Influence of the 2004 Indian Ocean Tsunami Recovery Process on Land Use and Land Cover in Banda Aceh, Indonesia

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ABSTRACT

Unchecked development and land occupation tend to occur during disaster recovery efforts, leading to land degradation. To investigate the influence of the 2004 Indian Ocean tsunami recovery process on land use and land cover (LULC) in Banda Aceh, Indonesia, a time-series of LULC changes was analyzed using Google Earth images from 2004 to 2013. During the first post-disaster recovery period (2004–2009), inland bare land and green spaces changed to built-up land because temporary shelters had been built in safer areas farther from the coast. Conversely, in coastal areas, the change from bare land to built-up land was greater during the second period (2009–2013) than the first period, possibly because evacuees had returned and rebuilt their houses. The increase in patch density in 2009 might have resulted from the evacuation and construction of temporary shelters in the inland area, forming an urban sprawl-like pattern. The Shannon Diversity Index of the inland area was smaller than that of the coastal area in all monitored years, although it decreased over time in both areas; this indicated that the coastal area was more homogeneous than the inland area, but the homogeneity increased over time in both areas. We observed LULC changes not only in the area affected directly by the tsunami, but also in the evacuation area. Although recovery efforts typically focus on LULC changes in areas directly affected by disasters, they should also consider evacuation areas.

Keyword: evacuated area, Google Earth, monitoring, rural landscape, Shannon diversity index

INTRODUCTION

Urbanization is a global phenomenon that has major social and economic implications (Cohen, 2006); however, rapid urbanization and population growth have driven land use and land cover (LULC) changes. In particular, urban areas have expanded into forests and agricultural lands in developing countries with high population growth rates (e.g., Kusimi, 2008; Dewan and Yamaguchi, 2009; Tsegaye et al., 2010). Rural landscapes composed of forests and agricultural lands provide valuable ecosystem services (Reyers et al., 2009). LULC change is the most important factor driving habitat and biodiversity loss (Falucci et al., 2007), and may even cause disasters (Glade, 2003). Therefore, it is important to appropriately manage and conserve rural landscapes to ensure optimal performance of ecosystem services.

Damage from natural disasters has increased exponentially over the last several decades (Millennium Ecosystem Assessment, 2005). Large-scale disasters such as earthquakes, tsunamis, and hurricanes have caused significant LULC changes, and can sometimes completely raze land cover (Costanza and Farley, 2007; Wang and Xu, 2009; Guo et al., 2011; Villa et al., 2012). During reconstruction processes, unchecked development can occur in devastated areas due to the mass confusion following disasters. Moreover, immediately after disasters, many people temporarily evacuate devastated areas. Although evacuation is important from a safety perspective, it could lead to uncontrolled LULC changes that persist even after evacuees return to their homes. Therefore, it is necessary to monitor LULC changes not only in areas directly affected by a disaster, but also in areas surrounding affected areas.

Remote sensing data, such as aerial photographs and satellite images, are useful for monitoring land cover changes after a disaster (Joyce et al., 2009; Bello and Aina, 2014). Although LULC monitoring has been conducted in areas directly affected by disasters (e.g., Suppasri et al., 2011; Liou...
et al., 2012), no reports have examined the effects of evacuation on surrounding areas.

In this study, we investigated the influence of the 2004 Indian Ocean tsunami recovery process on LULC changes in the area surrounding the directly damaged area in Banda Aceh, Indonesia. Although remote sensing data are useful for large-scale LULC monitoring efforts after disasters (Joyce et al., 2009), data collection is expensive; therefore, we used free images downloaded from Google Earth.

**MATERIAL AND METHODS**

**Study Site**

Banda Aceh, the capital of Aceh Province, Sumatra, Indonesia, was used as the study site (Fig. 1; 5°33′N, 95°19′E, 78.69 km²). Banda Aceh is located in a low-lying flat area along the northern coast of Sumatra (BAPPEDA Banda Aceh, 2009). Triggered by an earthquake, the 2004 Indian Ocean tsunami occurred on 26 December and completely destroyed coastal ecosystems, structures, public facilities and infrastructure. The land cover within approximately 4 km inland of the coast was swept away (Borrero, 2005; Tobita et al., 2006; Takahashi et al., 2007; Lavigne et al., 2009; Suppasri et al., 2012). In 2004, before the tsunami, the population of Banda Aceh was 265,098. Although the population decreased to 177,881 in 2005 (BPS Banda Aceh, 2006) because of the tsunami, it recovered to 250,303 in 2015 (BPS Banda Aceh, 2016). For the analysis, the study site was divided into two areas within and beyond 4 km of the coast. The area near the coast (hereafter, coastal area; 50.45 km²) was directly damaged by the tsunami, while the area farther from the coast (hereafter, inland area; 28.23 km²) experienced little direct damage.

**Images and LULC Detection**

LULC time-series monitoring was conducted using satellite images obtained from Google Earth, which is a standalone software program that provides satellite and aerial images of the Earth. Images were downloaded from Google Earth Pro (4,800 × 3,318 pixels per image, the highest available resolution for download) as RGB images, which had been taken on June 6, 2004, June 16, 2009 and May 8, 2013. In total, 39 images were collected for each year and combined into one mosaic image using Adobe Photoshop CS4 (Adobe, San Jose, CA, USA). This image was georeferenced using ArcGIS ver. 10 (ESRI, Redlands, CA, USA) with a spatial resolution of 0.5 m. The images in 2004 were taken before the tsunami, and the other images were taken after the tsunami.

The areas in the mosaic images were classified into nine LULC types (bare land, beach, building, grassland, paddy field, pond, road, trees, and water) based on an object-based image analysis using Feature Analyst software (Blundell and Opitz, 2006), which is an extension of ERDAS IMAGINE 9.3 (ERDAS). Object-based image analysis consists of image segmentation, which divides an image into homogeneous, continuous, and contiguous objects, and classification, which is based on a variety of features including pixel value, texture, and form (Gao and Mas, 2008). The classification results of an object-based image analysis were output as a polygon. In this study, a polygon was defined as a patch. For the nine LULC types, 71 training data points for classification and 164 testing data points for the accuracy assessment were specified based on a visual interpretation of Google Earth images. The accuracy assessment was conducted based on an error matrix and kappa values (Congalton, 1991).

**Derivation of Spatial Metrics**

To identify the LULC distribution characteristics, the number, density, and mean size of the patches, and the Shannon Diversity Index were calculated based on patches. The Shannon Diversity Index, which indexes patch diversity according to the number of patch types and the proportional distribution of the area of each patch type (1), is the most commonly used metric of landscape spatiotemporal diversity (O’Neill et al., 1988; Li and Reynolds, 1993; Ritters et al., 1995; Ricotta and Avena, 2003; Ricotta et al., 2003; Bogaert et al., 2005).
LULC Conversion

The land cover pattern in the coastal area was relatively consistent from 2004 to 2013 (Fig. 3). In all studied years, the coastal area was composed of approximately equal proportions of water, green space, and built-up land, whereas the inland area was dominated by green space. In both areas, the proportion of bare land decreased over time.

Table 1 presents a matrix of the changes in the LULC. In the coastal area, bare land showed the greatest changes. For example, 80% of bare land changed to other LULC types from 2004 to 2009, and 90% of bare land changed to other LULC types from 2009 to 2013. Specifically, 63.8% (366.34 ha) of bare land became built-up land between 2009 and 2013. In addition, other LULC types tended to become built-up land. Although green space was replaced by built-up land over time, some built-up land became green space.

Table 2 indicates the patch characteristics. The number of patches and patch density tended to decrease in the coastal area. Mean patch size became smaller, and standard deviation of spatial metrics also became smaller.

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Candra and Itaya

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tion became larger over time. On the other hand, in the inland area, the number of patches and patches density increased in 2009, and they decreased in 2013. Mean patch size became smaller in 2009, and it became larger in 2013. Standard deviation became smaller in 2009, and it became larger in 2013.

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Table 1 LULC changes from 2004 to 2013 in the (A, B) coastal area and (C, D) inland area

A

| Land Cover/Use 2009 (ha) | Built-up Land | Bare Land | Green Space | Water | Total |
|-------------------------|---------------|-----------|-------------|-------|-------|
| Land Cover/Use 2004 (ha) |               |           |             |       |       |
| Built-up Land           | 782.61        | 213.28    | 285.84      | 109.98| 1391.70|
| Bare Land               | 246.11        | 160.55    | 137.37      | 189.73| 733.76 |
| Green Space             | 334.67        | 128.48    | 867.93      | 268.93| 1600.01|
| Water                   | 94.92         | 71.49     | 340.59      | 813.22| 1320.21|
| Total                   | 1458.31       | 573.80    | 1631.73     | 1381.85| 5045.69|

B

| Land Cover/Use 2013 (ha) | Built-up Land | Bare Land | Green Space | Water | Total |
|-------------------------|---------------|-----------|-------------|-------|-------|
| Land Cover/Use 2009 (ha) |               |           |             |       |       |
| Built-up Land           | 940.92        | 35.15     | 299.90      | 182.35| 1458.32|
| Bare Land               | 366.34        | 50.94     | 93.33       | 63.20 | 573.80 |
| Green Space             | 507.68        | 48.44     | 886.20      | 189.41| 1631.73|
| Water                   | 256.90        | 72.71     | 255.49      | 796.76| 1381.86|
| Total                   | 2071.84       | 207.23    | 1534.92     | 1231.72| 5045.70|

C

| Land Cover/Use 2009 (ha) | Built-up Land | Bare Land | Green Space | Water | Total |
|-------------------------|---------------|-----------|-------------|-------|-------|
| Land Cover/Use 2004 (ha) |               |           |             |       |       |
| Built-up Land           | 325.06        | 66.81     | 156.06      | 9.69  | 557.61|
| Bare Land               | 89.63         | 41.86     | 75.91       | 4.18  | 211.58|
| Green Space             | 370.07        | 120.12    | 1282.44     | 51.83 | 1824.46|
| Water                   | 54.13         | 21.20     | 140.42      | 13.72 | 229.48|
| Total                   | 838.88        | 249.99    | 1654.83     | 79.42 | 2823.13|

D

| Land Cover/Use 2013 (ha) | Built-up Land | Bare Land | Green Space | Water | Total |
|-------------------------|---------------|-----------|-------------|-------|-------|
| Land Cover/Use 2009 (ha) |               |           |             |       |       |
| Built-up Land           | 445.53        | 7.98      | 350.95      | 34.43 | 838.88|
| Bare Land               | 141.25        | 13.99     | 83.33       | 11.41 | 249.99|
| Green Space             | 228.79        | 35.64     | 1382.01     | 8.40  | 1654.83|
| Water                   | 9.02          | 1.42      | 68.07       | 0.91  | 79.42 |
| Total                   | 824.58        | 59.03     | 1884.36     | 55.15 | 2823.13|

Fig. 3 Land cover pattern in the coastal and inland areas.
Meanwhile, the coastal area had a higher proportion of water area due to the presence of rural areas close to the mountains.

In this study, nine LULC types were identified, whereas previous studies have used four. Moreover, Li and Shao (2013) used the near-infrared band for LULC classification. To minimize misclassification, we combined the nine LULC types into four groups.

In the early phase of recovery (2004–2009), temporary shelters were built in safer locations farther from the coast (Achmad et al., 2014; Vale et al., 2014; Syamsidik, 2017). Therefore, in the inland area, bare land and green spaces changed to built-up land between 2004 and 2009, a process that continued after 2009. However, some bare land and built-up land became green spaces. Tree planting along roads and in home gardens has become increasingly prevalent in Indonesian towns, both to benefit the environment and create a relaxing atmosphere (Fuady, 2016; Irham et al., 2017). Awareness of green cities and eco-villages has grown in recent years (Steinberg, 2007; Fuady and Darjosanjoto, 2012; Fuady, 2015; Arif, 2017), which might also have encouraged such tree-planting activities. In the coastal area, more bare land changed to built-up land in the second period (2009–2013) than in the first period. This was likely driven by the return of evacuees from the inland area to the coastal area, and to the rebuilding of houses on bare land (Achmad et al., 2014; Vale et al., 2014; Syamsidik, 2017). Most of the water area that was subject to change became green space, possibly due to tree planting or the growth of trees crowns.

Patch density represents landscape fragmentation, which is often caused by urbanization (Jaeger, 2000). Since patch density was gradually decreasing in the coastal area, fragmentation might have been subsided. On the other hand, it increased in 2009 and decreased thereafter in the inland area; the increase in 2009 might have resulted from evacuation to the inland area, since temporary shelters could have constituted an urban sprawl-like pattern.

The LULC heterogeneity of inland and coastal areas was expressed as the Shannon Diversity Index, the values of which are influenced by the richness and evenness of LULC types, where richness represents the number of land cover types present in an area and evenness describes the relative proportion of each type. A Shannon Diversity Index of zero corresponds an area with only one LULC type, and areas that have one dominant LULC type have low Shannon Diversity Index values. The Shannon Diversity Index increases as the number of LULC types increases and/or the evenness becomes greater. In this study, since both inland and coastal areas had the same number of LULC types, in all years, the Shannon Diversity Index was influenced only by the evenness. The inland area had smaller Shannon Diversity Index values than the coastal area in all monitored years, although the values of both areas decreased over time. This indicated that the coastal area was more homogeneous than the inland area, and that

Table 2  Patch characteristics from 2004 to 2013 in the (A) coastal area and (B) inland area

|      | Number of Patches | Patches density (/100 ha) | Mean patch size (S.d) |
|------|-------------------|--------------------------|-----------------------|
| A    |                  |                          |                       |
| 2004 | 40,939           | 812.84                   | 0.12 (1.94)           |
| 2009 | 38,465           | 762.32                   | 0.13 (2.76)           |
| 2013 | 32,673           | 648.72                   | 0.15 (4.20)           |
| B    |                  |                          |                       |
| 2004 | 21,540           | 762.98                   | 0.13 (3.05)           |
| 2009 | 28,138           | 996.68                   | 0.10 (0.92)           |
| 2013 | 20,927           | 741.27                   | 0.13 (3.96)           |

**DISCUSSION**

High-resolution time-series remote sensing data can be difficult to obtain due to the high cost. Although images downloaded from Google Earth do not contain multispectral information, they are free. The accuracy of the results, which can be influenced by the number of LULC categories and available wavelength bands, was slightly lower in this study than in similar studies using color aerial photographs and object-based image analysis (Cleve et al., 2008; Li and Shao, 2013). In this study, nine LULC types were identified, whereas previous studies have used four. Moreover, Li and Shao (2013) used the near-infrared band for LULC classification. To minimize misclassification, we combined the nine LULC types into four groups.

The inland area had more green space than the coastal area due to the presence of rural areas close to the mountains. Meanwhile, the coastal area had a higher proportion of water than the inland area due to the presence of aquaculture ponds.

In Indonesia, the tiger prawn (Penaeus monodon) industry greatly expanded in the 1980s and 1990s, and shrimp pond development has since continued in the coastal area of Banda Aceh (Zainun et al., 2007; Giri et al., 2008). Although the 2004 Indian Ocean tsunami destroyed the coastal area, thus affecting the LULC types, the LULC composition did not change substantially in either inland or coastal areas after the tsunami.

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**Fig. 4 Shannon Diversity Index values from 2004 to 2013 in the coastal and inland areas.**
homogeneity increased over time in both areas.

CONCLUSIONS

In this study, we investigated the influence of the 2004 Indian Ocean tsunami recovery process on LULC in Banda Aceh, Indonesia. Evacuation areas are often built on unused land, such as bare land and forests. After evacuees return to their homes, these areas are either left as-is or developed further. In the inland area, large areas of bare land and green space became built-up land in the first post-disaster period (2004–2009), increasing landscape fragmentation. In the coastal area, more bare land became built-up land in the second period (2009–2013) than the first period. LULC homogeneity increased in both the coastal and inland areas. We observed LULC changes not only in the area directly affected by the tsunami, but also in the evacuation area. Although recovery efforts typically focus on LULC changes in areas affected directly by disasters, they should also consider evacuation areas.

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