Changes in Satoyama Landscapes in Sumedang, West Java, Indonesia

インドネシア，西ジャワ，スメダンにおける里山景観の変化

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Abstract

The purpose of this study was to investigate the impacts of recent urbanization and the change of Satoyama in *Sumedang*, West Java, Indonesia, based on land cover and use changes using satellite images in order to discuss a strategy for the conservation of Satoyama landscapes. Significant improvements in classification accuracy were achieved, with overall accuracy rising from 73% to 85% and Kappa accuracy from 66% to 79%. The analysis revealed a decrease in dryland agriculture and shrub-mixed dryland farms, alongside an increase in forested areas and settlements. These changes have important implications for the sustainability of Satoyama landscapes, as increased forest areas support biodiversity. The Satoyama Index, reflecting the health of socio-ecological landscapes, improved from 2003 to 2013 but slightly declined by 2023 due to urbanization pressures. Cluster analysis identified three watershed groups with distinct characteristics: Cluster 1, dominated by dryland agriculture and rice fields with a low Satoyama Index; Cluster 2, characterized by shrub-mixed dryland farms and the highest Satoyama Index; and Cluster 3, with diverse land uses and a moderate Satoyama Index. Each cluster requires tailored land use management strategies to balance development and conservation. The findings emphasize the need for integrated land management to preserve satoyama landscapes and promote biodiversity. Effective strategies include enhancing agroforestry, supporting sustainable agriculture, and implementing comprehensive urban planning. This research highlights the critical role of adaptive management in maintaining ecological resilience and supporting sustainable development in the face of ongoing land use changes.

Keywords: cluster analysis, land cover and use change, Satoyama index, Satoyama landscape

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1. Introduction

Urbanization is the result of urban population growth, urban expansion and from rural to urban migration. This process is rapidly changing, context-specific and driven by interrelated factors, including different economic developments, policy choices, availability of natural resources and external stressors such as conflict, climate extremes or environmental degradation (FAO, 2023). A 2021 World Bank report (Lall, et al., 2021) reveals that 55% of the world's population resides in urban areas. By 2050, this share is likely to exceed two-thirds (68%). Recently, urbanization has led to extremities and uncertainties in natural climate events (Kalnay and Cai, 2003), an increase in disaster susceptibility (Tibebe and Bewket, 2011), the extinction of biotic diversity (Magura et al., 2016), the depletion of non-biotic resources (Getachew and Melesse, 2013; Tolessa et al., 2017; Nath et al., 2021), and a decrease in the soil's ability to support all living things (Lambin and Geist, 2008; Tibebe and Bewket, 2011). Concern over land use and land cover studies has recently spread throughout the world as a result of knowledge about the substantial effects of these changes on natural features at regional and intercontinental scales (Mahmood et al., 2014).

Indonesia is no exception with its ever-growing population. Similar to the global population trend, Indonesia has transitioned from a rural to a predominantly urban society. The Intercensal Population Survey of 2015 showed that Indonesia had an urban population of 136.44 million and an urbanization level of 53.1% (BPS, 2015). Indonesia's urban population is projected to increase rapidly, reaching 203 million in 2035 with a level of urbanization of about 66.6% (BPS, 2018). The Jakarta Megapolitan Region, now exceeding 30 million inhabitants, has spawned four of Indonesia's most populous cities which are *Bogor, Depok, Tangerang,* and *Bekasi* in its periphery over the past three decades (Silver, 2024). However, negative effects of this process include income inequality, urban poverty (Batubara et al., 2023), urban sprawl (Wirawan and Tambunan, 2018; Hatab et al., 2019), traffic congestion, and losses of agricultural and natural land leading to excessive groundwater extraction, air pollution and urban food insecurity (Firman, 2009; Putra et al., 2020). For example, the study in *Cisadane* Watershed revealed that the most significant changes during the last 15 years from 2003 to 2018 was the increase in built-up areas (47%). On the other hand, forest and paddy field classes are experiencing a decrease of 7% and 31%, respectively. The projection under business-as-usual condition resulted in the continuous increase of built-up areas up to 36% in the year 2033, which most of the changes come from the conversion of paddy field and dryland farming (Wulandari et al., 2019). Satoyama landscapes, which include paddy fields and dryland farming, are important to ecosystems. Satoyama landscapes (*kebon tatangkalan* or kebun *campuran* in Indonesia) are mosaic landscapes composed of various ecosystems including paddy fields, dry fields, forests, grasslands, irrigation canals, storage reservoirs and human settlements (Takeuchi et al., 2016). The importance of the satoyama-like systems in harnessing the values of renewable natural resources in human-influenced natural environments is recognized throughout the world (Bélair et al., 2010). Satoyama landscapes as social and ecological networks of a village and its surroundings have maintained a high diversity of plants, insects and small-to-medium-sized animals in habitats shaped through interactions between people and nature over many years (Fukamachi et al., 2001; Duraiappah et al., 2012).

This study focused on *Sumedang*, West Java, Indonesia, where Satoyama landscapes have been rapidly developed recently. Honey is one of the benefits of the Satoyama landscape in *Sumedang*. It is a honey produced by stingless bees (*Tetragonula laeviceps* S., *Tetragonula drescheri* S.) (Withaningsih et al., 2023a) that is predicted to have a high sustainability value (Kouchner et al., 2019; Noorahya et al., 2023). Honey bee cultivation can generate large profits both from an economic and environmental perspective (Kritsky, 2017). It helps to generate income and provides entrepreneurial opportunities for poor and rural people, aiding in poverty alleviation (Gallai et al., 2008). Moreover, it plays a pivotal role in providing pollination ecosystem services for various types of crops and wild plants (Thapa, 2006). Bees are able to help increase agricultural productivity and preserve biodiversity and ecosystems in Sumedang (Withaningsih et al., 2023b). Thus, for that bee alone, Satoyama have played a major role in the ecosystem. However, these Satoyama, which are important for the ecosystem and people's livelihood, are being developed by urbanization in Indonesia. Although numerous studies have been conducted on the relationship between population growth and urbanization in Indonesia and land use and land cover changes (Rimba et al., 2021; Ambarwulan et al., 2023; Arifin et al., 2023; Rachman et al., 2024), there are few that analyze these phenomena from the perspective of Satoyama.

The purpose of this study was to investigate the impacts of recent urbanization and the change of Satoyama in *Sumedang*, West Java, Indonesia, based on land cover and use changes using satellite images in order to discuss a strategy for the conservation of Satoyama landscapes.

2. Materials and Methods

2.1 Study Site

The study area of this study is Sumedang Regency, which is one of regencies in West Java Province located at 6° 34’46,18’’- 7° 00’56,25’’ south latitude and 107° 01’45,63’’-108° 12’59,04’’ east longitude (Figure 1). The regency covers an area of 1,558.72 km^2 consisting of 26 sub-districts with 270 villages and 7 sub-districts and had a population 1,159,346. Most of Sumedang Regency area is rural landscapes with hills and mountains, except for a small area in the north of the regency. The lowest plateau is 26 m, and the highest is the peak of Mount Tampomas at 1,684 m. The topographic condition of the land slope of the Sumedang Regency area is dominated by the slope class of 15-25%, which is a hilly area covering 51.68 percent. Its distribution is in the center to the southeast, south to southwest and west (Bappppeda Kabupaten Sumedang, 2018). It has a tropical climate, an annual average temperature of 24.7 °C, and an average rainfall of 2,570 mm, with the highest rainfall occurring in the period of December–January. Based on hydrogeology, large rivers in the *Sumedang* Regency area together with their tributaries form a watershed pattern consisting of 4 watersheds with 6 sub-watersheds, namely *Cimanuk* watershed, *Citarum* Watershed, *Cipunegara* watershed and *Cipanas* watershed. The potential for natural disasters that are often found in Sumedang Regency are generally in the form of land movements, erosion, floods, whirlwinds and earthquakes. Apart from earthquakes, ground movements often occur due to continuous and quite large rainfall (Bappppeda Kabupaten Sumedang, 2018).

Sumedang Regency is currently considered as one of the regencies in West Java, Indonesia experiencing the most changes due to land-use change caused by the development of national infrastructure and the expansion of settlements, so the forest and agricultural land will be affected (Peng et al., 2017). One of the considerable developments that occurred from 2007 to 2022 was the construction of the *Jatigede* Dam, the second-largest Dam in Indonesia. It changed the land cover by 4,980.3 ha, of which 1,400 ha was paddy fields (Simangunsong and Kurnia, 2018). The construction began in 2008 and was inaugurated in 2017 on the *Cimanuk* River with a capacity of 979.5 million m^3. In 2016, the construction of the toll road *Cisumdawu* also started and passed through *Sumedang* Regency (Bappppeda Kabupaten Sumedang, 2018). Land conversion for national strategic projects, including the construction of toll roads, often occurs at the expense of productive agricultural land (Utami et al., 2022), particularly Satoyama landscapes in *Sumedang.*

The main industry in the region is the processing industry from agricultural and forestry products. Many people depend on it for their livelihood (BPS, 2024). Based on 2017 data, there are 121, 138 residents of *Sumedang* Regency who work in the food crop agriculture sector around 9% of the total population (Bappppeda Kabupaten Sumedang, 2018). The leading commodities in the agricultural sector consists of paddy, maize, sapodilla, mango, banana, salak fruit, cassava, sweet potato, soybeans, and peanuts. The regency is also rich in vegetables, ranging from cabbage, cucumbers, red chilies, shallots to cayenne peppers. These agricultural products are spread across various areas in *Sumedang* Regency and the potential for the products produced is different according to the existing environmental conditions. It is an area with thriving agriculture and is famous for producing sweet potatoes in *Cilembu* village, *Pamulihan* subdistrict, gedong gincu mangoes from *Tomo* subdistrict and coffee (BPS, 2024). However, although the main food ingredient for the population in *Sumedang* Regency is rice, the productivity trend of rice or other main local food ingredients in *Sumedang* Regency experienced a decline in 2013-2017 (Bappppeda Kabupaten Sumedang, 2018). This happened because of the shift in people's livelihoods from the agricultural sector to the industrial sector (BPS, 2024). While, in the forests, it is dominated by teak plantation covering an area of 13,727.78 ha, pine plantation covering an area of 13,871.52 ha and rubber plantation covering an area of 8,948.09 ha (Perhutani, 2024).

2.2 Digital Elevation Model (DEM)

The boundary to delineate the watershed was generated from Digital Elevation Models (DEM, Aster GDEM: 30-m spatial resolution) using the hydrology tool of ArcGIS Pro 3.2. In this study, we used the watersheds as the unit of analysis. Watersheds were generated using flow directions and accumulations calculated from DEM. When determining the size of a stream networks and watersheds, a threshold should be set for the area of the slope into which water flows. In this study, we used 10,000 for the threshold, while adjusting it to match the actual location of rivers. Finally, total of 104 watershed was generated (Figure 2).

2.3 Satellite Images

Land cover and use in 2003, 2013, and 2023 were obtained from satellite imageries (Landsat 7 ETM+ and Landsat 8 OLI-TIRS) providing from United States Geological Survey (https://earthexplorer.usgs.gov/). The spatial resolution of the images was 30m, and the proportion of clouds in the images was less than 10% (Table 1, Figure 3-5). The images were analyzed using Maximum Likelihood Classification using R, G, B and NDVI (Normalized Difference Vegetation Index) calculated as the difference between near-infrared and red reflectance divided by their sum by ArcGIS Pro 3.2, a method of image analysis. Each 100-training data as polygons were set in each image for each land cover and use category, including bareland, water body, dryland agriculture, forest, shrub-mixed dryland farm, rice field, and settlement. Forest in this research included natural forest, secondary forest, pine and teak plantation forest. Subsequently, 20 points were set for each land cover and use category for the purpose of accuracy analysis. he accuracy of obtained land cover data for each year from 2003, 2013, and 2023 was assessed by calculating overall accuracy and Kappa. The land cover and use for each year were aggregated for each watershed, and the watersheds were characterized using Satoyama Index and cluster analysis using R ver. 4.3.1.

2.4 Satoyama Index

The Satoyama Index (SI), a biodiversity indicator calculated based on habitat diversity was calculated in each land cover. The Satoyama Index is an index based on the diversity of land cover and land use in agricultural areas and their surrounding environments. The higher the value, the greater the mosaic nature of land cover and use in the target area. Areas with a high Satoyama Index can be considered to indicate areas that are important as potential habitats for plants and animals that utilize specific environments that comprise Satoyama, or a combination of multiple environments. Conversely, areas with a low Satoyama Index are perceived as homogeneous regions comprising extensive agricultural land with minimal environmental heterogeneity. In particular, areas with a Satoyama Index of 0 are entirely occupied by farmland and are therefore deemed unsuitable for the habitat of species requiring a mosaic-like environment (Hanski and Ovaskainen, 2000; Kadoya and Washitani, 2011).

If a watershed contained even one land cover and use category that could be considered agricultural land use (dryland agriculture or rice field), it was included in the index calculation. Land cover classified as settlement were excluded from the calculation. The Simpson Diversity Index (SDI) of land cover and use in the targeted watersheds was calculated. The share of land cover and use other than agricultural land use among the land cover and use including bareland, water body, forest and shrub-mixed dryland farm in the watershed was multiplied by it. Kadoya and Washitani (2011) defined the Satoyama Index (SI) as the product of the Simpson Diversity Index (SDI) and the proportion of natural elements P (i.e., SI = SDI × P) per land unit, as follows:

$$P = \sum_{natural} \frac{n_i}{N-1}$$

where the summation is for all land cover classes other than urban or agriculture. The denominator N– 1 was used to make P range from 0 to 1, since at least 1 pixel was considered agriculture due to how the land units were selected for the Satoyama Index computation.

$$SDI = 1 - \sum_{i=1}^{S} {p_i}^2 = 1 - \frac{n^2 + {n_2}^2 + \cdots + {n_{20}}^2}{N^2}$$

where i is the land cover class, pi is the proportion of the land unit occupied by land cover class i, S is the total number of land cover classes, ni is the number of pixels of land cover class i in a land unit, and N is the total number of pixels in a land unit; and

2.5 Cluster Analysis

A cluster analysis (the Euclidean distance and Ward's method) was conducted on the basis of Satoyama index, the area percentage of land cover and use (bareland, water body, dryland agriculture, forest, shrub-mixed dryland farm, rice field, and settlement), minimum elevation and maximum elevation included in each watershed in order to analyse the characteristics of each watershed to be classified according to their respective land cover and use patterns.

3. Results

3.1 Land Use and Land Cover Changes

Figure 6-8 show land cover and use in 2003, 2013, 2023 obtained from satellite images. Table 2-4 shows accuracy matrix of classification respectively. In 2003, it had an overall accuracy of 73% and Kappa accuracy of 66%. Dryland agriculture mostly covered the west and northern part. On the other hand, in the east and southern part, it had a major land cover and use of shrub-mixed dryland farm. Waterbody was not detected and it might be classified as rice field. In 2013, it had an overall accuracy of 81.3% and Kappa accuracy of 76.4%. In 2013, shrub-mixed dryland farm was mostly distributed in the southwest part. Meanwhile, dryland agriculture was found in the northeast part. Forest was mostly detected in the center of the regency and the southern part. In 2023, land cover and use classification had an overall accuracy of 85% and Kappa accuracy of 79%. Shrub-mixed dryland farm and dryland agriculture were evenly distributed in the whole area. Water body was able to detected particularly in the southeast part. Settlement could be found at the center of regency extending to the southwest and northeast.

Figure 9-11 show the area of each land cover and use in 2003, 2013, 2023 obtained from satellite images. In 2003, dryland agriculture and shrub-mixed dryland farm were the highest land cover covering the area of Sumedang. Dryland agriculture had an area of 56,621 ha and the area of shrub-mixed dryland farm was 52,177 ha. Rice field and bare land covered the area of 15,638 ha and 16,940 ha, respectively. The coverage of forest in the region was

10,183 ha, while the settlement area was only 6,108 ha. In 2013, shrub-mixed dryland farm covered the largest area of the regency with a total area of 60,958 ha. The area of dryland agriculture was 47,424 ha and followed by forest with 22,289 ha. Rice field had an area of 14,642 ha, while the area of settlement and bare land were 7,600 ha and 3,197 ha. Water body was detected with an area of 1,559 ha. In 2023, dryland agriculture and shrub-mixed were the major land cover and use with area of 51,260 ha and 50,694 ha, respectively. Forest had an area of 24,513 ha. Settlement covered 15,076 ha of the region. Bare land had an area of 6,142 ha and water body was detected with an area of 2,446 ha.

3.2 Satoyama Index

Figure 12-14 show Satoyama Index of each watershed in 2003, 2013, 2023. In 2003, the minimum and maximum of Satoyama Index were 0.00091 and 0.54, respectively. The watersheds with high values which was more than 0.50 were only 4 watersheds located in the west and south. In 2013, it showed the value of Satoyama index with minimum value of 0.007 and maximum value of 0.89. The watersheds detected with the index higher than 0.5 were 12 watersheds. They were distributed in the center and south part of the region. In 2023, Satoyama index had the minimum value of 0.037 and maximum value of 0.54. The index greater than 0.5 could be found in 7 watersheds distributed in the south to the southeast part.

3.3 Cluster Analysis

Figure 15 shows the dendrogram of the cluster analysis. The hierarchical relationships among watersheds as a unit of analysis based on Satoyama index, percentage of each land use and land cover, maximum elevation, and minimum elevation showed that land use and its changing patterns could be classified into three groups. The three clusters classified over 200 in squared Euclidean distance were adopted for further discussion. The vertical axis represents the distance or dissimilarity between clusters. The higher the merging occurs on the vertical axis, the more dissimilar the clusters being merged are. The horizontal axis shows the individual data points (watersheds) that are being clustered. Each point represented a watershed, and they were grouped together based on their similarity in terms of the average values for each variable in each cluster.

Cluster 1 formed the leftmost group of branches merging below the height of 200. This cluster contained 34 watersheds. Watersheds in this cluster predominantly had specific types of land use and land cover, such as dryland agriculture (55%) and rice field (18%). The average minimum and maximum elevation ranges for these watersheds were from 90 m to 404 m. The average value of Satoyama index across these watersheds showed the low value of 0.15.

Cluster 2 formed the middle group of branches merging just below the height of 200, but to the right of Cluster 1. This cluster was larger than Cluster 1 but similar with Cluster 3, containing 35 watersheds. Watersheds in this cluster were more similar to each other in terms of Satoyama index and maximum elevation than to those in Cluster 1 or Cluster 3, but they displayed more variability compared to Cluster 1. The Satoyama index ranged from 0.14 to

0.54 with an average value of 0.41. This cluster represented watersheds with the major land use and land cover patterns of shrub-mixed dryland farm with an average percentage of 52.36%, followed by dryland agriculture (22.90%). These watersheds could be found at mid- to high-elevations ranging from 391 m to 1467 m.

Cluster 3 was formed by the watersheds on the rightmost group of branches merging just before the large jump in height, indicating more dissimilarity from clusters 1 and 2. This was the largest cluster with cluster 2, containing 35 watersheds. Cluster 3 included watersheds with more diverse land use and land cover, highly covered by shrub-mixed dryland farm (42.94%), settlement (20.87%), and rice field (20.13%). The Satoyama index in this cluster was higher than cluster 1, but lower than cluster 2, with an average value of 0.21. These watersheds were located in the area with mid-range elevations from 367 m to 519 m.

4. Discussion

4.1 Land Use and Land Cover Changes

The classification accuracy in land use and land cover change studies is a critical measure of reliability. In this study, the accuracy of the land cover and use classification had shown significant improvement over the three periods studied. In 2003, the overall accuracy was 73% with a Kappa accuracy of 66%, indicating moderate reliability. By 2013, the accuracy had increased to 81.3% with a Kappa of 76.4%, reflecting a substantial improvement. This upward trend continued in 2023, with overall accuracy reaching 85% and Kappa accuracy at 79%, indicating a high level of agreement between the classified data and ground truth. The accuracy appeared to be relatively high, as suggested by the overall kappa coefficient and the user's and producer's accuracy for each class. A high kappa coefficient (above 0.8) generally indicates a strong agreement between the classified data and the ground truth, implying that the classification model is performing well. These figures compared favorably with the standards set by Congalton and Green (2019), who advocate for high accuracy in remote sensing classifications for reliable analysis. Similarly, the study aligned well with Olofsson et al. (2014), which underscored the importance of accuracy assessments in land use and land cover studies, demonstrating that the classification process in this study is robust and reliable. These references highlight that high accuracy is essential for reliable analysis of land use and land cover changes and subsequent policy-making.

Between 2003 and 2023, notable changes in land use and land cover have been observed. Dryland agriculture, which was predominant in 2003 with an area of 56,621 ha, decreased to 47,424 ha in 2013 and further to 51,260 ha in 2023. Shrub-mixed dryland farm initially increased from 52,177 ha in 2003 to 60,958 ha in 2013 but then decreased to 50,694 ha in 2023. Forest saw a significant increase, expanding from 10,183 ha in 2003 to 22,289 ha in 2013 and 24,513 ha in 2023. Settlement areas more than doubled from 6,108 ha in 2003 to 15,076 ha in 2023. The rise in forested areas could be attributed to reforestation efforts and conservation policies, as discussed by the FAO (2020). Early in 1920, Perhutani, a state-owned company responsible for managing production forest in Java Island, introduced Sumatra pine (*Pinus merkusii*) from its natural population in Aceh to Java with the main target at that time as timber production. As the value of pine timber escalated at that time, tree improvement was also started. Producing superior genotypes was the main objective for the first Sumatran pine tree improvement program that took place in 1976. Selection of elite trees or known as plus trees was the initial activity performed to discover more than 1000 families. This was followed by the establishment of seedling seed orchard in Sumedang (West Java), Sempolan (East Java), and Baturaden (Central Java). During that time, resin production was categorized as a by-product (Imanuddin et al., 2020). Meanwhile, urban expansion and population growth likely drove the increase in settlements, aligning with global trends of urbanization noted by Seto et al. (2012).

The changes in land use and land cover had significant implications for the satoyama landscapes or *kebun campuran* in Indonesia. The increase in forest was crucial for the sustainability of satoyama, as forests are integral to maintaining biodiversity and traditional ecological practices. Forests in *Sumedang* Regency including natural forest, secondary forest and plantation forest provide tangible and non-tangible multiple benefits for the human being. In terms of its tangible benefit of pine plantation forests as reforestation effort in the region, the pine produces non-timber forest products such as resin or pine resin, as well as wood forest products. Meanwhile, the intangible benefit is provided in the form of environmental services such as pine forests as a nature tourism location, land and water protection services, and hydrological function (Imanuddin et al., 2020). In addition, the pine forest also provides social benefits for people residing near the forest. Through the social forestry program, the pine forest is allocated to be managed by the community. The community is given access to manage the state forests with a shared revenue mechanism. This shows that pine forests in Indonesia provide multiple benefits that are very important for human welfare.

However, the decline in shrub-mixed dryland farms and the transformation of agricultural lands into urban settlements pose challenges. Shrub-mixed farms are a key component of satoyama, supporting a variety of species and agricultural diversity. The decrease in these areas suggests a potential loss of traditional land use practices and biodiversity, as highlighted by Takeuchi (2010). As agricultural land decreases, further socio-economic development poses an additional threat to the biodiversity in the future because traditional agriculture and agroforestry are still practiced by resource-poor farmers (Parikesit et al., 2021). The expansion of settlements, while indicative of development, can lead to habitat fragmentation and ecological degradation, threatening the integrity of satoyama landscapes. These findings underscore the need for balanced land management strategies that promote both development and conservation to sustain the socio-ecological functions of satoyama.

4.2 Satoyama Index

The Satoyama Index, which measures the sustainability and health of socio-ecological production landscapes, showed varying trends in land use and land cover across different watersheds from 2003 to 2023. In 2003, the Satoyama Index ranged from 0.00091 to 0.54, with only four watersheds having high values (>0.50) located in the west and south. These areas were characterized by a balanced mix of forest, dryland agriculture, and shrub-mixed dryland farm, suggesting sustainable land use practices. By 2013, the minimum and maximum values of the Satoyama Index had increased to 0.007 and 0.89, respectively, with 12 watersheds exceeding a value of 0.50, now distributed more centrally and towards the south. This indicated an expansion of sustainable practices and improved land cover management. However, by 2023, the maximum value dropped back to 0.54, and the number of watersheds with an index over 0.50 decreased to seven, concentrated in the south to southeast. These watersheds still maintained a healthy balance of diverse land covers but showed signs of stress due to external pressures, such as the development of *Jatigede* dam and *Cisumdawu* toll project. In watersheds where the Satoyama Index has increased, the land cover and use typically reflect a balanced mosaic of forest, agricultural land, grassland, and water bodies. These areas often exhibit high biodiversity and sustainable land management practices that maintain ecological and cultural integrity. Conversely, watersheds with a decreased Satoyama Index usually exhibit increased urbanization, intensive agriculture, or industrial activities, leading to habitat fragmentation, loss of biodiversity, and degradation of traditional land management practices. This dichotomy is consistent with findings by Takeuchi et al. (2016), who emphasized the importance of diverse and well-managed landscapes for a high Satoyama Index.

The changes in the Satoyama Index could be attributed to several local conditions impacting land cover and use. Between 2003 and 2013, the increase in the number of watersheds with high Satoyama Index values suggested effective conservation efforts and the adoption of sustainable land management practices. Factors contributing to this increase included reforestation programs, such as plantation forest in high elevation area and mixed-garden near settlement area), sustainable agricultural practices (organic farming), and community engagement in conservation efforts, consistent with strategies highlighted by Takeuchi et al. (2016). These practices help maintain biodiversity and ecosystem services, crucial for high Satoyama Index values. However, the decline in the index from 2013 to 2023 reflected challenges such as urbanization, industrial development, and population pressures. The conversion of agricultural and forested lands into urban settlements led to habitat fragmentation and loss of biodiversity, as noted by Seto et al. (2012). Additionally, economic development often prioritized short-term gains over long-term sustainability, resulting in decreased Satoyama Index values. Local policies and land use planning might not have adequately mitigated these pressures, underscoring the need for more integrated and sustainable land management approaches to preserve the socio-ecological balance of satoyama landscapes. These trends aligned with observations by Ichikawa et al. (2012), who highlighted the impact of socio-economic factors on the health of satoyama landscapes. Additionally, climate change and natural disasters may exacerbate these changes by altering land cover and affecting the resilience of socio-ecological systems.

4.3 Cluster Analysis

Cluster analysis revealed three distinct groups of watersheds based on land use and cover, Satoyama Index, and elevation. Cluster 1, comprising 34 watersheds, is characterized by predominant dryland agriculture (55%) and rice fields (18%), with low elevation ranges (90 m to 404 m) and a low average Satoyama Index of 0.15. This cluster's homogeneity in land use and low Satoyama Index suggested limited biodiversity and traditional ecological practices. Cluster 2, with 35 watersheds, showed more variability in land use and elevation (391 m to 1467 m), primarily featuring shrub-mixed dryland farms (52.36%) and dryland agriculture (22.90%). This cluster has a higher average Satoyama Index of 0.41, indicating a healthier socio-ecological balance. Cluster 3 also contained 35 watersheds but exhibited the highest diversity in land use, including shrub-mixed dryland farms (42.94%), settlements (20.87%), and rice fields (20.13%), with mid-range elevations (367 m to 519 m). The average Satoyama Index for Cluster 3 was 0.21, higher than Cluster 1 but lower than Cluster 2, reflecting moderate biodiversity and mixed land management practices. Clusters with high Satoyama Index values typically have a balanced mix of forests, agricultural land, and water bodies, reflecting sustainable land management practices and high biodiversity. These clusters are often characterized by traditional satoyama landscapes, where human activities are harmoniously integrated with nature. In contrast, clusters with low Satoyama Index values often show a dominance of urban areas, industrial zones, or monoculture agricultural fields. These areas have experienced significant land cover changes, such as deforestation and wetland drainage, leading to decreased biodiversity and disrupted ecosystem services. Differences between clusters are primarily driven by the extent of urbanization, intensity of agricultural practices, and the presence or absence of traditional land management practices. This variation aligns with findings from studies like those by Takeuchi et al. (2016), which emphasize the importance of diverse land use patterns for maintaining high Satoyama Index values.

Management strategies should be tailored to the specific characteristics and challenges of each cluster. For Cluster 1, strategies should focus on enhancing biodiversity and ecological practices within the dominant agricultural landscape. This could involve integrating agroforestry, promoting sustainable agricultural practices, and restoring native vegetation to improve the Satoyama Index. These approaches are consistent with the strategies recommended by Ichikawa et al. (2012) for enhancing socio-ecological landscapes. Cluster 2 requires a balanced approach to maintain the existing biodiversity and land use diversity. Strategies could include protecting and expanding shrub-mixed dryland farms, supporting sustainable agriculture, and implementing conservation practices that enhance the ecological functions of mid- to high-elevation areas. This cluster's relatively high Satoyama Index suggests that it is already benefiting from sustainable practices, and these should be reinforced and expanded. For Cluster 3, the most heterogeneous group, comprehensive land use planning is essential. Strategies should aim to integrate urban development with green infrastructure and conservation efforts, mitigating the environmental impacts of settlements while preserving and enhancing shrub-mixed dryland farms and rice fields. This cluster would benefit from policies that promote green spaces, community-based conservation programs, and sustainable urban planning, aligning with the broader recommendations by Seto et al. (2012) to balance development with ecological sustainability. These efforts are crucial for improving the Satoyama Index and overall ecological resilience, as highlighted by research on sustainable watershed management (Sayer et al., 2013). The cluster analysis highlights the diverse approaches to land use management across different watersheds, reflecting the balance between development and conservation efforts necessary for maintaining healthy socio-ecological landscapes.

5. Conclusion

- The classification accuracy of land cover and use improved significantly from 73% in 2003 to 85% in 2023, with Kappa accuracy increasing from 66% to 79%. Dryland agriculture and shrub-mixed dryland farm decreased while forest and settlement expanded.
- The Satoyama Index rose significantly from 2003 to 2013, but slightly declined from 2013 to 2023 due to increased pressures from urbanization and development.
- Cluster analysis identified three watershed groups: Cluster 1 with low elevation, dryland agriculture, and a low Satoyama Index; Cluster 2 with higher elevation, shrub-mixed dryland farms, and a higher Satoyama Index; and Cluster 3 with diverse land use, mid-range elevation, and a moderate Satoyama Index.
- Tailored management strategies are needed: Cluster 1 should enhance biodiversity in agriculture, Cluster 2 should maintain biodiversity through conservation, and Cluster 3 should integrate urban development with green infrastructure, highlighting the need for diverse land use management to balance development and conservation.

Acknowledgement

I would like to express my greatest gratitude to my academic supervisor, Dr. Akemi Itaya for her support and guidance studying at Mie University. I would also like to thank Prof. Ishikawa who provided helpful comments and suggestions. Finally, I would like to acknowledge Graduate School of Padjadjaran University and JASSO for the double degree program and the scholarship that made it possible to complete this study.

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Fig 15. Cluster dendrogram of land use and land cover in each watershed grouped into 3 clusters based on the value of satoyama index, minimum elevation, and maximum elevation. Cluster 1, dominated by dryland agriculture and rice fields with a low Satoyama Index; Cluster 2, characterized by shrub-mixed dryland farms and the highest Satoyama Index; and Cluster 3, with diverse land uses and a moderate Satoyama Index.

Table 1. Detailed information about the satellite data used in this study for land cover and use classification. The time series of the Landsat Enhanced Thematic Mapper Plus (ETM+) of 2003 and 2013 and The Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) of 2023 with spatial resolution of 30m and path 121 and row 065 images were acquired from earth explorer website (http://earthexplorer.usgs.gov).

Satellite	Sensor	Path/Row	Acquisition Date	Spatial Resolution (m)	Data Sources
Landsat 8	OLI/TIRS	121/065	2023/10/01	30	USGS
Landsat 7	ETM+	121/065	2013/09/11	30	USGS
Landsat 7	ETM+	121/065	2003/01/19	30	USGS

Table 2. Error matrix (confusion matrix) showing overall accuracy and Kappa statistics from accuracy assessment of 2003 land cover classification map. The overall accuracy of the classification for the year 2003 was 73% with kappa value of 0.66.

Class	Bareland	Water body	Dryland Agriculture	Forest	Shrub-mixed	Rice Field	Settlement	Total	User Accuracy	Kappa
Bareland	5	0	0	1	1	2	2	11	0.45	0
Water body	0	0	0	0	0	0	0	0	0	0
Dryland Agriculture	0	0	24	8	0	4	0	36	0.67	0
Forest	0	0	0	8	1	1	0	10	0.8	0
Shrub-mixed dryland farm	0	0	1	7	25	0	0	33	0.76	0
Rice Field	0	1	0	0	0	9	0	10	0.9	0
Settlement	0	0	0	1	0	0	9	10	0.9	0
Total	5	1	25	25	27	16	11	110	0	0
Producer Accuracy	1	0	0.96	0.32	0.93	0.56	0.82	0	**0.73**	0
Kappa	0	0	0	0	0	0	0	0	0	**0.66**

Table 3. Error matrix (confusion matrix) showing overall accuracy and Kappa statistics from accuracy assessment of 2013 land cover classification map. The overall accuracy of the classification for the year 2003 was 81% with kappa value of 0.76.

Class	Bareland	Water body	Dryland Agriculture	Forest	Shrub-mixed	Rice Field	Settlement	Total	User Accuracy	Kappa
Bareland	6	0	1	0	0	2	1	10	0.6	0
Water body	0	7	2	0	1	0	0	10	0.7	0
Dryland Agriculture	0	0	21	3	5	1	0	30	0.7	0
Forest	0	0	0	13	1	0	0	14	0.93	0
Shrub-mixed dryland farm	0	0	1	0	36	2	0	39	0.923	0
Rice Field	0	0	0	0	1	9	0	10	0.9	0
Settlement	0	0	0	0	2	0	8	10	0.8	0
Total	6	7	25	16	46	14	9	123	0	0
Producer Accuracy	1	1	0.84	0.81	0.78	0.64	0.89	0	**0.813**	0
Kappa	0	0	0	0	0	0	0	0	0	**0.764**

Table 4. Error matrix (confusion matrix) showing overall accuracy and Kappa statistics from accuracy assessment of 2023 land cover classification map. The overall accuracy of the classification for the year 2023 was 85% with kappa value of 0.79.

Class	**Bareland**	**Dryland Agriculture**	**Forest**	**Shrub-mixed**	**Rice Field**	**Settlement**	**Total**	**User Accuracy**	**Kappa**
Bareland	1	0	0	0	0	0	1	1	0
Dryland Agriculture	0	21	5	0	1	0	27	0.78	0
Forest	0	0	12	1	1	0	14	0.86	0
Shrub-mixed dryland farm	0	3	4	42	0	0	49	0.86	0
Rice Field	0	0	0	0	6	0	6	1	0
Settlement	0	0	0	0	0	4	4	1	0
Total	1	24	21	43	8	4	101	0	0
Producer Accuracy	1	0.88	0.57	0.98	0.75	1	0	**0.85**	0
Kappa	0	0	0	0	0	0	0	0	**0.79**

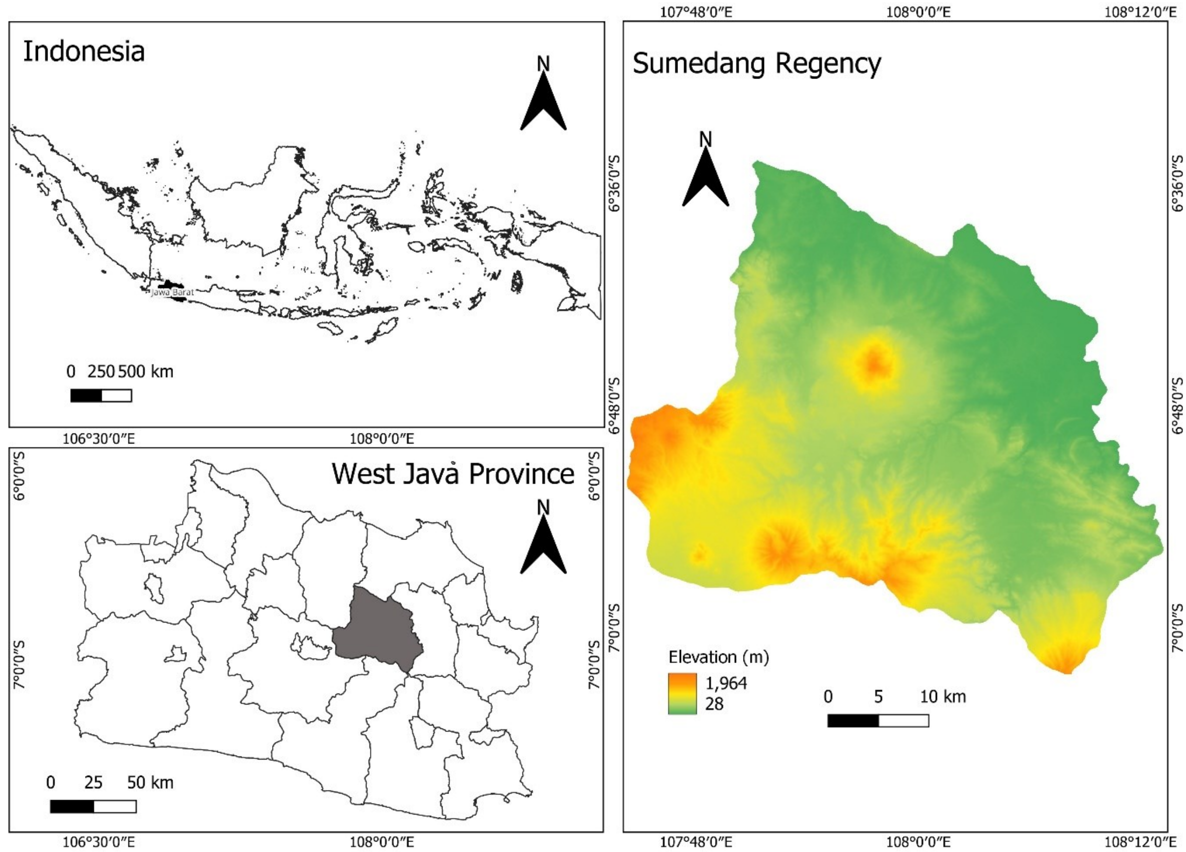


Fig 1. Location and topography of the study area in Sumedang Regency, West Java, Indonesia. The top left shows Indonesia with Sumedang Regency's location marked; the bottom left highlights Sumedang Regency within West Java Province; and the right map details the topography of Sumedang Regency, indicating its mountainous regions.

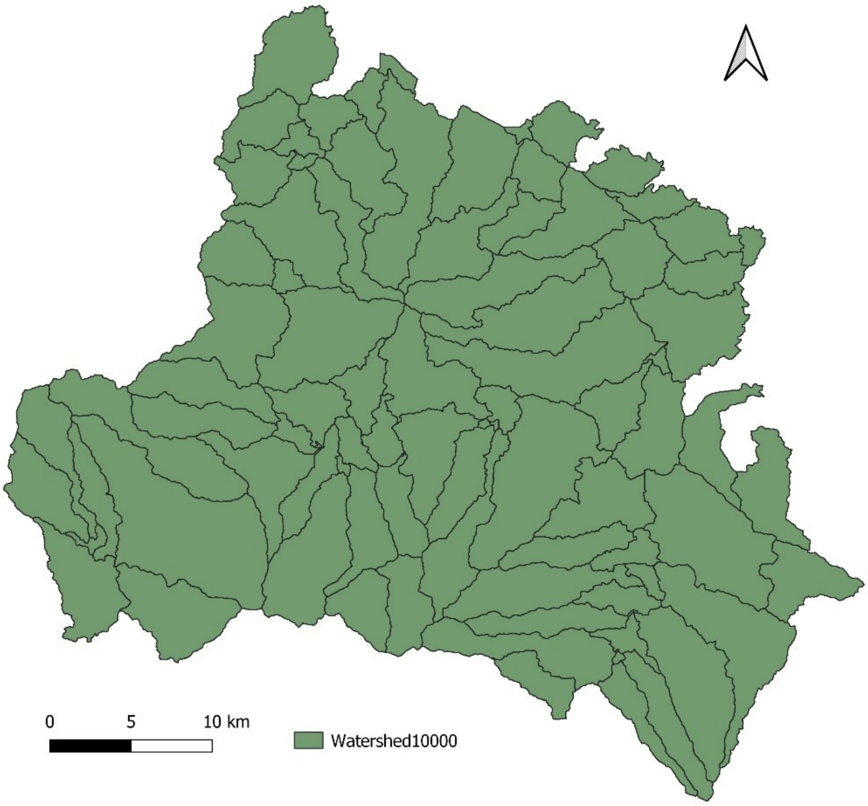


Fig 2. Watershed as unit of analysis showing 104 watersheds with threshold value greater than or equal to 10000. This figure illustrates the delineation of watershed boundaries within Sumedang Regency, highlighting the drainage patterns and hydrological divisions across the region.

Fig 3. Composite Band of Landsat 7 Satellite Image in 2003. Band combination (3-2-1) were applied to create the composite image where band 3 is Red, band 2 is Green, and band 1 is Blue. This satellite image captures the land cover and vegetation patterns in 2003.

Fig 4. Composite Band of Landsat 7 Image in 2013. Band combination (3-2-1) were applied to create the composite image where band 3 is Red, band 2 is Green, and band 1 is Blue. This satellite image captures the land cover and vegetation patterns in 2013.

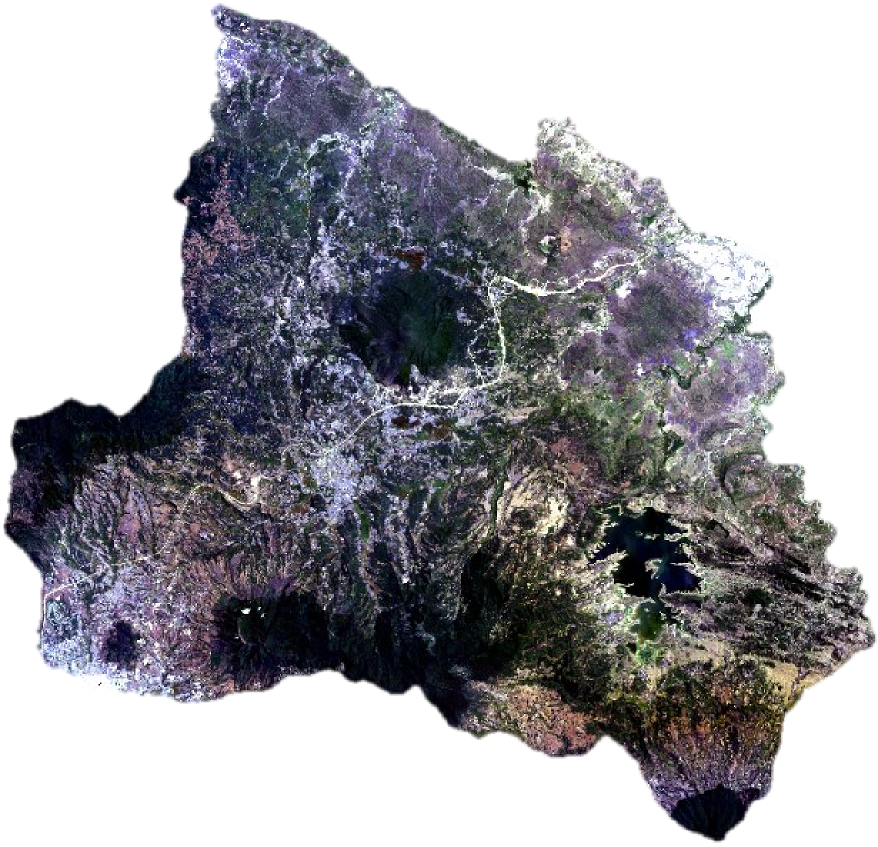


Fig 5. Composite Band of Landsat 8 Image in 2023. Band combination (4-3-2) were applied to create the composite image where band 4 is Red, band 3 is Green, and band 2 is Blue. This satellite image captures the land cover and vegetation patterns in 2023.

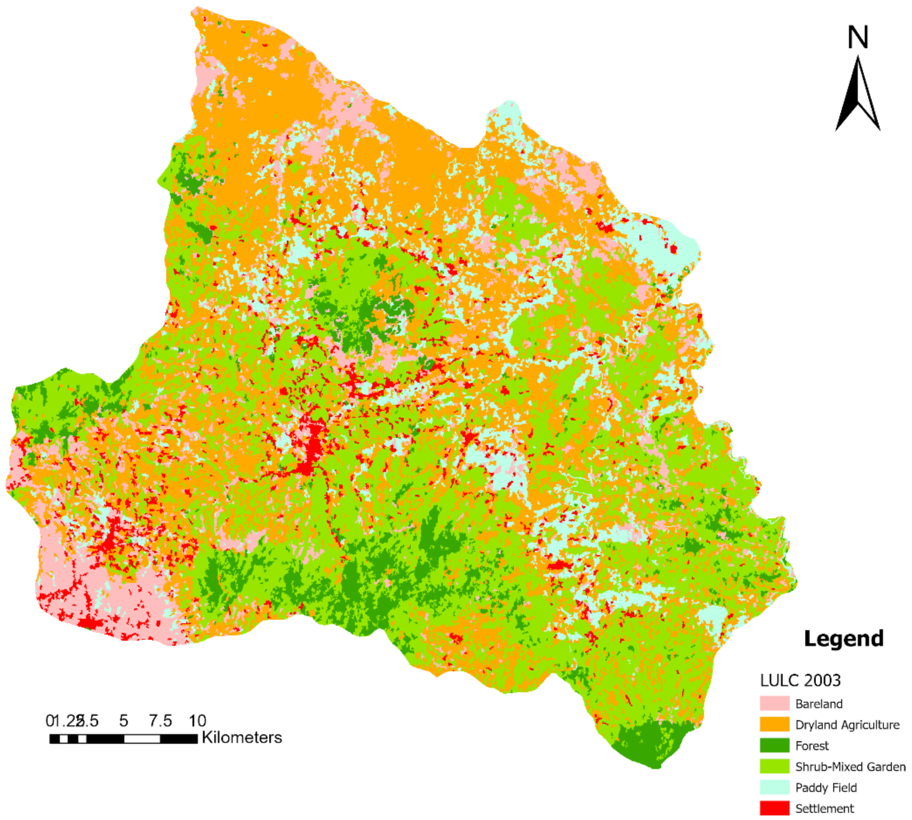
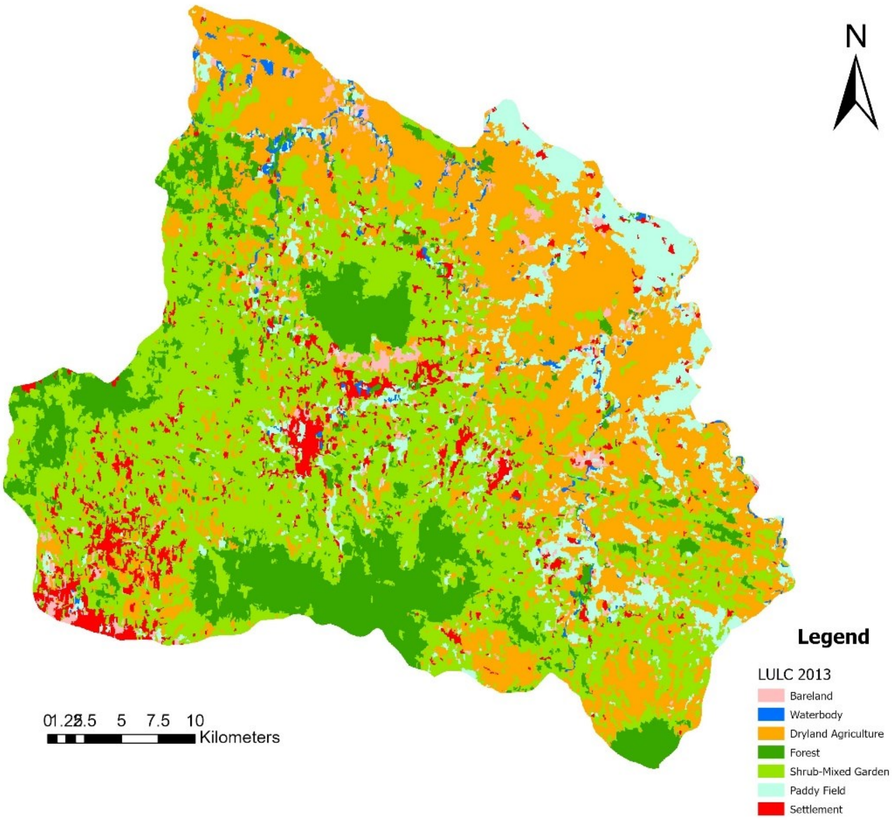


Fig 6. Land use and land cover classification map of Sumedang in 2003. 6 of 7 types of land cover and use were classified. Waterbody could not be detected due to misclassified with paddy field.



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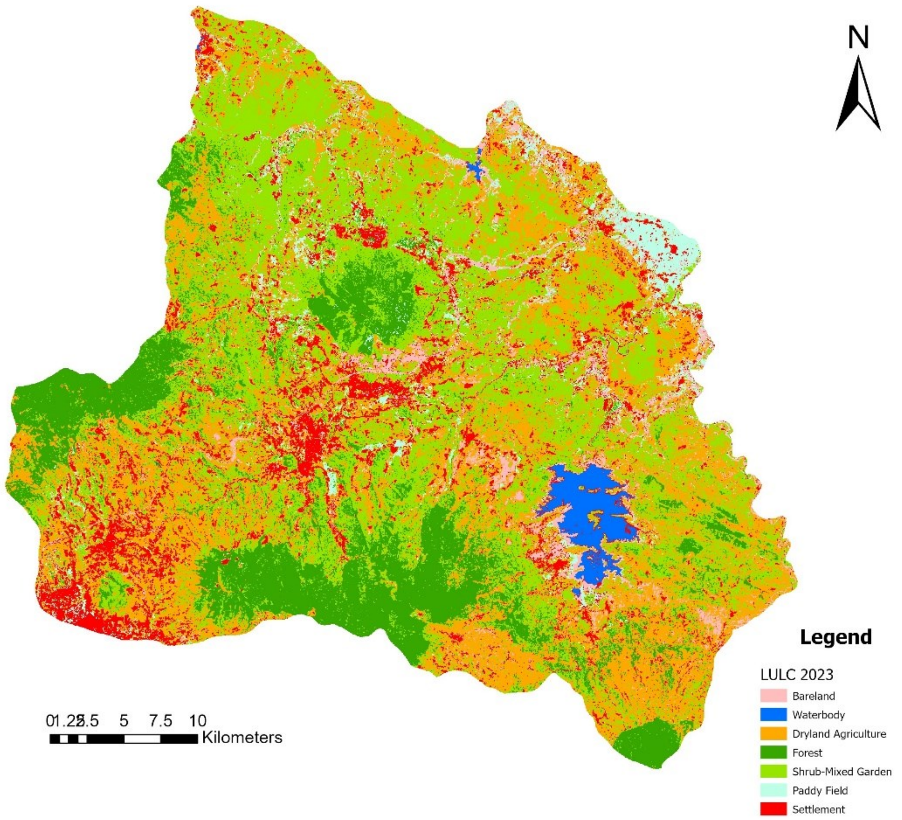

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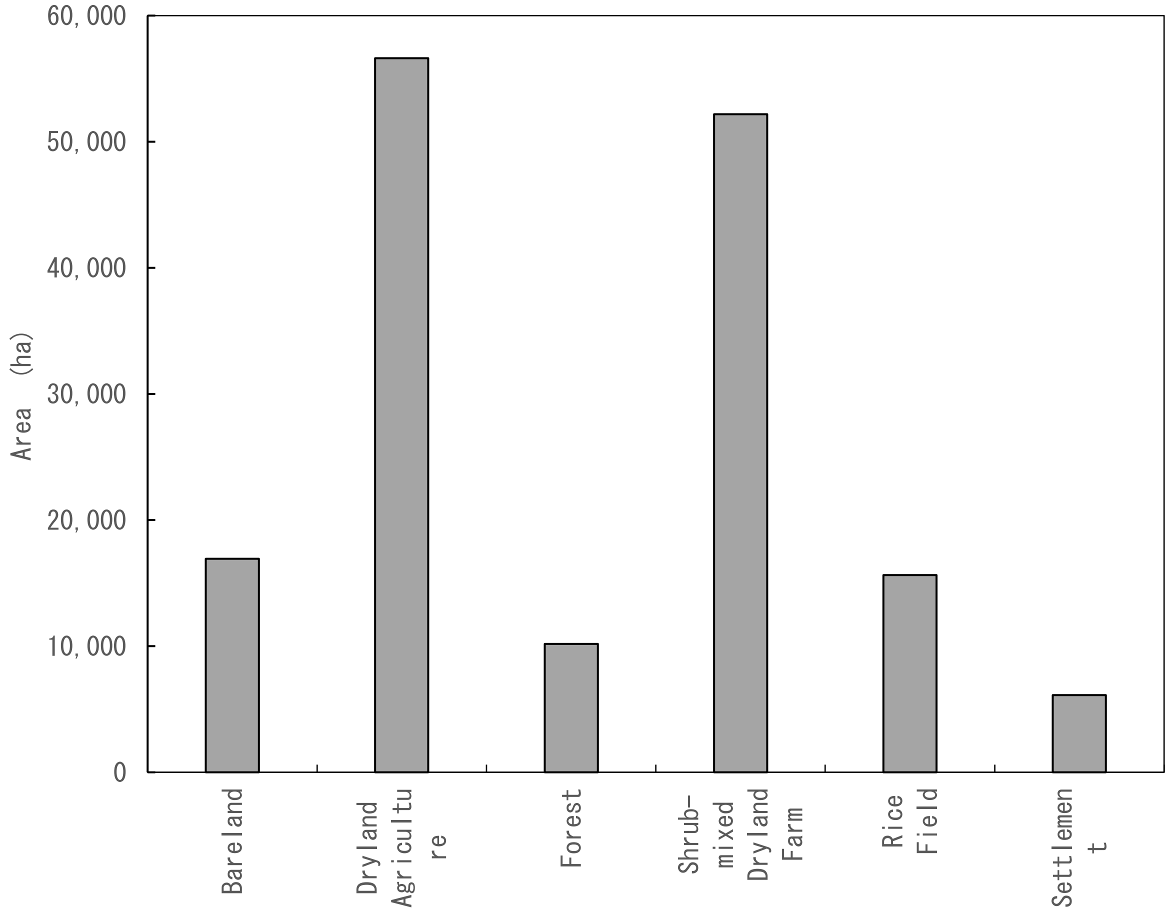

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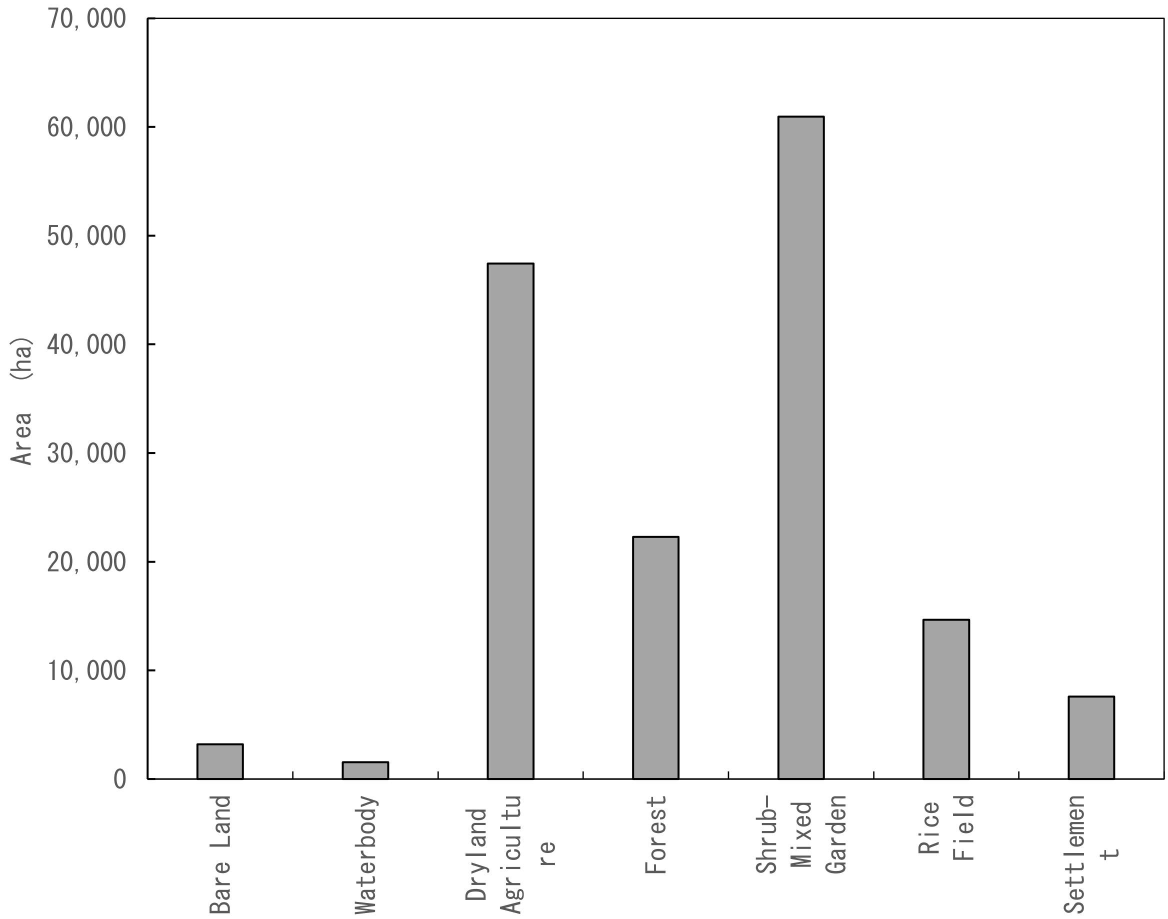

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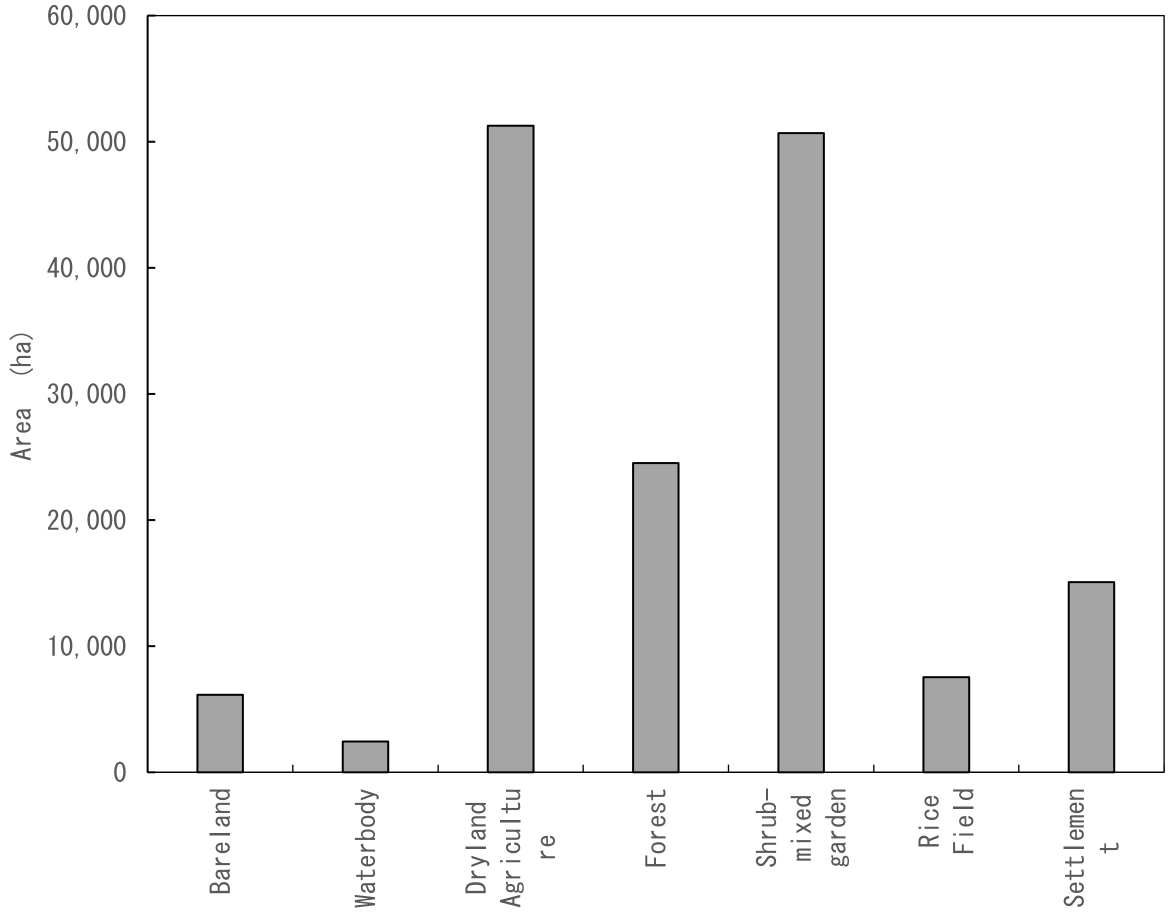

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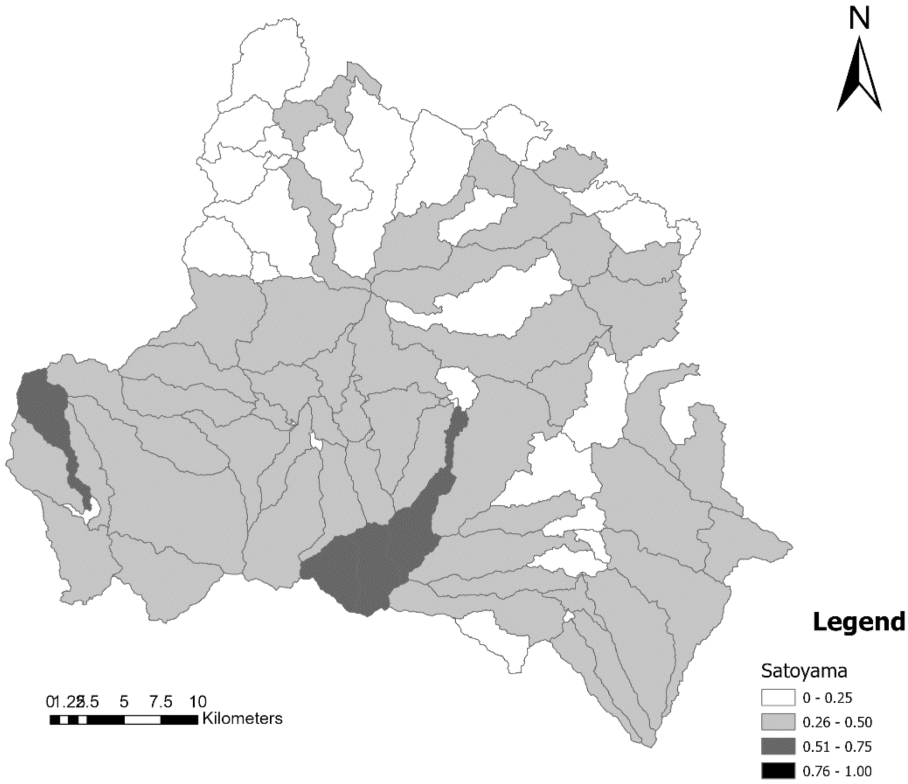

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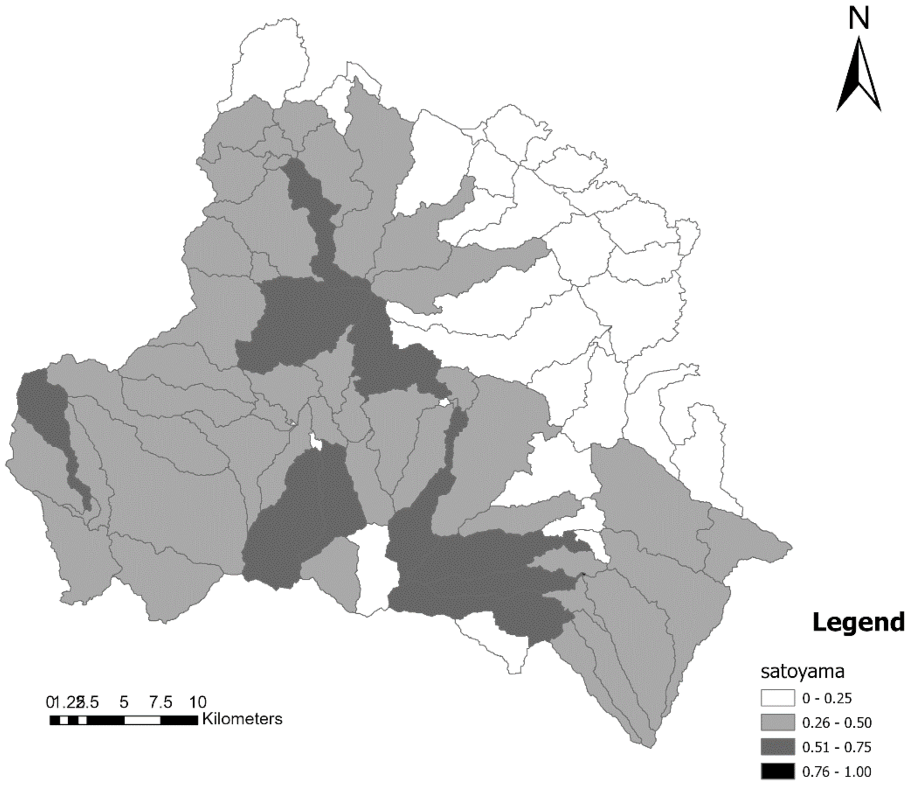

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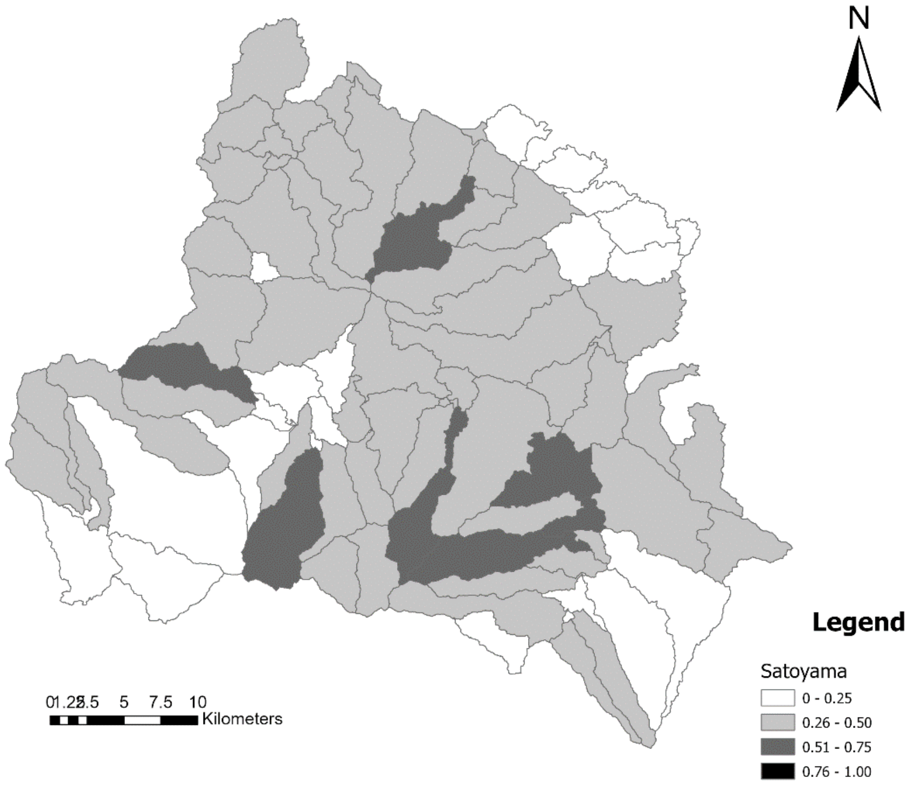

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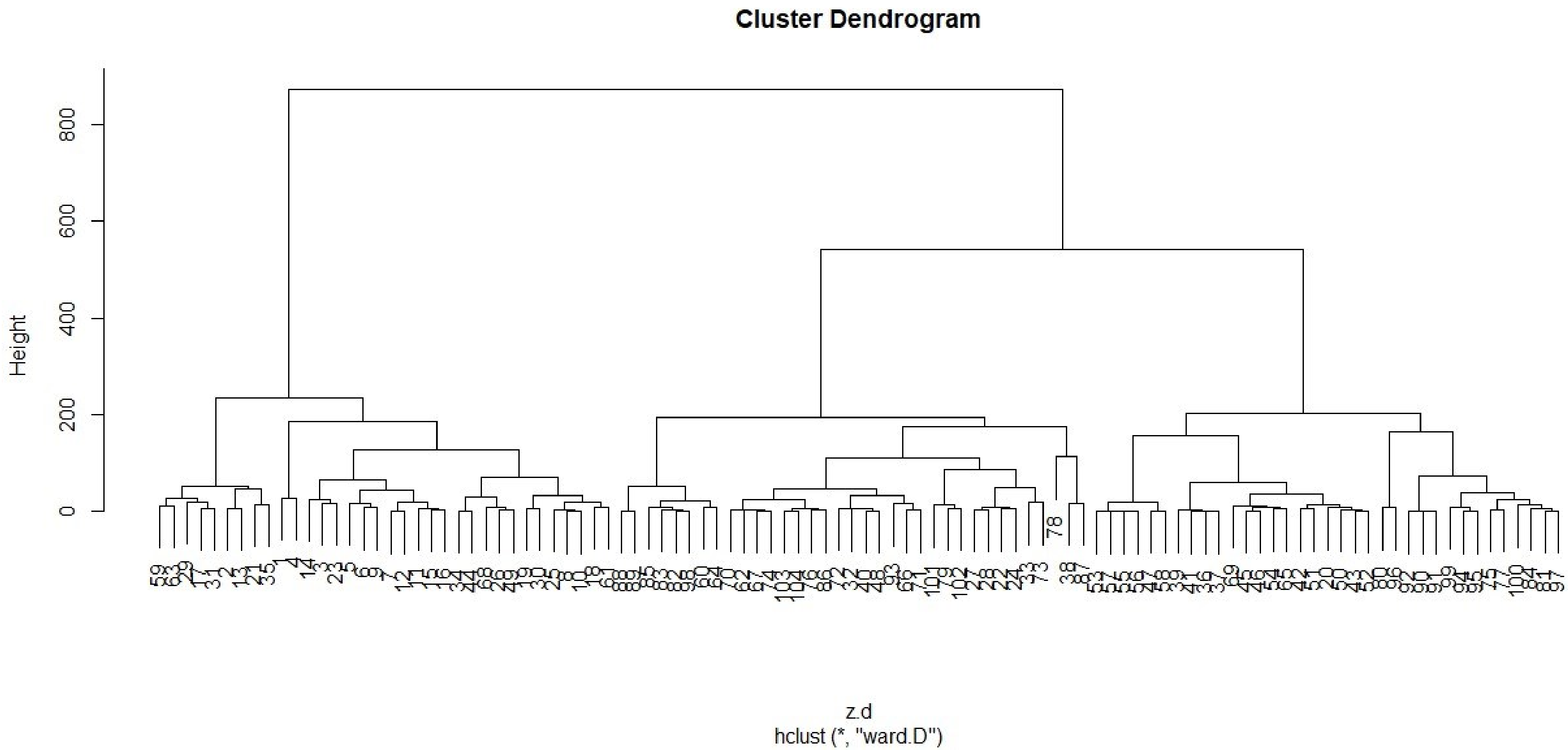

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