Fire severity assessment on peatland vegetation diversity

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Abstract. Forest fires have a significant impact on peatland ecosystem, including its vegetation diversity. Several approaches applied for forest fire severity assessment are available in the literature. This study aimed to implement field-based and spatial-aware fire severity assessments and to compare both approaches. Peat swamp forests of Ogan Komering Ilir, South Sumatera Province, for field assessment and Siak, Riau Province, for spatial assessment were selected in this research. Field-based fire severity assessment used indicators of vegetation analyses (individual tree damages, burned vegetation severity, and diversity index), which were measured and analyzed from sample plots in both burned and unburned areas. Spatial analyses of fires severity assessment employed Sentinel-2 satellite imagery with Normalized Burn Ratio (NBR) approach. The research revealed a significant change in tree species diversity, indicating a lower diversity in burned areas than the ones in pristine fields. Magnitude of changes in diversity was influenced by fire severity levels in burned areas and pre-fire condition of burned areas. Spatial analyses indicated low to high fire severity with burned area estimation for each fire severity class. Both approaches have their own benefits and challenges. Field-based severity assessment is beneficial for a detailed assessment of fire damages and losses, whereas spatial analyses would be considered for a broader estimation of fire severity. Both assessments are mutually implemented. Field-based assessment can serve as a verification tool for spatial assessment.

1. Introduction

Peatland is a terrestrial ecosystem that has a vital role in maintaining environmental balance, especially in regulating water systems, conserving biodiversity, mitigating climate change, and supporting community welfare. Indonesia occupies 14.9 million hectares of tropical peatlands [1], spread over Sumatra, Kalimantan and Papua; making the country the largest tropical peatland in the world. Peatland is rich in biodiversity, including vegetation diversity. *Gonyostylus bancanus* (‘ramin’), *Dyera lowii* (‘jelutung rawa’), *Shorea* sp. (‘meranti’), *Melaleuca leucadendron* (‘gelam’), *Fragraea fragrans* (‘tembesu’), *Combretocarpus rotundatus* (‘perepat’) are among endemic species of peatland.

Despite ecological and economic importance of those species, fire has been a severe threat to the species. Since 1997/1998, fire occurrences in Indonesia have been dominated by peatland fire, which has more significant impacts than non-peatland fire [2]. Peatland fire has continuously occurred every year. The reason to this is mostly due to degraded peatland conditions, as the outcome of human-induced disaster such as over-drainage and over-exploitation [2, 3]. This issue has remained in decades, with the scale escalates from local and national into a global concern.
Regulation of the Minister of Environment and Forestry Number P.32/MinLHK/Setjen/Kum.1/3/2016 concerning forest and land fire control states that Forest and Land Fire Control includes business/activities/organizational actions, management of human resources and infrastructure and operational prevention, suppression, post-fire handling, support for evacuation and rescue, and support for forest and land fire control management. Compared to prevention and suppression of forest and land fires, development of science and technology for post-fire management remains insufficient.

Formulation of Post Forest Fire Area Assessment Method on vegetation conditions and soil characteristics was based on 18 years of field research on various types of vegetation and soil types on the islands of Java, Sumatra and Kalimantan [4]. Fire Severity approach is an appropriate method for assessing impacts of forest and land fires. Fire impact assessments are generally carried out for research purposes, forest rehabilitation planning, conservation, and law enforcement. Impact of fires can be assessed through fire severity level, which measures the influence of fire to ecosystems, including soil, flora, fauna, water, and other ecosystem elements. Magnitude of the impact depends on several factors: fire intensity, fire severity, soil type, rain that falls after the fire, and fire extent [5]. Although research on fire severity has been accumulating, limited implementation is observed. Assessing the severity has been carried out in various forest types both at field level and spatial level.

Spatial analysis in forest and land fire research has widely been used, among others, to determine classification of burned lands, impact of fires on land cover change, and carbon emissions [6-8]. However, spatial analysis for fire impact assessment is still limited.

This paper aims to apply field-based fire severity assessment and to investigate spatial-aware fire severity assessment and to compare both types of assessment.

2. Materials and methods
Field-based assessment was conducted in peat swamp forest of Ogan Komering Ilir (OKI) Regency, South Sumatera Province. Meanwhile, spatial analyses assessment was conducted over Siak Regency, Riau Province (Figure 1.).

2.1. Field-based assessment
The study was conducted in a burned peat swamp forest, about 196.70 ha. Materials used in this study covered vegetation conditions in burned and unburned areas. Equipment and instruments included a camera, measurement tape, compass, rope, GPS, tally sheet, and plant identification book. JASP 0.14.1.0 was employed for analyzing differences between vegetation parameters in burned and unburned plots, using an independent t-test for mean values of the parameters. GoogleMaps was exploited for creating the location map.
2.1.1. Vegetation analysis

Three transect lines were established in each area. For each, sample plots were established, consisting of three 20×20 m² plots for trees, three 10×10 m² plots for poles, three 5×5 m² plots for saplings and 2×2 m² plots for seedlings. In total, there were 72 nested sample plots for tree, pole, sapling, seedling stages measurement and fire severity assessment. Vegetation parameters, which include Density (D), relative density (RD), frequency (F), relative frequency (RF), dominancy (Dom), relative dominancy (RDom), and Important Value Index (IVI), were analyzed using the following formulas:

\[ D = \text{Total number of individuals of the species/sample plot area} \]
\[ RD = \left( \frac{\text{Density of a given species}}{\text{Total densities of all the species}} \right) \times 100\% \]
\[ F = \frac{\text{Total number of plots found a species}}{\text{Total number of plots}} \]
\[ RF = \left( \frac{\text{frequency of a species}}{\text{frequency of a total species}} \right) \times 100\% \]
\[ \text{Dom} = \frac{\text{number of basal area of a species/sample plot area}}{\text{Total number of basal areas of all species/sample plot area}} \]
\[ RDom = \left( \frac{\text{Dominance of a species}}{\text{Dominance of the total species}} \right) \times 100\% \]
\[ \text{IVI} = RD + RF \] (for seedling and sapling stages)
\[ \text{IVI} = RD + RF + RDom \] (for pole and trees)

2.1.2. Data analysis

2.1.2.1. Biodiversity Analysis

Vegetation diversity condition was evaluated using Shannon Index of General Diversity, as follows:

\[ H' = -\sum_{i=1}^{s} \left( \frac{n_i}{N} \right) \ln \left( \frac{n_i}{N} \right) \]

where:
\[ H' = \text{Diversity Index of Shannon-Wiener, } s = \text{species number} \]
\[ n_i = \text{The i-th species density, } N = \text{Total density} \]

Species Diversity Index of Shannon-Wiener (H’) has three groupings, namely: \( H' \leq 2 \) (low), \( 2 < H' \leq 3 \) (moderate), and \( H' > 3 \) (high)

2.1.2.2. Fire Severity Assessment

Fire severity was assessed by tree damages condition [9], as follows:

a. **Low fire severity**: at minimum, 50% of trees do not show any damage, while the rest shows burned crown, dead sprouts (upper part is dead but sprouting) or dead root, but >80% burned trees survived.

b. **Moderate fire severity**: 20-50% of trees do not damage, while 40-80% of burned trees survive.

c. **High fire severity**: <20% of trees do not show any damage, the rest mostly shows dead roots, while 40% of burned trees survived.

2.2. Spatial-aware fire severity assessment

Satellite images used in this study were Sentinel-2, which has a higher spatial resolution compared to other public infrared images. They were downloaded based on prior hotspot data analyses (pre-fire) and after burned (post-fire).

Detection of burned areas consisted of 3 stages [10] as follows:

a. **Channel fusion**

In burn area detection, combined data files were band 8a and 12.

b. **NBR image generation**

NBR image was created for all image data, both before and after fire events, so that NBRpre (NBR before the fire) and NBRpost (NBR after the fire) images were obtained. The equation below was used to calculate NBR [11]:
\[ \text{NBR} = \frac{B8a - B12}{B8a + B12} \]

where:
- NBR = Normalized Burn Ratio
- B8a = reflectance band 8a (Red Edge 4; 0.865 \( \mu \text{m} \))
- B12 = reflectance band 12 (SWIR1; 2.190 \( \mu \text{m} \))

c. NBR image fusion

NBR image fusion combined NBR prefire and NBR postfire into single dataset.

2.3. Difference Normalized Burn Ratio (dNBR) calculation

Difference Normalized Burn Ratio (dNBR) compares pre-fire and post-fire data, making it suitable for analyzing severity of forest and land fires (Table 1). Higher dNBR value suggests a more severe fire. The following is the equation for calculating dNBR based on the UN-SPIDER:

\[ \Delta \text{NBR} = \text{Pre fire NBR} - \text{Post fire NBR} \]

Table 1. Burn severity levels obtained from dNBR

| Value | Description                  |
|-------|------------------------------|
| 0.1   | Unburned                    |
| 0.27  | Low severity                |
| 0.44  | Moderate - Low Severity     |
| 0.66  | Moderate-High Severity      |
| 1.3   | High Severity               |

3. Results and discussion

3.1. Field-based fire severity assessment on vegetation diversity

Vegetation analysis indicated that all vegetation stages (seedling, sapling, pole, and trees) were found in unburned plots. In contrast, only seedling stage was found in burned plots. Four peatland endemic species were found in tree stage, including Meranti (Shorea balangeran), Tembesu (Fragraea fragrans), Perepat (Combretocarpus rotundus, and Jelutung (Dyera lowii), while other stages were found in single species. Meranti (Shorea balangeran) (Table 2). Most of the vegetation has been burned out; therefore, only seedling stage appeared after eight months of fire, consisting of Tembesu (Fragraea fragrans), Perepat (Combretocarpus rotundus) and Gelam (Melaleuca leucadendron). Important Value Index (IVI) in Table 2 shows the role of species in the community; the higher the IVI, the higher the role of the species as a dominant one. Dominant species in unburned areas were Meranti in seedling, sapling and pole, with IVIs 200 for seedling and sapling stages and 300 for pole stage. Jelutung became the dominant species in tree stage with an IVI of 143.09. Perepat was the dominant species in burned area, with an IVI value of 97.77. Dominant species has high density, high frequency, and high dominancy. They were generally having adaptive ability/trait to the environment and distributed evenly in the area.
Table 2. Density, Relative Density, Frequency, Relative Frequency, Dominance, Relative Dominance, and Important Value Index in Unburned and Burned Plots at peat swamp forest of Ogan Komering Ilir (OKI) Regency, South Sumatera

| Plots/vegetation stages | Species | D     | RD   | F    | RF   | Dom  | RDom | IVI |
|-------------------------|---------|-------|------|------|------|------|------|-----|
| Unburned plots          |         |       |      |      |      |      |      |     |
| Seedling                | Meranti | 5833.33 | 100  | 0.56 | 100  | 200  | 200  |     |
| Sapling                 | Meranti | 355.60  | 100  | 0.44 | 100  | 200  | 200  |     |
| Pole                    | Meranti | 33.33   | 100  | 26.67| 100  | 0.23 | 100  | 300 |
| Tree                    | Meranti | 44.44   | 18.18| 14.22| 18.26| 0.34 | 20.94| 57.38|
|                         | Tembesu | 44.44   | 18.18| 10.67| 13.69| 0.28 | 16.86| 48.74|
|                         | Perepat | 75      | 30.68| 24   | 30.81| 0.47 | 23.89| 90.38|
|                         | Jelutung| 80.56   | 32.95| 29   | 37.23| 0.54 | 33.31| 103.49|
| Burned plots            |         |       |      |      |      |      |      |     |
| Seedling                | Gelam   | 6111.1 | 21.70| 0.56 | 22.73| -    | -    | 44.30|
|                         | Tembesu | 6111.1 | 21.70| 0.89 | 36.37| -    | -    | 57.93|
|                         | Perepat | 16111.1| 56.60| 1    | 40.90| -    | -    | 97.77|
| Total                   |         | 28333.3| 100  | 2.45 | 100  | -    | -    | 200 |

Figure 2. Number of plants, Relative Density, Relative Frequency and Relative Dominance of plant species in burned and unburned plots at peat swamp forest

Number of individual plants in burned plots was lower than that of unburned plots, similar to that of Relative Density, Relative Frequency, and Relative Dominance (Figure 2). It seems that forest fire occurred in the study area has affected those parameters. Similarly, IVI value of burned plots was lower than that of unburned plots. It means that the role of dominant species after the fire was reduced than that of in unburned plots (Figure 3). Survival of trees depends on several factors, including food storage of the vegetation, fire-adaptive traits, location, tree size, and crown damage [12].
In an ecological study, Shannon-Wiener Index (H’) indicates species abundance as it has high sensitivity to describe community structure and changes of non-dominancy species or scarce species. Diversity Index for seedling, sapling, and pole stages in unburned areas was zero, as only single species found in plots (S. balangeran). Meanwhile, Diversity Index for tree stage was 1.35, suggesting low diversity (H’<2). Similarly, Diversity index in burned areas of 0.98 showed low diversity as well (Table 3).

### Table 3. Diversity Index in unburned and burned plots at peat swamp forest

| Growth stage | Diversity Index (H’) |
|--------------|----------------------|
| Unburned plots |                     |
| Seedling     | 0                    |
| Sapling      | 0                    |
| Pole         | 0                    |
| Trees        | 1.35                 |
| Burned plots |                      |
| Seedling     | 0.98                 |

Statistical analyses suggested that all parameters in vegetation analyses, i.e. number, Density, Relative Density, Frequency, Relative Frequency, Dominance, Relative Dominance, and Important Value Index of burned areas, had significant differences with unburned regions (Table 4). Fire has altered vegetation parameters, particularly vegetation diversity [12].

### Table 4. T-test results of vegetation analyses parameters

|                | t      | df | p      |
|----------------|--------|----|--------|
| Number         | 9.743  | 116| <.001  |
| Density        | 5.099  | 116| <.001  |
| Relative Density| 6.776  | 116| <.001  |
| Frequency      | 8.603  | 116| <.001  |
| Relative Frequency| 7.226 | 116| <.001  |
| Dominance      | 6.668  | 115| <.001  |
| Relative Dominance| 5.131 | 115| <.001  |
| Important Value Index| 7.650 | 116| <.001  |

*Note.* For the Student t-test, the alternative hypothesis specifies that the mean is different from 0.
Fire severity assessment using vegetation criteria [9] indicated that fire occurrence was categorized as high severity with all trees were burned (Table 5).

**Table 5.** Tree condition in the burned area of peat swamp forest

| Plot No | Tree species | Condition                                           |
|---------|--------------|-----------------------------------------------------|
| 1-16    | Meranti      | Dead trees, scorched and burned trunks, crowns, branches and roots. |
| 1-27    | Perepat      | Dead trees, scorched and burned trunks, crowns, branches and roots. |
| 1-29    | Jelutung     | Dead trees, scorched and burned trunks, crowns, branches and roots. |
| 1-16    | Tembesu      | Dead trees, scorched and burned trunks, crowns, branches and roots. |

Forest fire has significantly contributed to decreasing biodiversity, number of individuals, and number of plant species [12, 13]. Frequent or severe fire affects diversity of forest regrowth by its proximity to forest remnants, which are dominated by pioneer species; indicating that forest recovery begins [14].

3.2. **Fire severity using spatial analyses approach**

Sentinel-2 images composite 12-8A-4, shown in Figure 4, depicts color change from pre-fire and post-fire image. Visually, burned areas are indicated by (1) brown-reddish color, darker than its surrounding; (2) generally forming square polygons; (3) covering areas from 0.87-216.49 ha; (4) irregular pattern; (5) fine texture; (6) mostly found in shrubs, oil palm plantations, forest plantations and secondary forest; (7) associated with roads or canals [15].

![Figure 4](image)

(a) Pre-fire, (b) Post-Fire

**Table 6.** Forest fire severity classes in 2021

| Fire severity class         | Area (ha) | Percentage (%) |
|-----------------------------|-----------|----------------|
| Unburned                    | 361,844   | 87.36          |
| Low fire severity           | 34,724    | 8.38           |
| Moderate-low fire severity  | 11,467    | 2.77           |
| High-moderate fire severity | 6,081     | 1.47           |
| High fire severity          | 93.33     | 0.02           |
This fire severity classification was analyzed visually, showing green color for unburned areas, low fire severity in yellow, moderate-low fire severity in orange, moderate-high fire severity in red, and high fire severity in purple (Figure 5).

![Fire severity classification map at Siak Regency, Riau Province in 2021](image)

**Figure 5.** Fire severity classification map at Siak Regency, Riau Province in 2021

### 3.3. Comparison of assessments

Our comparison indicated that fire severity assessment has differences in magnitude, area coverage, detailed results, costs, importance and objectives. Characteristics of each assessment is summarized in Table 7. Field-based assessment possessed specific advantages, including direct, accurate measure of burned areas and detailed vegetation analyses (vegetation damages, soil damages, number of trees, density, frequency, dominancy, Important Value Index and Diversity Index). These characteristics are essential for post-fire management, including forest loss valuation, rehabilitation planning and laws enforcement. However, this method seemed to have limitations in area coverage, costs, and requiring authorization. Meanwhile, spatial assessment had benefits, including extensive area coverage, unrestricted access for the public, and a relatively lower cost.

Remote sensing technologies provide a low-cost, multi-temporal means for conducting local, regional, and global-scale fire ecology research. Current research is rapidly evolving with new technologies and techniques that increase accuracy and efficiency [16]. Burn severity refers to the degree of change in vegetation reflectance captured in pre- and post-fire satellite images. The difference in near-infrared reflectance of satellite images over pre- and post-fire has effectively captured burn severity in many forest fire studies [17].
Table 7. Comparison of forest fire severity assessments

| No. | Assessment characteristics | Field assessment | Spatial assessment (using Sentinel-2) |
|-----|---------------------------|------------------|--------------------------------------|
| 1.  | Area coverage             | 0.1-1 ha         | 290 km field of view, resolution 10m-60m |
| 2.  | Burned area               | Direct measured  | Estimated                            |
| 3.  | Vegetation damages        | Observed         | It cannot be observed                 |
| 4.  | Soil damages              | Observed         | It cannot be observed                 |
| 5.  | Number of trees           | Observed         | It cannot be observed                 |
| 6.  | Density                   | Observed         | It cannot be observed                 |
| 7.  | Frequency                 | Observed         | It cannot be observed                 |
| 8.  | Dominance                 | Observed         | It cannot be observed                 |
| 9.  | Important Value Index     | Observed         | It cannot be observed                 |
| 10. | Diversity                | Observed         | It cannot be observed                 |
| 11. | Fire severity classes     | Classified       | Classified                            |
| 12. | Permit                    | Need authority permit | Free access                        |
| 13. | Cost                      | Higher cost      | Lower cost                           |
| 14. | Importance and objective  | Field verification, detail loss estimation | Preliminary assessment, rough loss estimation |

4. Conclusion

Forest fire severity assessment is an essential tool to evaluate post-fire conditions. In-situ fire severity assessment in Ogan Komering Ilir Regency, South Sumatera Province, resulted in a high fire severity class, which was indicated by remaining seedling in burned areas. Meanwhile, fire severity assessment in spatial context, applied in Siak Regency, Riau Province, indicated that burned areas were classified as low fire severity (34,724 ha), moderate-low fire severity (11,467 ha), moderate-high fire severity (6,081 ha) and high fire severity (93,333 ha). Field-based assessment has a detailed information on vegetation damages, soil condition and diversity. However, it was limited in terms of area coverage and costs.

On the other hand, spatial analyses for fire severity assessment had a broader coverage and low cost. Both assessments need to be mutually applied. Spatial analyses assessment may be applied for the first instance, and field-based severity assessment continues for further verification.

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