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Urbanization and Decline of Old Growth Windbreak Trees on Private Homesteads: A Case Study in Ryukyu Island Villages, Japan

Bixia Chen

Faculty of Agriculture, University of the Ryukyus, Nishihara, Okinawa 903-0213, Japan; chenbx@agr.u-ryukyu.ac.jp; Tel.: +81-98-8958733

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Abstract: Urban trees are under unprecedented pressure and competition worldwide with other land uses. Homestead windbreaks in urban areas are an important part of urban forests because of their proximity to settlements. To aid in the conservation of old-growth homestead trees in the urban setting on Ryukyu Archipelago, Japan, this article surveys the dimensions and spatial distribution of century-old trees planted as windbreaks along homestead borderlines on Ishigaki Island in the Ryukyu Archipelago and the historical change caused by urban sprawl. The homesteads studied in this article do not match the scale of a traditional Western context and usually consist of an area of less than 200 square meters on Okinawa. A combined approach consisting of field surveys and the study of aerial photos was applied to identify changes in spatial distribution of tree lines surrounding the houses in 1945, 1972 and the present. We measured the dimensions of 1659 Fukugi trees with a minimum diameter at breast height (DBH) of 5 cm. The mean tree height, mean DBH and mean estimated tree age were 7.3 m, 26.9 cm and 107.5 years, respectively. Homestead trees are not only useful as windbreaks, timber sources and musical instruments, but have also been historically resilient in the face of strong typhoons and catastrophic tsunamis in the region. Over 60% of the surveyed trees were planted on the east and north sides of homesteads as protection from typhoons and monsoonal winds in the winter. In addition to *G. subelliptica*, other tree species, namely *Podocarpus macrophyllus* and *Diospyros egbert-walkeri*, have been commonly used as homestead windbreaks. However, homestead windbreaks in highly urbanized regions are generally declining and have experienced fragmentation, lower tree density and shorter tree height than those in rural areas. Because of the small number of trees older than 200 years, we assume that high urbanization has jeopardized old-growth trees. The demand for settlement land dramatically increases as the population increases and household-size decreases, creating more households. Therefore, a conservation project involving multiple stakeholders must be developed to conserve old-growth trees in urban settings.

Keywords: coastal forests; heritage trees; private residential parcels; tree conservation; urban trees

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1. Introduction

The homestead windbreak landscape on the Ryukyu Islands, established approximately 300 years ago, is an important part of urban forests and residential landscapes, as its proximity to human settlements, and which provides psychological, sociological, and esthetic benefits. However, the remaining old-growth homestead trees on private residential parcels have been largely neglected by the administration in Japan [1]. In contrast, considerable effort has been exerted to improve the biodiversity and natural environment in urban settings. Natural hazards and fast urbanization affect the removal of planted trees in the central cities of the Okinawa Prefecture. Moreover, no active public conservation program exists in the Okinawa Prefecture because of private land ownership [2], which allows homeowners to dispose of trees freely without legal regulations or the responsibility to secure good care and management for the trees. An appropriate conservation scheme must be established to conserve traditional residential landscapes and old-growth windbreaks.

Many studies focus on identifying a wide range of ecological functions performed by urban forests [3]. The percentage of greenspace, particularly of trees, has the greatest influence on the ecological performance of urban areas [4–6]. The role of urban trees in carbon sequestration [7,8], air pollution mitigation [9], air-cooling effect [10], energy conservation [11] and storm water attenuation [12], must be considered. Carbon sequestration in urban trees is considered an especially important ecosystem service because of its role in mitigating the adverse effects of climate change [3,13]. Moreover, buildings with more tree shade consume lower energy for cooling [14,15]. Urban "greening" is important for enhancing the economic and esthetic value of urban housing [16,17], although a few studies [13,18] report that urban trees provide a minimal increase in property prices in developing countries. Research on the structure, function, and conservation strategy of residential landscapes, particularly privately owned urban forests, is largely lacking compared to the significant ecosystem services provided by urban forests [19].

Moreover, old-growth trees have ecological and spiritual/religious value, are an invaluable national asset [20] and sequester more carbon than young trees [19]. A heritage tree selection criterion for old-growth conservation developed by Jim [21] states that, regardless of species or provenance, trees older than 100 years and a small number of commemorative trees must remain healthy and robust. The first step for conserving old-growth trees in the Ryukyu Islands is to inventory the locations and dimensions of existing trees. Knowledge of the size and location of large old trees is critical to guide management [22,23] and understanding the changes in old tree distribution and population can help estimate the past impact and future potential of forest ecosystem services [24].

Urban populations are the primary drivers of global environmental change [25]. Air pollution caused tree and forest decline in the East Asia region [26]. The hypothesis for this study is that urbanization in the island city has caused homestead windbreak decline. A social-ecological systems approach will be applied to evaluate the drivers of spatial distribution changes of homestead trees that serve as windbreaks. Residential landscapes are coupled and intricately linked with human environmental systems. A multidisciplinary framework is needed to understand the complex social-ecological system [27].

Surveying the structure and function of large old trees growing in private residential areas greatly contributes to the current research gap in the international urban forest field, adding to the knowledge related to the coexistence of human settlement and woody windbreaks. The overall objective of this research is to investigate how social factors affect the changing spatial distribution of homestead windbreak cover in Okinawa from 1845–2017. Furthermore, the purpose of this article is to provide tree inventory information for city planners and forest management staff who wish to further understand the old-growth forests surrounding homesteads. As the Ryukyu Islands extend in a chain over 1000 km from the south part of Kyushu to the southern-most part of Japan, the geographical specifics of the characters of homestead windbreaks are discussed. Additionally, an appropriate management strategy based on this case study is addressed. Specifically, four research questions are addressed and discussed in this article.

(1) What is the inventory of the remaining old trees and what are their dimensions?
(2) What is the actual spatial distribution of the remaining trees in the tree belts surrounding the homesteads?
(3) How are the surveyed trees different from trees at the other survey sites in the Okinawa Prefecture? What do these differences mean for management and conservation?
(4) What are the historical changes leading to a decline in the number of trees? Why and how has urbanization affected forest degradation? Did old trees survive the great historic tsunami in 1771?

2. Homestead Windbreak on the Ryukyu Archipelago

The Ryukyu Islands are isolated from the mainland and, therefore more vulnerable to natural disasters. The Okinawa Prefecture, Japan, consists of 160 islands; strong winds have caused significant damage to fields and settlements. Tree belts were planted during the Ryukyu Kingdom Period (1429–1879) to protect houses and farmlands from strong winds in the coastal areas of the Ryukyu Archipelago. The landscape established during this period was structured according to the Chinese fengshui concept of *hougo* (embraced protection). Before World War II, coastal forests and homestead windbreaks were prevalent on the Ryukyu Islands. These trees are still widely distributed among the Ryukyuan villages [28,29]. However, most old trees and forests were destroyed by fires during World War II or removed after land development projects undertaken to consolidate fragmented farmland in the 1960s. The conservation of vanishing old-growth trees in the traditional village landscape is vital because of their historical and cultural value [30].

Homestead trees on the Okinawa Islands are man-made forests, which we define in this article as trees planted at the borderline/periphery of a private residence that primarily function as windbreaks. Homestead is a literally translation of the Japanese term *yashiki*, which means a house with a garden, regardless of its size. In this article, I use the English word homestead in that sense, which is slightly different from the traditional use in the United States and Australia, denoting a large land area. In early American history, a homestead was an area of rural land of 160 acres given to people as the country was opened to European settlement. In Australia, the term typically refers to a much larger land area, which includes domestic dwellings and a range of outbuildings (sheds, stables, and other structures) to support agricultural and pastoral activities. The Australian homesteads are measured in tens or hundreds of square kilometers. This term does not seem to match the scale of the undertakings in the Japanese context, where a homestead usually consists of an area of less than 200 square meters on small islands on the Ryukyu Archipelago. A rural farmstead in the past usually consisted of a house, a pig hut and a small home garden in the front or at the back of the house. Windbreaks were planted along the homestead vicinity. A Ryukyu village during the pre-industrial era was usually clustered and reduced in size to fit along the narrow flat land near the seaside for convenience. Although some planned village settlements remain, most have been urbanized and lost the farm house function.

The Fukugi tree (*Garcinia subelliptica*) was only naturally distributed in tropical regions, such as the Philippines, Taiwan and Okinawa [31]. The straight trunk and dense, thick leaves provide wind and fire resistance [2].

Previous case studies [30,32–34] report the existence of well-preserved homestead woodlands in the rural regions of Okinawa. We recently extended our survey of the remaining Fukugi trees to the Yaeyama Island group—the southernmost islands in the Okinawa Prefecture—to clarify the dimensions and spatial distribution of the remaining homestead trees on isolated land and coastal villages.

3. Materials and Methods

The survey site was selected for: (1) the location in downtown Ishigaki City, which is highly and densely urbanized with, for example, apartment buildings; and (2) the presence of districts or villages with the most well-preserved homestead woodlands and existing historical aerial photos. The survey site, consisting of Hirae and Maezato villages (Figure 1), is located at 24°2220″ N, 12°1030″ E on the southern part of Ishigaki Island. The two villages are circular in shape, abut each other and are separated only by a road. The village of Hirae was divided into the villages of Hirae and Maezato in 1665 [35]; Maezato was later established in the southern part of Hirae village. From a historical and landscape perspective, the two villages are an integrated village landscape.

Hirae and Maezato villages had populations of 2741 and 5132, respectively, as of December 2015 [36]. In 1771, the populations of the two villages were 1178 and 1173, respectively. The 1771 record high 38 m Meiwa tsunami killed 560 and 908 people and left 618 and 265 survivors in Hirae and Maezato, respectively [35]. Under the modern Ryukyu *yosebyakushou* system (*Yosebyakushou* is a compulsory system of the immigration of a farming population to villages with drastically reduced populations.), 419 farmers emigrated from Iriomoto Island—approximately 10 km west of Ishigaki Island—to help rebuild Maezato village after the Meiwa tsunami [35]. The area was densely populated before the tsunami. Maezato is closer to the seashore than Hirae and suffered more severe damage. Only stony fields remained of Maezata Village after the catastrophic wave retreated [35].

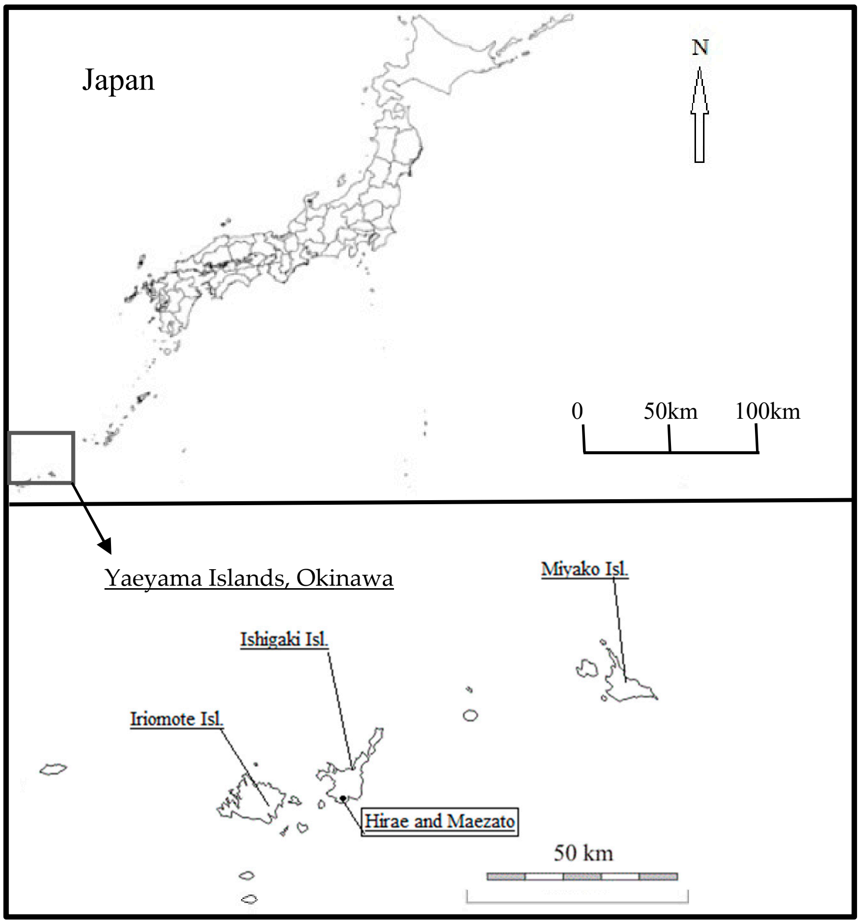

Figure 1. Location of Hirae and Maezato villages.

Field surveys were conducted to collect the diameter at breast height (DBH) (measured at a height of 1.3 m) and the diameter measured at a height of 20–30 cm above the ground. All Fukugi trees in the village with a DBH greater than 5 cm were surveyed. Tree age was estimated based on DBH (see below). All Fukugi trees with a DBH greater than 25 cm were estimated to be approximately over 100 years old [37]. A local volunteer team assisted in data collection in November 2017 and a supplementary survey was conducted in March and November of 2018.

The methods for estimating the age of Fukugi trees are Equation (1), derived by Hirata [38] and Equation (2), developed by Nakama et al. [39]:

$$y = x_1 \div 2 \times 8 \tag{1}$$

$$y = x_2 \div 2 \times 6.2 \tag{2}$$

where y is estimated tree age, x_1 is the DBH (cm) at 1.3 m above ground level and x_2 is the diameter (cm) at approximately 0.2–0.3 m above ground level. We adopted Hirata's method (Equation (1)), because the DBH measured at 0.2–0.3 m above ground level was not available for many trees (because the lower parts of their stems were surrounded by and buried in stone fences). Age classes of 50 years were used in the analyses because of possible calculation errors. Statistical analysis was performed using IBM SPSS Statistics (Version 24, Armonk, NY, USA).

The trees surrounding each private residential plot were counted, and their cardinal direction relative to the house was noted. Maintaining a dense tree belt on the east and north sides of homesteads occurred elsewhere on the Ryukyu Islands [33,34,40–42]. On the east and north sides of the houses, the trees were counted to ascertain how the trees had been maintained. We assumed that house owners selectively cut Fukugi trees for specific reasons, such as use as timber or after strong typhoons. However, to maintain the windbreaks, the local population did not clear-cut all the trees at once. Selective cutting allowed the oldest trees to survive, thereby providing historical data regarding residential land changes. Next, the locations of the Fukugi trees with a DBH > 5 cm were identified on a residential map (Zenrin Co., LTD, Kitakyushu City, Fukuoka Prefecture, Japan). Belts of other tree species were also identified. The surveyed trees were classified into five groups according to estimated age: 100–149 years old, 150–199 years old, 200–249 years old, 250–300 years old and over 300 years old and the age of each tree was recorded. The spatial distribution of the tallest Fukugi trees on each property was also mapped. The cardinal directions of trees relative to the homesteads were recorded using the residential map.

Aerial photos of the area were studied to compare tree-belt distribution changes over time. We collected photos taken in 1945, 1962 and 1977 from the Okinawa Prefectural Archives and the Geospatial Information Authority of Japan (Figure 2). The 1962 photo was not clear enough to identify tree belts. We observed that the tree distribution in 1977 was very different from the present one. Our observations were supported by the results of past studies that determined that trees were destroyed by fire during World War II and that road construction and other village infrastructure improvement projects were the primary causes of tree cutting during the 1960s and 1970s [40]. Therefore, the photo taken by the United States Army before World War II was selected for comparison with the current situation.

Figure 2. Aerial photo of (**upper**) Hirae and (**lower**) Maezato taken by the United States Army in 1945. (source: library of Cheju University, South Korea).

4. Results

4.1. Tree Age and Dimension

A total of 1771 Fukugi trees in the Hirae and Maezato villages were evaluated (Figure 3). However, 12 tree height measurements and nine tree DBH measurements (and consequently nine estimated ages) were missing from our record. The latter data were missing because the lower trunks of these trees were embedded in a stone fence, prohibiting tree diameter measurements.

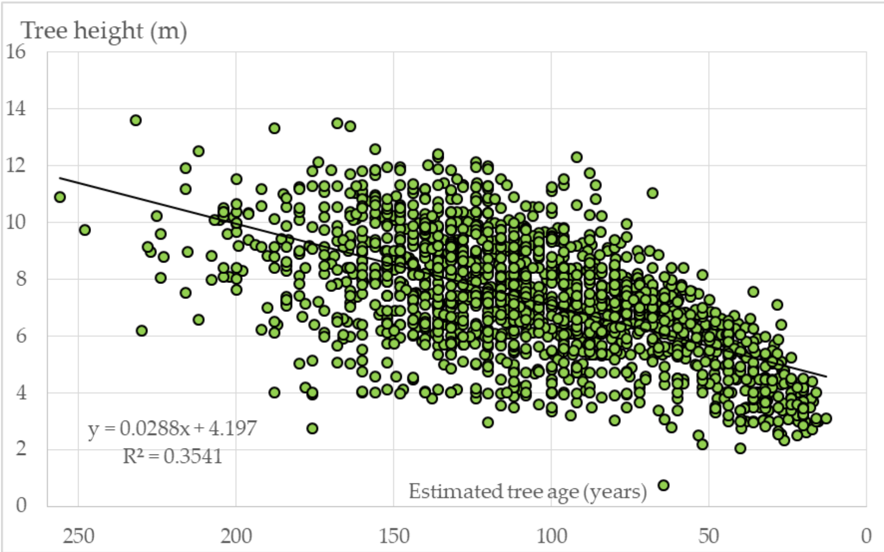

Figure 3. Distribution of age and height of Fukugi trees in Hirae and Maezato.

Most of the surveyed trees were <9 m in height and <130 years old (Figure 3). The values of the mean and median tree heights were similar (7.25 m and 7.31 m, respectively) (Table 1). The mean and median DBH were 26.4 cm and 27.7 cm, respectively. The mean and median tree ages were 106 and 108 years, respectively. The smallest 5% of the surveyed trees were <3.2 m tall, had a DBH of <8 cm and were <32 years old; the largest 25% were >8.8 m tall, had a DBH of >34 cm and were >136 years old. The biggest tree had a DBH of 64 cm and was approximately 256 years old. The tallest tree was measured to be 13.6 m.

Table 1. Dimensions of Fukugi trees at the survey site.

		Tree Height (cm)	DBH (cm)	Tree Age (Year)
N	Valid	1719	1717	1717
	Missing	7	9	9
Mean		725.5	26.4	105.7
Median		731	27.7	108
Std. Deviation		215.3	11.0	44.2
Minimum		73	3.2	12.8
Maximum		1360	64	256
Percentiles	5	367	8	32
	25	580	18.2	72.8
	50	727	27	108
	75	880	34	136

4.2. Spatial Distribution of Houses and Age Distribution

We measured 38 trees older than 200 years, including one tree older than 250 years (Table 2). The oldest tree was in the center of the villages and 37 trees less than 250 and older than 200 years were widely distributed on 32 different homesteads (Figure 4). The spatial distribution map will be used to raise the residents' conservation awareness and basic information for landscape conservation master plan in the future.

Table 2. Age distribution of Fukugi trees in Hirae and Maezato.

Survey Site	Total Number	Tree Number by Estimated Age (Year)					
		0–49	50–99	100–149	150–199	200–249	250–299
Hirae and Maezato	1717 *	223 (13) *	510 (30)	718 (42)	228 (13.3)	37 (2.1)	1 (0.06)
Hirae	1350	192	451	519	158	30	0
Maezato	367	31	59	199	70	7	1

* numbers in parentheses are percentages.

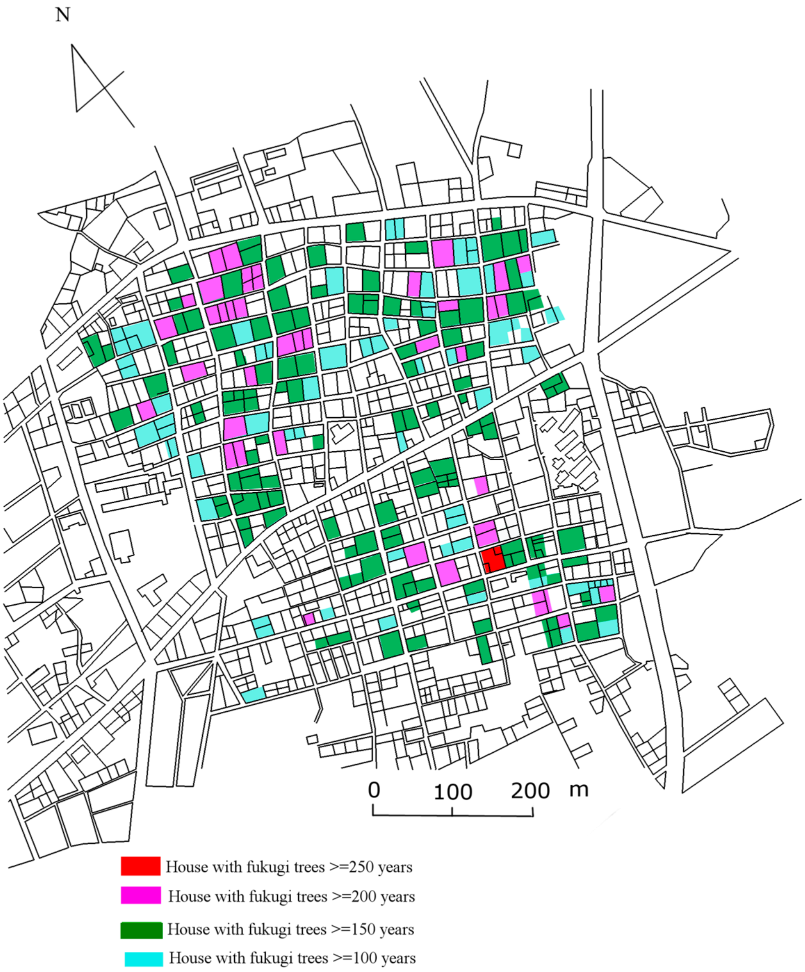

Figure 4. Spatial distribution of homesteads in Hirae and Maezato with old Fukugi trees.

The tree belts surrounding the homesteads were surveyed and recorded (Figure 5). Like the trees in many other villages on the Ryukyu Islands, Fukugi trees are the most common tree species planted around homesteads. Two other common tree species are *Podocarpus macrophyllus* and *Diospyros egbert-walkeri;* other species, such as *Ficus microcarpa*, are also present. The former two species, *P. macrophyllus* and *D. egbert-walkeri,* are considered useful for local populations. *D. egbert-walkeri* can be used to make a traditional musical instrument (*sanshin*) and *P. macrophyllus* is an important timber source used for pillars in traditional timber houses. Additionally, old-growth *D. egbert-walkeri* is common and generally grows alone.

Figure 5. Remnant Fukugi tree lines in (**left**) 1945 and in (**right**) 2017. Identified Fukugi tree lines marked in green.

4.3. Cardinal Directions of Standing Trees

The four directions were approximated, and north did not necessarily refer to true north in this study. Approximately 92% of all trees were on the north (26.8%), south (14.0%), east (35.5%) or west (15.6%) sides of each homestead. The other 8% of trees were located on the corners and were categorized as "Other." Approximately 2.4%, 1.7%, 2.8% and 1.2% faced northeast, northwest, southeast and southwest, respectively.

Approximately one-third of the Fukugi trees (35.5%) were on the east side of homesteads, and 26.8% were on the north side. South-facing trees had the lowest occurrence (14.0%), followed by west-facing trees (15.6%).

4.4. Urban Sprawling and Decrease in Tree-Belt Distribution

The number of homesteads with Fukugi trees has decreased by approximately 30% since 1945 (Table 3). Additionally, the length of the tree belts and tree density decreased (Figure 5). The vanishing tree lines can clearly be seen in the two aerial photos (from 1945 and the present) (Figure 5). More specifically, the tree belts in the center of the residential area vanished more quickly than those on the periphery.

Population increase and decreasing household size (because of changes in family structure from extended to nuclear families) in recent decades increased urban settlements and land use. The population increased by eight times from 1945–2015 (Figure 6). Average household size was five before 1945; the average household now has approximately two people (Figure 6).

Table 3. Loss of Fukugi tree lines from 1945–2017 by geographic area.

	Homesteads in the North Part of Hirae and Maezato				Homesteads in the South Part of Hirae and Maezato			
Westside to Eastside	Homestead Number	Number of Homesteads with Fukugi Trees			Homestead Number	Number of Homesteads with Fukugi Trees		
		1945	Present (2017)	Decrease Rate (%)		1945	Present (2017)	Decrease Rate (%)
Line 1	13	10	10	0.0	12	10	8	16.7
Line 2	20	19	13	30.0	11	11	8	27.3
Line 3	31	28	25	9.7	14	14	8	42.9
Line 4	22	17	13	18.2	15	14	11	20.0
Line 5	19	17	4	68.4	15	13	9	26.7
Line 6	23	20	7	56.5	10	10	6	40.0
Line 7	18	17	10	38.9	10	9	6	30.0
Line 8	14	12	9	21.4	–	–	–	–
Line 9	15	15	11	26.7	–	–	–	–
Total	175	155	102	30.3	87	81	56	30.9

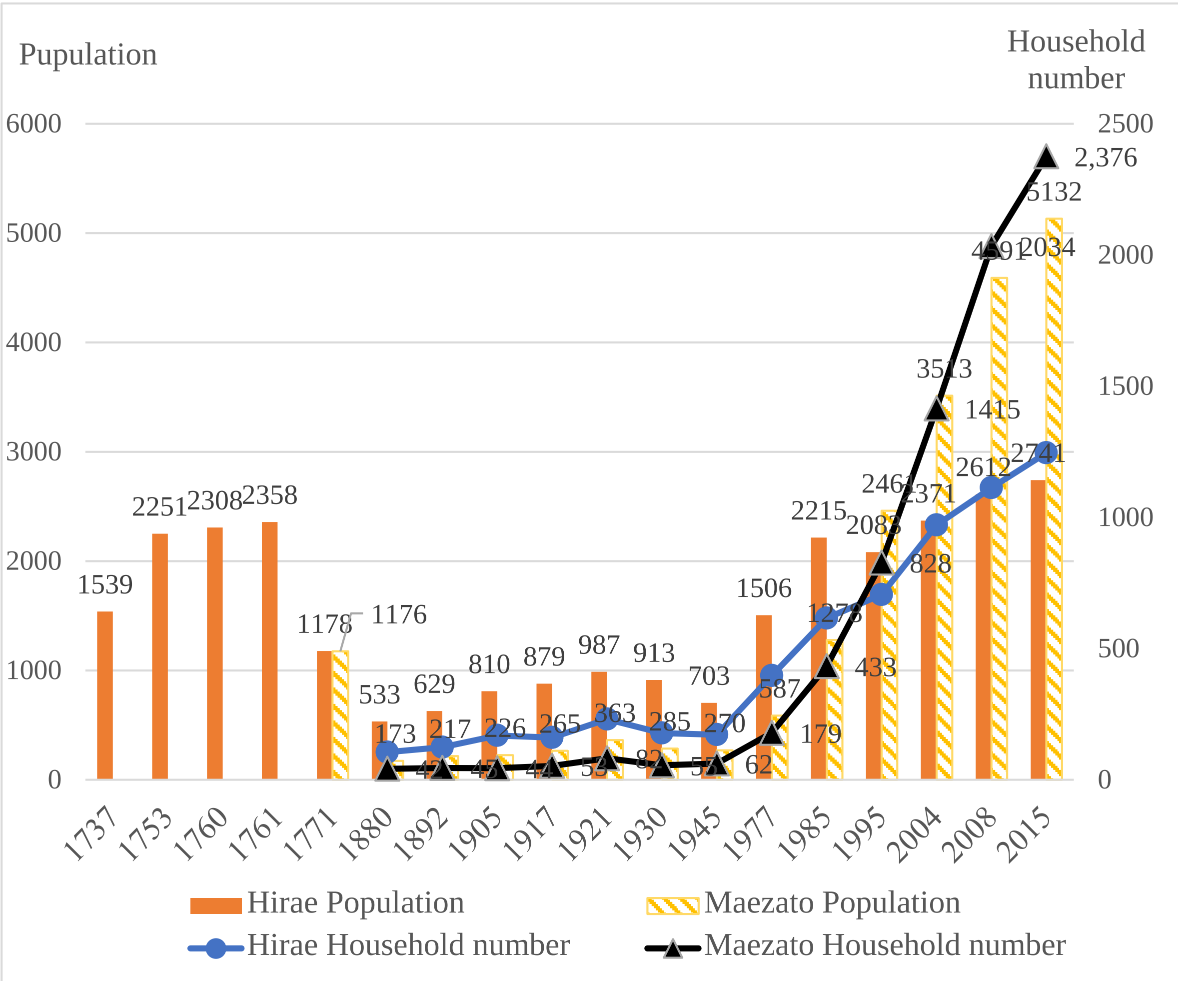

Figure 6. Population and household number increase.

5. Discussion

Homestead windbreaks in highly urbanized regions are in decline and experience fragmentation, lower tree density and shorter tree height compared to previous survey sites on Okinawa and the

Ishigaki Islands [32–34,43]. For example, the tallest trees were 17.7 m and 20.3 m on Hateruma Island and Shiraho Village on Ishigaki Island, respectively. The mean DBH of the surveyed Fukugi trees in Hirae village and Maezato village were slightly higher than that of the trees on Taketomi Island, with an average height of 13.6 m. Trees have been kept at a lower height and urban tree density is much smaller than in the rural setting of previous survey sites.

Because there are fewer trees older than 200 years on Takitomi Island (which is close to Ishigaki Island), we assume that high urbanization has jeopardized old-growth trees. The oldest trees primarily dwell in low-stress and spacious conserved sites [44] and tree survival and growth are affected by the increased surface temperature of paved land [45]. The mean and median DBH of the Fukugi trees in the Hirae and Maezato villages are almost the same as those from previous studies [43]. The density and length of tree belts have declined dramatically since the 1970s, due to the competition for land use as a result of dense human settlement and the rapid urbanization of the islands in the southernmost part of Japan [40]. Urban sprawl and construction of high-rise apartment buildings are the primary reasons for tree-belt degradation in Hirae and Maezato and are caused by increasing population and development of nuclear households. The position of trees in different cardinal directions supports a windbreak function. The location pattern was similar when comparing Hirae and Maezato to previous survey sites [32–34].

The study found that coastal homestead windbreaks provide significant services for preventing houses from natural hazards, such as typhoons, salt water spray and tsunamis. Fukugi trees and trees of other species protect houses in coastal communities in Okinawa from frequent typhoons. From historic records, we know that nearly all trees were destroyed in the Great Tsunami of 1771—the second largest tsunami ever recorded. However, by studying the ages of the remaining Fukugi trees, we found some of the large Fukugi trees survived. The current tree distribution reveals that trees were planted around houses after the Great Tsunami of 1771. The survival of multiple Fukugi trees in the historic tsunami is consistent with another Shiraho village site [34].

The demand for settlement land dramatically increases with population growth and decreasing household size creates more households [46–48]. Therefore, high-rise apartment buildings were constructed in old residential communities to accommodate the large population increase; additionally, urban development has extended into the surrounding areas. Unlike the rapid increase in residential areas, new tree plantation area did not change from 1945 to the present. The spatial distribution seen in the aerial photos indicates that people planted almost no trees around residences in the past 100 years after the Ryukyu Kingdom was formally dissolved to form the Okinawa Prefecture in 1879. A lack of environmental legislation is also a problem threatening Fukugi tree conservation. To date, the local landscape ordinance does not accompany with any penal provisions [1]. In addition, in some cases, the local governments were responsible for old-growth tree cutting for the reasons of potential risks from typhoon-damaged trees [1].

This article aims to inform policymakers and urban planners (at the city and prefecture levels) about the risk of allowing the number of old-growth trees on the urbanized part of the island to continue to decrease. Air pollution, land use competition, a deteriorating ecological environment for tree growth and abandonment of appropriate tree management programs are jeopardizing urban old-growth trees. Government decisions at the city and prefecture level and the actions and behaviors of residents play a vital role in determining the nature of the urban landscape and biodiversity management.

The benefits provided by urban trees should be emphasized and a change in public awareness of the need for the development of procedures for tree conservation and management is needed. Trees were planted as windbreaks for the houses of people living on the island of Okinawa and became useless for many home owners when concrete houses—built using improved architectural technology—became strong enough to resist wind [49]. Identifying the diverse sociocultural values of ecosystem services is increasingly important for the planning and management of forest resources [50–52]. Alternative uses of Fukugi trees, such as beautification as a tourist attraction [53], should be demonstrated to administrative staff and residents to develop conservation awareness. A conservation project involving multiple stakeholders is urgently needed for the preservation of old-growth trees in urban settings.

6. Conclusions and Research Limitations

This study contributes to an understanding of the importance of urban greening and adds to the shortage of global research on the relationship between urban greening and the island topography of East Asia [3]. The survey of homestead tree belts in an urban context was first conducted on the islands of the Okinawa Prefecture, Japan. Local people constructed tree belts as homestead windbreaks, consisting primarily of Fukugi trees. Other species were planted in an orderly way to protect houses from frequent, strong typhoons. Our inventory of the remaining old-growth trees, including their height, girth and spatial distribution examined and compared to the results obtained from previously studied sites in the Okinawa Prefecture.

This study has some limitations. A social-ecological systems approach should include integrated assessment indicators of social and ecological factors. This study addressed only vegetation structure and urbanization, but the ecological impacts of homestead windbreaks should also consider air pollution, provision of habitat, carbon storage and local temperature regulation. Social factors, such as resident perception of windbreak management, property value effects, and household owner income should be included in future studies.

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