GIS analysis for vulnerability assessment of salt damage on coastal agricultural fields: a case of Taro Patch in the Republic of Palau

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Abstract. Due to the global climate change, sea level rise and storm surges are worried to accelerate salt damage to coastal agricultural fields. The Republic of Palau, a small island nation in the Pacific Ocean is suffering from increasing taro patch abandonment. The purpose of this paper is to clarify the characteristics of taro patches which are damaged by seawater based on the GIS analysis and clusterings, such as elevation, distance from the sea, slope, catchment area, and area of a taro patch. The target area was the Babeldao Island, which is the largest island in Palau. The results showed that the taro patches were mostly distributed in less than 10 m in elevation, within 1 km in distance from seawater and on slopes below 3%. We divided taro patches into two clusters by k-means clustering; cluster 1 which the elevation was low with catchment area and area of taro patch were small; cluster 2 which the elevation was high with catchment area and area of taro patch were large. These results imply that the large catchment area might lead to suppression of salt damage.

1. Introduction

Current and future climate-related drivers of risk for small islands include sea level rise, tropical and extratropical cyclones, increasing air and sea surface temperatures, and changing rainfall patterns. Soil salination from inundation is one of the impacts from those drivers on ecosystems and natural resources and threatens the sustainability of agriculture [1].

Taro, which is an inclusive term of araceous plants with edible corms, is indispensable for Palauan people as a staple food. Figure 1 is a schematic of a Paluan traditional village for the reference to a picture in the possession of Bureau of Art and Culture. The taro paddy field is drawn in the center of this picture and called ‘Taro Patch’. Each taro patch is flat and partitioned into small grids and connected to a stream via small channels for the purpose of irrigation and drainage. The irrigation system allows water to enter on top and the side of the soil as well as the bottom of the soil. The field is protected by embankments. An outflow is created at the downstream end of the taro patch to allow excess water to flow back into the mainstream. This structure ensures a steady flow of water that neither dries up or floods the taro patches [2].
The taro patches are important in terms of cultural succession as well as food supply and their sustainable management that is expected. However, the area of abandoned fields is currently increasing. There should be some reasons for this abandonment, and the soil salination is regarded as one of the major reasons, especially after a big typhoon attacked in 2013 [3]. Kimura et al. continuously measured the groundwater level and water salt concentration at two taro patches in Babeldaob Island and revealed that the water salt concentration was mainly affected by the daily variance of groundwater level engaged with the tidal level and that the supplied water on the surface in a rainfall event also influenced the salt concentration [3]. These results imply the importance of water availability from the catchment as well as the seawater impact from the sea to assess the vulnerability of taro patch to soil salinity. Here, we set the purpose of this paper to investigate the characteristics of taro patches which are vulnerable to salt damage using the GIS analysis based on the geographical parameters such as elevation, distance from the sea, catchment area, and area of a taro patch.

![Figure 1. Schematic of a traditional village in Palau.](image)

2. Methods

2.1. The study area
The Republic of Palau located in Oceania, a group of islands in the North Pacific Ocean, southeast of the Philippines (Figure 2). Palau locates at about 7 degrees north latitude and about 134 degrees east longitude [4]. The climate is tropical; hot and humid; wet season is from May to November. The total area is 459 sq km, with 10.8% agricultural and 87.6% forest land covers. The highest point is Mount Ngerchelchuus (242 m asl). The population is 21,431 people, with the GDP per capita is $16,700 whereas agriculture accounts for 1.2%, industry for 12.4%, services for 86.4% of the GDP [4]. The economy dominated by tourism, fishing, and subsistence agriculture.

The target of this study was the taro patches in Babeldaob Island, the Republic of Palau. Babeldaob is the largest island, with 409 sq km [5]. We analyzed all 84 taro patches in Babeldaob Island.
2.2. Data analysis

In this study, DEM (digital elevation model) data in the spatial resolution of 10 m [6] and land-use map of 2011 [7] were analyzed using ArcGIS 10.5. From the land-use data, taro patches were extracted and numbered from 1 to 84. The land-use map and the DEM were overlaid, and the average of the elevation, the distance from the sea of each taro patch were calculated. The distance used the length between the edge of taro patches and the line of elevation at zero meters. The slope calculated with elevation/distance (Figure 3). In addition, using Special Analysis Tool of ArcGIS 10.5, flow accumulation calculated from DEM and the maximum value in each taro patch was taken as the catchment area of the taro patch where grids supposed to be a river was excluded (Figure 4). Furthermore, the area of each taro patch was obtained from the land-use map.
2.3. K-means clustering and Euclidean distance

The elevation, the distance, the catchment area, and the area of taro patch standardized by mean and standard deviation as the following equation:

\[
 z = (x - \mu) / \sigma 
\]  

(1)

\(z\): standardization score \(x\): the value of our variable \(\mu\): mean \(\sigma\): the value of the population standard deviation.

K-means clustering was developed by James MacQueen in 1967 [8] with the following algorithm:

\[
 \arg \min_{V_1, \ldots, V_k} \sum_{i=1}^{n} \min_j ||x_i - V_j||^2 
\]

(2)

We used K-means in order to determine the number of clusters arbitrarily since the plots of the preceding research were only two points. These data were subjected to k-means clustering with two clusters, 10 times repetition. The clustering results were assumed to be “cluster1” and “cluster2”, and an average of each element between two clusters was tested for the significant difference by the Wilcoxon Rank Sum. These analyses were conducted by R 3.5.0 statistical.

In addition, the Euclidean distance between cluster1 and cluster2 was obtained from the following formula:

\[
 \text{Distance} = \sqrt{(e_1 - e_2)^2 + (d_1 - d_2)^2 + (c_1 - c_2)^2 + (p_1 - p_2)^2} 
\]

(3)

Where \(e, d, c, p\) indicate elevation, distance, catchment area, and area of taro patch, respectively, and the suffix of 1 and 2 indicate the average value in each cluster. The larger Euclidean distance indicates, the larger dissimilarity between objects. Using the Euclidean distance, we can examine the contribution of variables. In figure 5, it can be said that \(x_2\) is a variable which greatly contributes to clustering of A and B.

*Figure 5. The figure of clusters and the Euclidean distance.*
3. Results

3.1. Distribution trend of taro patches by histograms
Histograms for all 84 taro patches of elevation, distance from the sea, slope, catchment area were shown in Figure 5. The median of elevation was 5.7 m asl, and the range of 2-10 m asl occupied more than 90%. The median of distance from the sea was 0.4113 km, and the range within 1 km occupied more than 90%. The median of the slope was 1.7%, and the range within 3% accounted for more than 90%. The median of the catchment area was 1.78 ha, and the range of 0 to 1 ha was the largest. On the other hand, 9.5% of taro patches which had a larger catchment area than 15 ha. Water flow linkage with the catchment area is not explicitly illustrated in Figure 1 but it can work as a flash flow in a large rainfall event, and the impact depends on the scale.

![Histograms of geographical parameters of the taro patches.](image)

3.2 Clustering

3.2.1 K-means clustering. We divided the 84 taro patches into two clusters by the k-means method; cluster 1 and 2 consisted of 69 and 15 fields, respectively. The spatial distribution of cluster 1 and 2 is shown in Figure 6. The taro patches in the cluster 1 and 2 distributed not biased in specific areas, and no regional tendency was found in the result of clustering.
3.2.2 Boxplot. Box plots of elevation, distance, catchment area, and area of taro patch in cluster 1 and 2 are shown in Figure 7. The elevations of the taro patches in the cluster 2 were significantly lower (p<0.05), and the catchment area and area of taro patch in the cluster 2 were highly significant bigger than those in the cluster 1 (p<0.001). There was no significant difference in the distances from the sea between cluster 1 and 2. The differences in the catchment area and area of taro patch between the two clusters were remarkable. The cluster 1 was a group with a low elevation, and small catchment area and area of taro patch and the cluster 2 was a group with a high elevation and large catchment area and area of a taro patch.
3.2.3 Euclidean distance. The results of the Euclidean distance analysis between the cluster 1 and 2 are shown in Table 1. The Euclidean distance of all data (elevation, distance, catchment area, area of taro patch) was 2.81. The value of three data without catchment area (elevation, distance, area of taro patch) decreased to 1.93. The Euclidean distance without the catchment area was smaller than the other three elements. The Euclidean distance between the clusters containing the catchment area was larger.

|                | All data | Without elevation | Without distance | Without catchment area | Without area of a taro patch |
|----------------|----------|-------------------|------------------|------------------------|------------------------------|
| Euclidean      | 2.81     | 2.76              | 2.80             | 1.93                   | 2.15                         |

4. Discussion

Taro patches had low elevation and distributed more on flat land in the coastal area near the sea (Figure 5). Flatlands can store water like rice paddy and are suitable for growing taro because taro prefers peaty soil with poor drainage[7]. There are, many steep terrains and flat land spreads only in the coastal area; this is a typical topography in small islands.

Two taro patches which investigated in the previous study [3] can be adopted as reference points: Plot A located in Airai state, the south part of the island where the water salt concentration was high and Plot B in Ngaraard state, the northeast part, without salt damages. Plot A and Plot B were included in the cluster 1 and 2, respectively (Figure 6). Generally, low elevation land is considered to be susceptible to the impact from seawater, such as high tide or inundation. The results shown in Figure 7 means the taro patches in the cluster 2 had received the higher impact of salination than those in the cluster 1. However, since Plot B with lower salt content in its soil included in the cluster 2, it is hypothesized that taro patches in the cluster 2 suppress the influence of salt water from the sea due to large catchment area and area of a taro patch. The large catchment area supplies much water flow in a rainfall event. Therefore, the taro patches in the cluster 2 assumed to have a larger amount of inflow water in a rainfall event.

Figure 8. Boxplot for geographical parameters of the taro patches in cluster 1 and 2
event than those in the cluster 1 and that the salt damage could be alleviated. The result of the Euclidean distance (Table 1) also support this assumption; catchment area was a factor that was more involved in clustering than the other factors, and the Euclidean distance between the clusters containing the catchment area was large.

5. Conclusion
Taro patches of 84 fields in Babeldaob Island divided into two clusters: cluster 1 and 2. In the cluster 1, the elevation was low, with the small catchment and taro patch area. In cluster 2, the elevation was high, with the large catchment and the taro patch area. Taro patch which has features such as cluster 1 with high elevation and small catchment and taro patch area is considered to be vulnerable to salt damage. The fact that it divided by the area of catchment means that the amount of water coming from the area of catchment affects the vulnerability of the taro patch to salt damage. It has been known that climate change will derive sea level rise and changes in the frequency and intensity of cyclones causing salt damage on agricultural land. It was, at the same time, suggested that the ability to flush the stored salt damage away was also important.

To support this conclusion, it is expected to measure the salt concentration in soil water actual in various taro patches to validate the relationship between the topographic parameters and the vulnerability to the salt damage.

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