretzsch 2009; Pretzsch et al. 2013; Pretzsch and Schütze 2009). From a silvicultural perspective, this suggests that a considerable proportion of the plantation estate still retains significant growth potential.

Regional variation in growing stock and annual increment further demonstrates that plantation productivity is not directly proportional to plantation area. Regions such as Prishtina and Peja exhibited higher mean growing stock per hectare despite having smaller plantation areas than Mitrovica. This discrepancy indicates that stand productivity is influenced by a combination of site quality, species suitability, stand age, and management history rather than plantation extent alone. Similar observations have been reported in plantation studies where differences in site conditions and stand structure lead to substantial spatial variation in productivity (Forrester 2014; Forrester and Bauhus 2016; Liang et al. 2016; Paquette and Messier 2011; Pretzsch and Schütze 2009).

Species composition represents another important structural feature of the plantation estate. The overwhelming dominance of conifers, particularly Pinus nigra and Pinus sylvestris, indicates that plantation establishment relied heavily on a limited group of species. Such reliance is common in protective afforestation programs because these species are generally tolerant of poor soils and harsh site conditions. However, strong species concentration may also reduce ecological resilience and increase vulnerability to disturbance under changing climatic conditions (Brockerhoff et al. 2008; Carnus et al. 2006; Allen et al. 2010; Felton et al. 2010; Jactel and Brockerhoff 2007; Seidl et al. 2014). Increasing species diversity in future plantation programs may therefore contribute to greater ecological stability and improved adaptive capacity.

Plantation condition also emerged as a major issue. A substantial proportion of conifer growing stock was classified as damaged, and fire represented the dominant damage factor. Fire vulnerability in conifer-dominated plantation landscapes has been widely documented, particularly where structural homogeneity, fuel continuity, and climatic stress increase the probability and spread of disturbance

(Allen et al. 2010; Bonan 2008; Reyer et al. 2017; Seidl et al. 2014; Stephens et al. 2013; Turner 2010). The high proportion of damaged growing stock observed in this study suggests that disturbance processes already constitute a significant limitation to plantation performance and that fire risk management should be treated as an integral component of plantation planning.

The comparison of plantation statistics derived from different data sources further highlighted methodological challenges in plantation assessment. Differences between inventory data, historical management plans, and newer planning documents demonstrate that plantation statistics may vary substantially depending on the source used. Similar discrepancies between administrative records and inventory-based assessments have been documented in forest inventory literature, emphasizing the importance of integrating geospatial and field-based evidence when evaluating forest resources at large spatial scales (Chirici et al. 2012; Corona 2016; Köhl et al. 2006; McRoberts 2011; McRoberts and Tomppo 2007; Tomppo et al. 2010; Westfall and Patterson 2007). The integrated methodology applied in this study therefore provides a more reliable representation of the current plantation estate than reliance on a single data source.

Overall, the results indicate that forest plantations in Kosovo represent a significant but structurally simplified forest resource. Their spatial concentration, limited species diversity, and exposure to disturbance highlight the need for more diversified plantation strategies in future forest planning. Increased species diversification, improved fire management, and continued monitoring of stand development may contribute to enhancing both the productivity and resilience of the plantation estate. At the same time, the large area identified as suitable for afforestation suggests that forest plantations could play an important role in future landscape restoration and climate mitigation strategies.

5. Conclusions

This study delivered an integrated geospatial and statistical assessment of forest plantations in Kosovo by combining GIS based delineation, orthophoto and satellite image interpretation, field inventory, and historical forest management documentation. The analysis provided a spatially explicit evaluation of plantation extent, growing stock, annual increment, species composition, and condition, thereby establishing a more coherent evidence base than would be possible from historical management records alone. From a geospatial perspective, the study showed that forest plantations are not randomly distributed across the territory, but exhibit a clear pattern of spatial concentration at both regional and municipal levels. From a statistical perspective, the study demonstrated that area, growing stock, stocking intensity, species composition, and damage are not uniformly related, and that plantation quantity and plantation quality do not coincide spatially.

The geospatial results showed that the plantation estate covers 7803 ha and is strongly concentrated in a limited number of territorial units, especially Mitrovica, Gjilan, and Prishtina. This concentration indicates that plantation development has historically followed spatially selective processes rather than balanced territorial distribution. In practical terms, this pattern is important because it identifies where

the national plantation resource is most strongly aggregated and where monitoring, rehabilitation, and protection measures can be prioritized geographically. The same spatial logic applies to future forest establishment. The identification of 8068.36 ha suitable for reforestation and 87,035.99 ha suitable for afforestation shows that Kosovo possesses a considerable land reserve for future intervention, but that this reserve is itself unevenly distributed. The much greater afforestation potential indicates that future expansion of forest cover is likely to depend more strongly on new establishment on suitable non forest land than on restorative intervention alone.

The statistical results further showed that plantation performance cannot be inferred from plantation area alone. The total plantation growing stock was estimated at 966,326 m^3, with a total annual increment of 46,064.3 m^3 $year^{-1}$, but the regional distribution of these variables differed from the regional distribution of area. Regions with the largest plantation surfaces did not necessarily support the highest mean growing stock per hectare. For example, Prishtina and Peja exhibited the highest stocking intensity, whereas Mitrovica, despite having the largest plantation area, showed lower mean growing stock per hectare. This discrepancy confirms that plantation extent is not a reliable proxy for plantation productivity and that statistical evaluation must include both absolute and area standardized indicators in order to characterize stand performance adequately.

The structural statistics also showed that the plantation estate is dominated by lower diameter classes, especially 7–30 cm and 30–50 cm, whereas larger diameter classes contribute only a minor share of total growing stock. This indicates that much of the plantation resource remains in relatively early or intermediate stages of stand development and has not yet reached structural maturity. From a statistical standpoint, the diameter class profile suggests that the current plantation estate still contains unrealized growth potential, but also that large parts of the resource have not yet developed into mature, high growing stock stands. This is a critical conclusion for future forest planning because it distinguishes between present plantation quantity and long-term structural development.

Species composition analysis revealed a strongly simplified plantation structure. Conifers accounted for 88% of total plantation growing stock, and *Pinus nigra* together with *Pinus sylvestris* represented approximately 83% of the total. These statistics indicate a high degree of compositional concentration and confirm that the plantation estate is dominated by a narrow conifer base. From a geospatial and ecological perspective, this matters because large, spatially concentrated plantation areas composed of the same dominant taxa may exhibit greater continuity of disturbance risk across the landscape. Thus, the compositional statistics are not only descriptive; they also help explain why plantation resilience may be limited and why diversification should become a priority in future management.

Plantation condition represented another major conclusion of the study. A total of 285,972 m^3 of conifer growing stock was classified as damaged, corresponding to 33.8% of total conifer growing stock, with fire identified as the dominant damage factor. These values show that plantation damage is not marginal but structural. Statistically, one third of the conifer estate is already affected by disturbance. Spatially, this means that concentrated plantation landscapes may also be concentrated landscapes of risk. The

combination of strong conifer dominance, territorial clustering, and a high proportion of damaged growing stock indicates that future plantation policy must address not only establishment and production, but also disturbance mitigation, protection planning, and resilience building.

The cross-source comparison further demonstrated the importance of integrated assessment. Plantation area and growing stock values differed substantially among Inventory 2014, old management plans, and new plans, showing that plantation statistics are strongly dependent on source provenance. This is an important methodological conclusion because it confirms that legacy records alone cannot provide a sufficiently robust basis for current plantation evaluation. The integration of GIS based delineation, contemporary image interpretation, and field inventory therefore represents not only a technical improvement, but a necessary condition for statistically credible and spatially explicit assessment of plantation resources.

Overall, the study shows that forest plantations in Kosovo constitute a valuable but spatially concentrated, structurally simplified, and partially degraded forest resource. Their future role in restoration, timber production, and climate related land policy will depend on a transition from area-based plantation development toward a more advanced strategy grounded in geospatial targeting, statistical monitoring, species diversification, and risk sensitive management. In this regard, the main contribution of the study is not only the quantification of plantation resources, but also the demonstration that plantation planning in Kosovo must be informed simultaneously by where plantations are located, how they are structured, how they perform statistically, and how vulnerable they are within the broader landscape system

Declarations

Author Contributions

Perparim Ameti, Ymer Kuka, and Besim Ajvazi contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Perparim Ameti and Ymer Kuka. The first draft of the manuscript was written by Ymer Kuka and Perparim Ameti, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Clinical Trial Registration

Not applicable.

Ethics and Consent to Participate

Ethics and Consent to Participate declarations: not applicable.

Consent to Publish

Consent to Publish declaration: not applicable.

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Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Figures

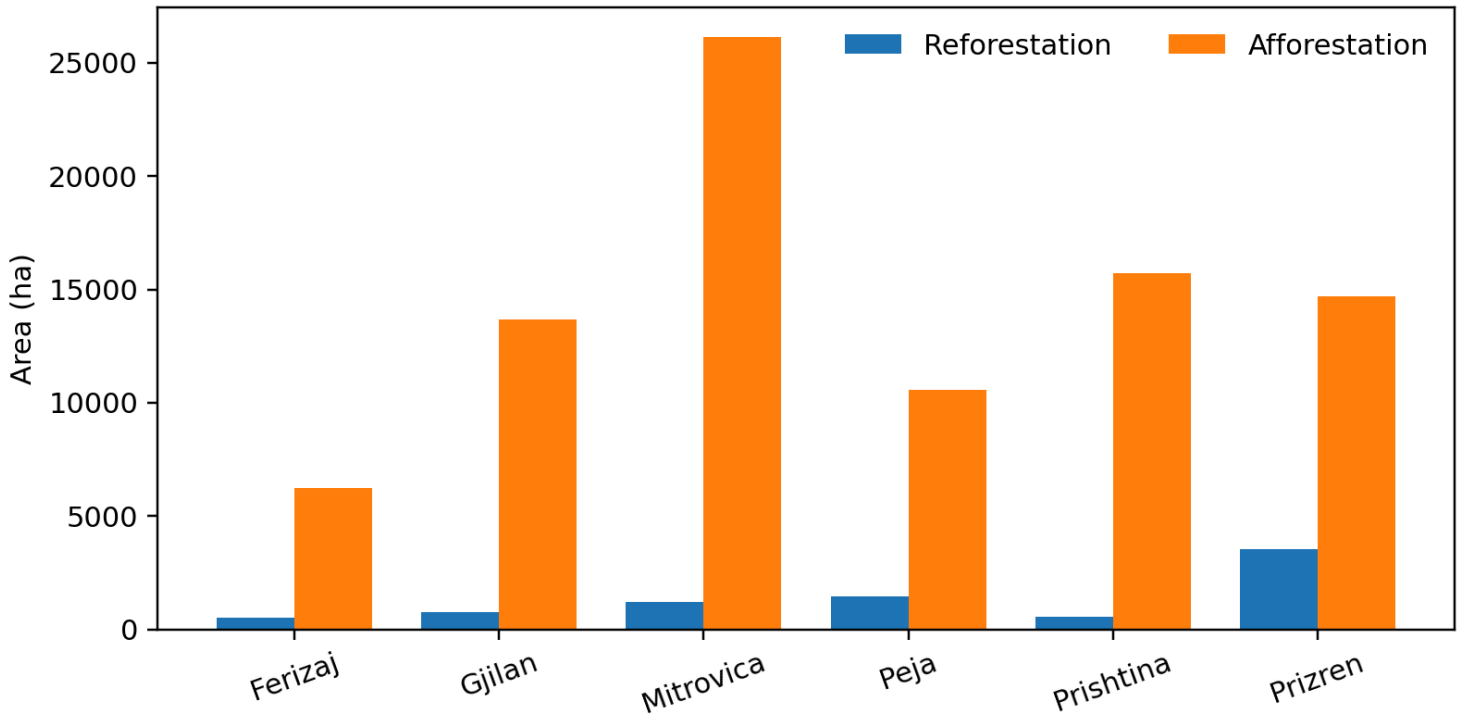


Figure 1

Afforestation potential

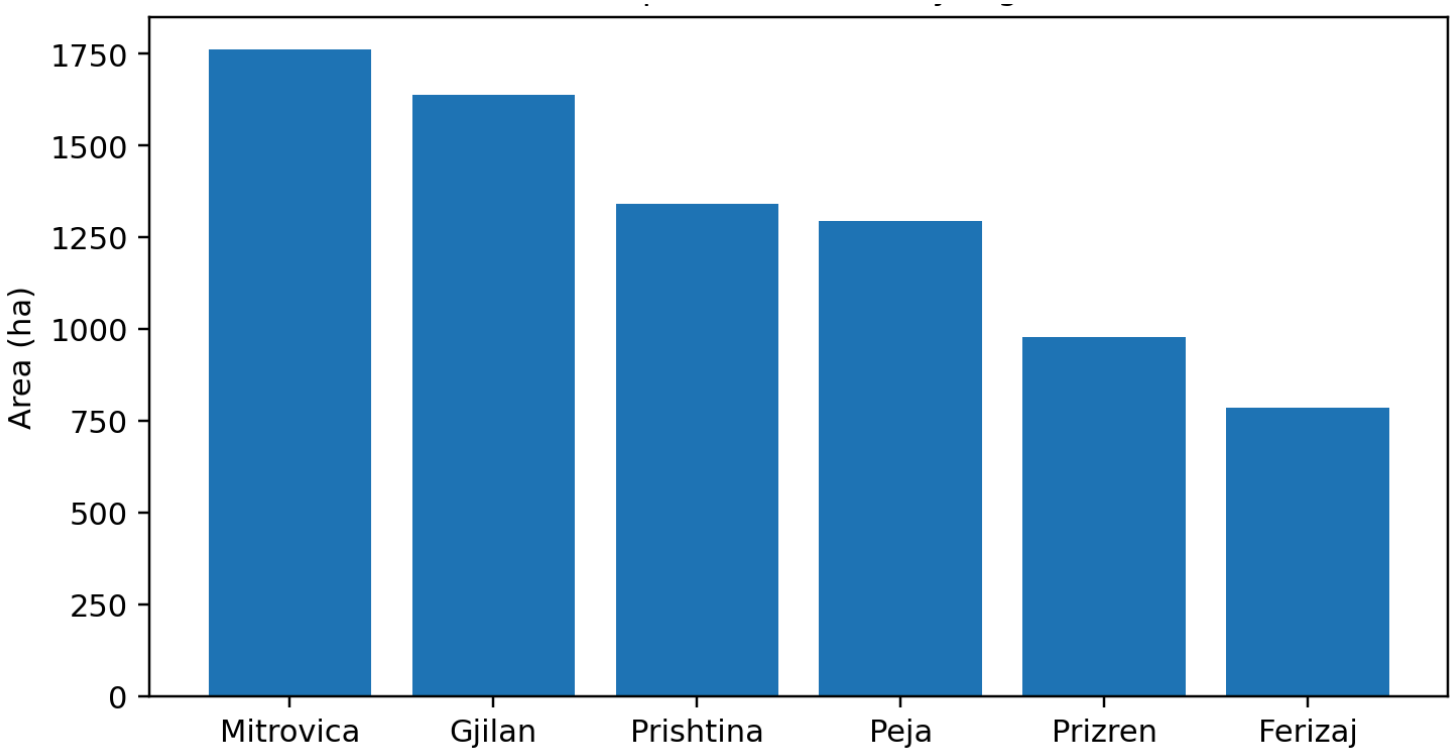


Figure 2

Plantation area by region.

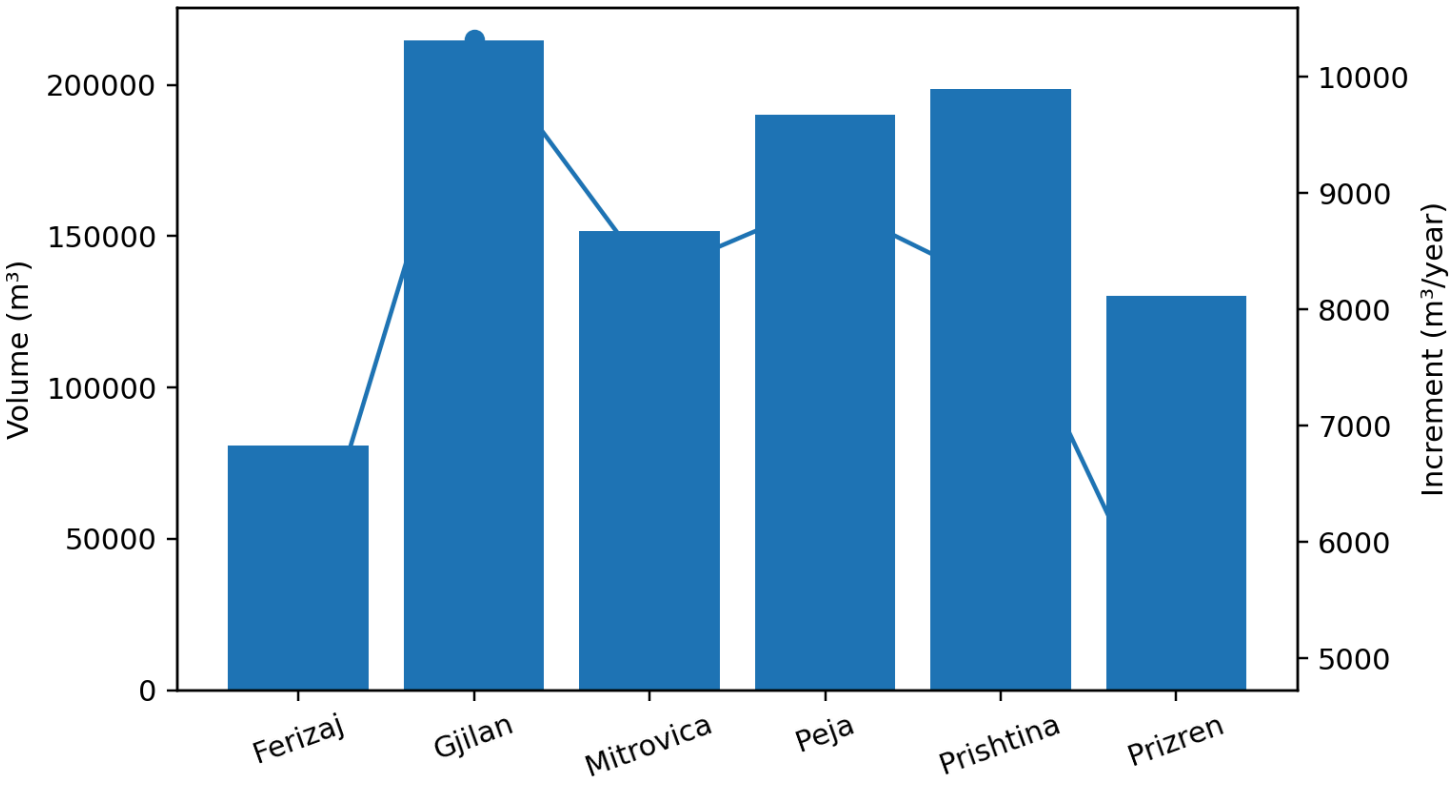


Figure 3

Growing stock and annual increment by region.

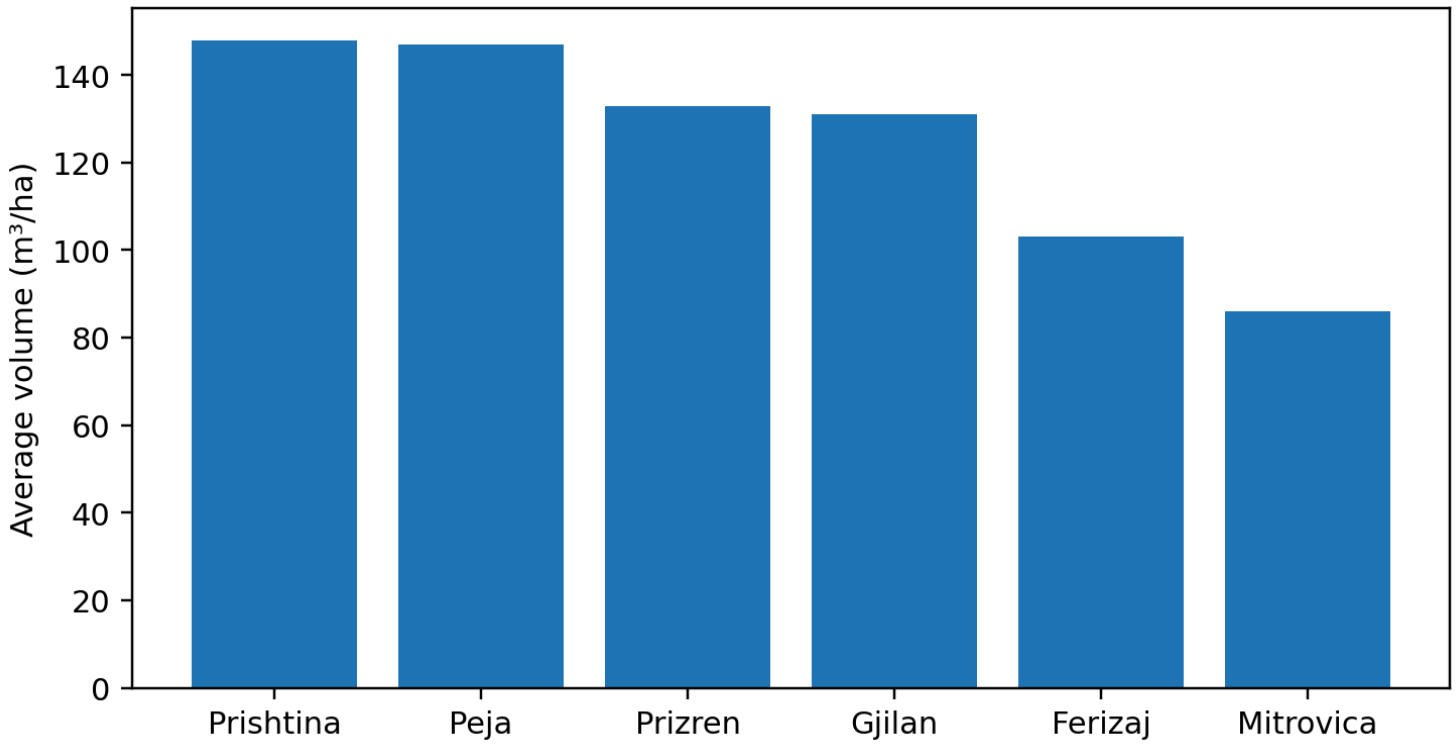


Figure 4

Mean growing stock by region

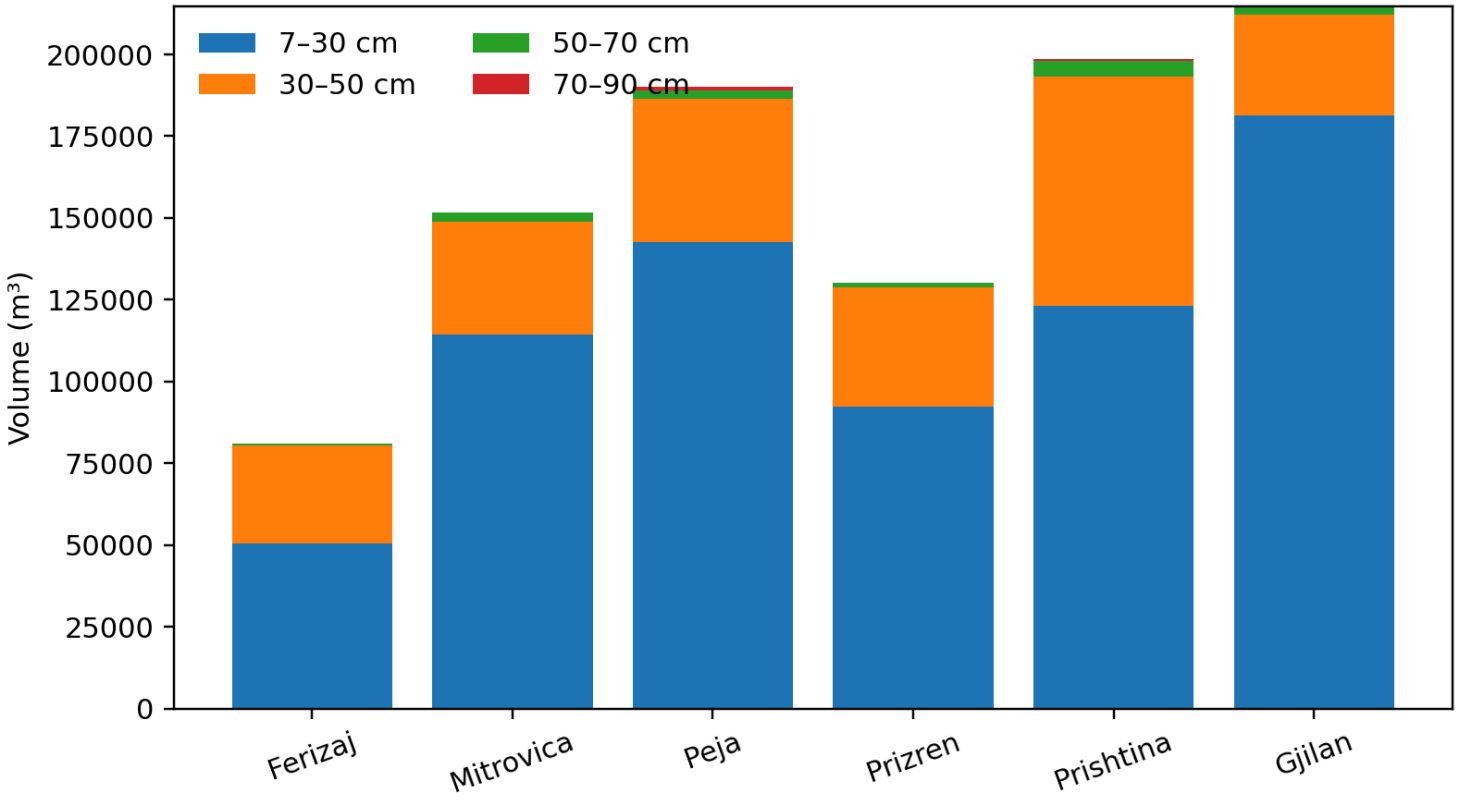


Figure 5

Diameter class distribution of growing stock by region.

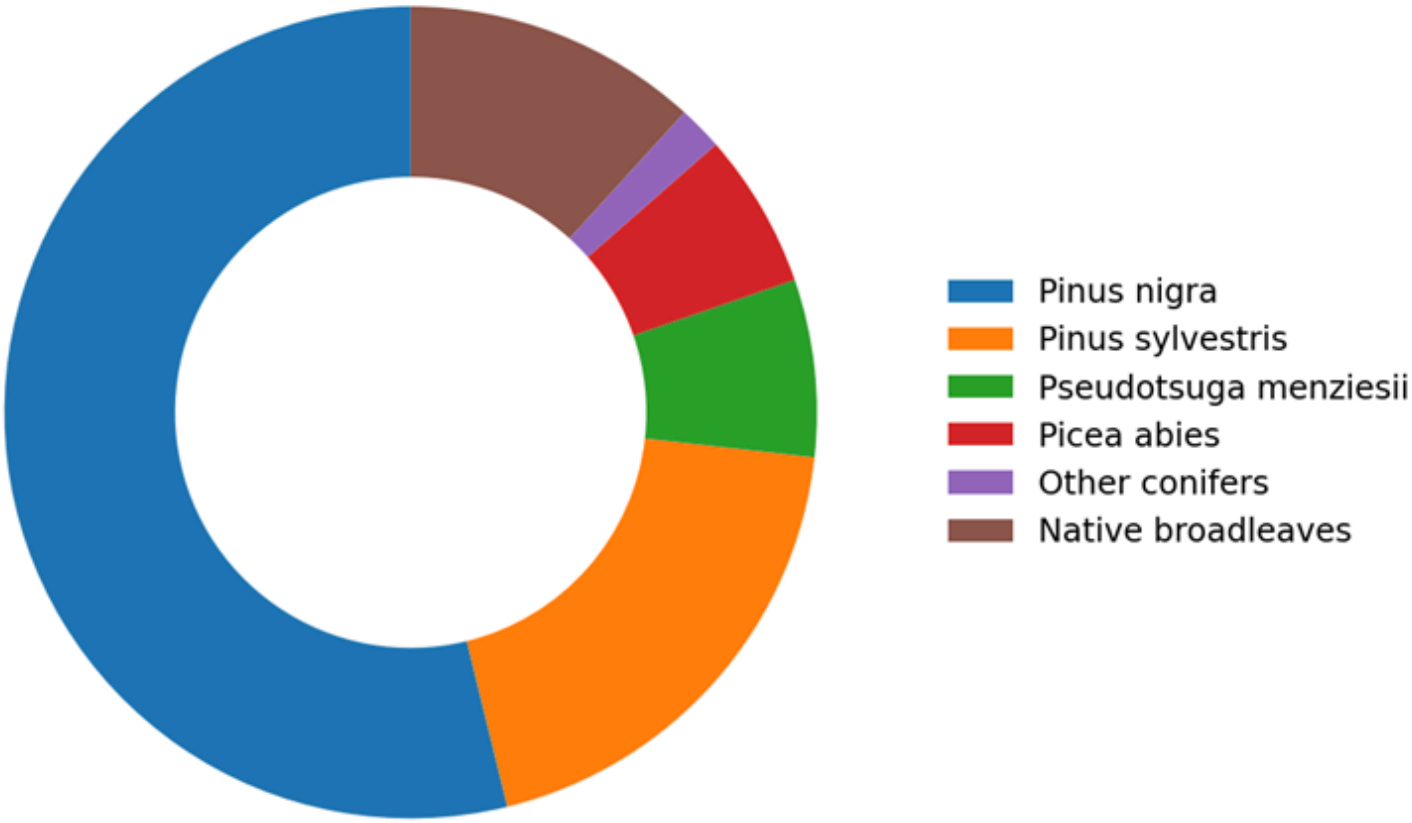


Figure 6

Figure 7. Species composition of plantation volume.

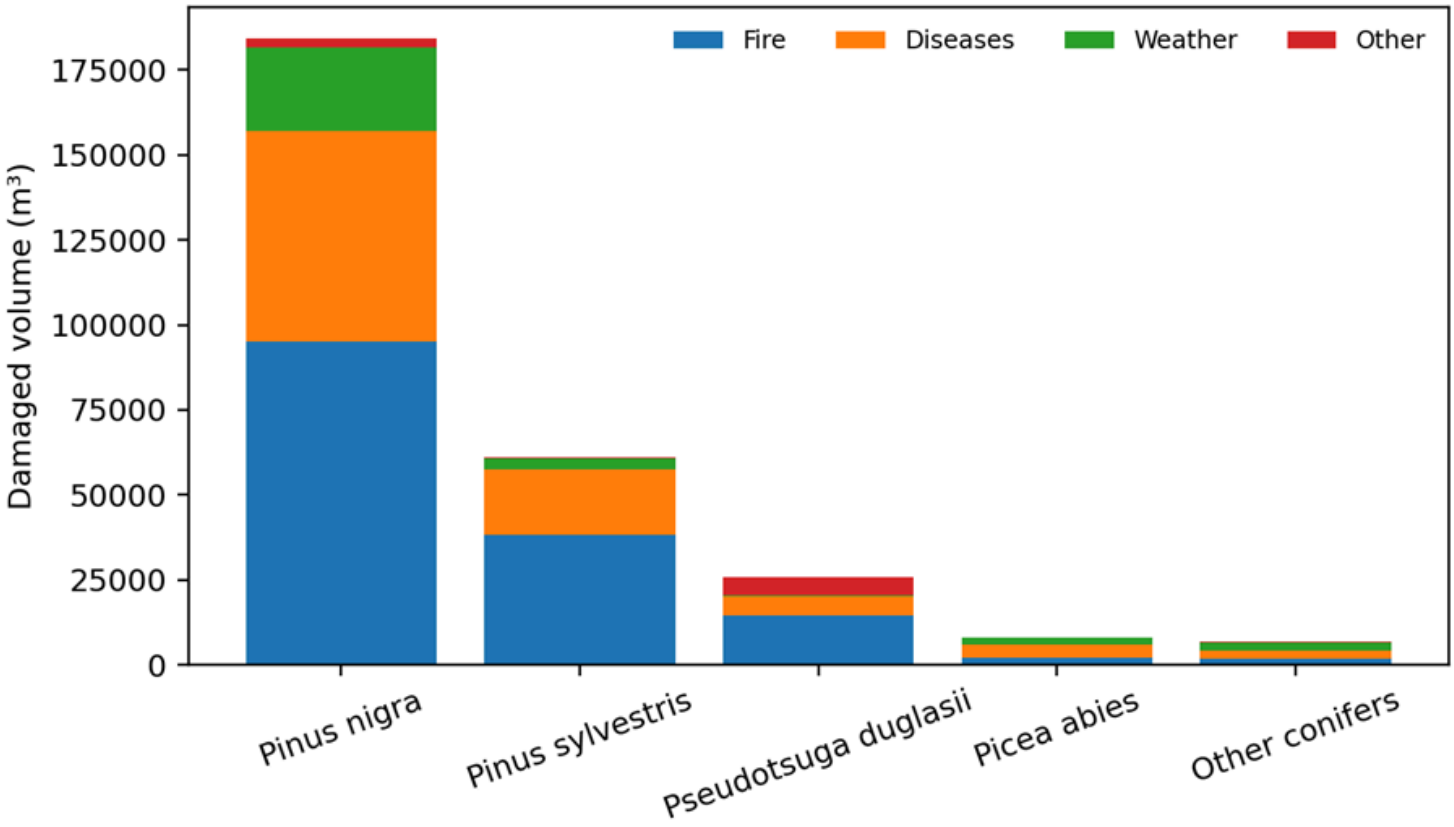


Figure 7

Figure 8. Plantation damage by cause and species.

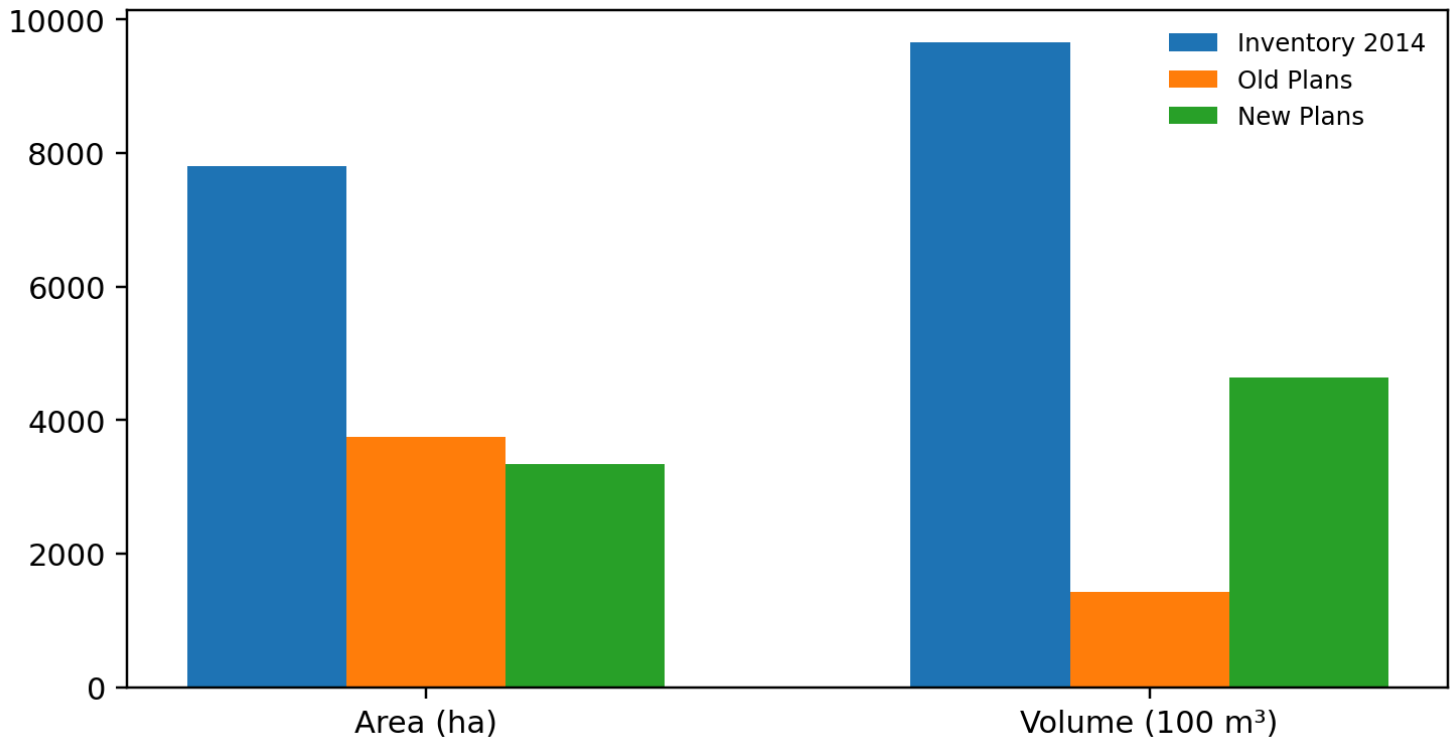


Figure 8

Figure 9. Comparison of area and volume values reported by Inventory 2014, old plans, and new plans for Kosovo