Tracking the Progression of Burned Areas in Tropical Peat Swamp Forests by Integrating Sentinel Optical and SAR Imagery: A Case Study of Binsuluk Forest Reserve in Sabah, Malaysia

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Abstract: Climate change and rising global temperatures are driving forest fires to become more intense and frequent worldwide, particularly in peat swamp forest. Since the predominant burning mechanism in peatland forest is smouldering combustion, it causes widespread air pollution and emits massive amounts of carbon due to prolonged episodes of fire events. Therefore, the development of a unique approach to monitor forest fire progressions through burned area mapping mainly in persistent cloud cover is vital for the estimation of fire extent, location, and land cover affected. Thus, this research aims to evaluate the capabilities of Sentinel-1 SAR and Sentinel-2 optical time series in boosting the frequency and accuracy of burn area progression mapping in peatland areas. Results from the forest fire series in Binsuluk Forest Reserve, which occurred from February to April 2024, indicated a reduction in the backscatter value of the cross-polarized (VH) signal in the burned area for Sentinel-1 SAR C band. Despite the cloud cover challenge, Sentinel-2 continues to deliver essential data on the positioning of active fires and smoke plumes, with burn area detection being more precise when utilizing the Normalized Difference Moisture Index (NDMI) compared to the Normalized Burn Ratio (NBR). The integration of Sentinel optical and SAR imagery has effectively facilitated an increased tracking frequency and precision for the evolution of burned areas.

1 INTRODUCTION

Tropical peat swamp ecosystems are widespread in Southeast Asia, particularly in Borneo. More than half of Malaysia's 2.6 million hectares of peat swamp forest are situated on Malaysian Borneo (Meiling L., 2016), while Sabah was believed to have 86,000 hectares of peat swamp forest, with roughly 60,000 ha of mixed peat swamp forest on the Klias Peninsula. Agricultural growth and fires caused by El Niño/Southern Oscillation have led to the fast disappearance of peat swamp forests. Kamlun, K. U., & Phua, M. H. (2024) indicate that agriculture is the most influential anthropogenic factor associated with the fire-affected areas while the distance to settlement played an increasingly important role in the fire affected areas and contributes to the deforestation of the peat swamp forest in Klias Peninsula.

Satellite-based earth observation (EO) systems are able to provide consistent and frequent measurements over vast remote areas on the earth's surface. This allows the monitoring of forest fire progressions across the globe in a timely and cost-effective way (Engelbrecht et al., 2017; Chuvieco et al., 2020). Phua et al. (2007) examined the use of several vegetation indices in image differencing technique for detecting burned peat swamp forest. Phua et al. (2008) has further investigated into a fast approach for detecting disturbances in multiple change events.

In previous studies, Sentinel-2 MSI data has been effectively used to assess burn severity, or the degree to which an area has been affected by a fire. This is

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because the MSI data is sensitive to changes in the chlorophyll content of vegetation, which is typically reduced in areas that have been burned. In general, the accuracy of burned area mapping increases with higher spatial resolution data. Using a lower spatial resolution image, such as the 20 m spatial resolution of Sentinel-2 data, may result in less accurate burned area maps.

In the context of identifying burn areas, Normalised Burn Ratio (NBR), and Normalised Difference Moisture Index (NDMI) are among the indices used in the context of determining burn regions; each has certain advantages and disadvantages. Phua et.al (2007) found that NBR is especially good at identifying burn intensity and defining burn scars. In dry conditions or when attempting to distinguish between different kinds of vegetation, NDMI may be less effective. However, it is useful for determining the moisture level of vegetation, which can indirectly suggest disease susceptibility or recovery.

In tropical rainforests, burned areas may fade within a few weeks as fresh foliage grows. Some satellites can detect actively burning places, but may not detect the entire charred area due to cloud cover or delays in satellite images. Thus, SAR could serve as an alternative data source of information since radar sensors can image day and night, and are capable of penetrating clouds, smoke, and smog. Further, SAR is sensitive to changes in vegetation structure and soil moisture following wildfire (Bourgeau-Chavez et al., 2007). These characteristics give SAR unique advantages in monitoring on-going forest fire event.

Tanase, Mihai A., et al (2010) has analyzed SAR data at X-, C-, and L-bands to investigate the relationship between backscatter and forest focusing on both HH and VV polarizations as well as on cross polarized (HV). Results obtained in Spain highlighted that for X- and C-bands, the copolarized (HH and VV) backscatter increased with burn severity, in detail: 1) for all frequencies, the cross polarized (HV) decreased with burn severity; 2) C- and L-bands cross-polarized backscatter showed better potential for burn severity; and 3) the small dynamic range observed for X-band data could prevent its use in vegetation affected by fires.

Gaveau, D., Descals, A., Salim, M., Sheil, D., & Sloan, S. (2021) present new and validated 2019 burned-area estimates for Indonesia using a time series of the atmospherically corrected surface reflectance multispectral images (level 2A product) taken by the Sentinel-2A and B satellites. The frequency–area distribution of the Sentinel-2 burn scars follows the apparent fractal-like power law or Pareto pattern often reported in other fire studies, suggesting good detection over several magnitudes of scale with 97.9% accuracy.

This research aims are to assess the effectiveness of both Sentinel-1 SAR and Sentinel-2 optical time series images in improving the frequency and precision of burn area progression mapping in peatland regions. Various approaches for optical and SAR will be suggested to monitor the size of the burned area in near real-time.

2 MATERIAL AND METHODS

The primary objective of the suggested methodology is to utilise image differencing techniques to detect burned areas in the Binsuluk Forest Reserve through optical and SAR imagery, hence assessing the evolution of fire in the affected region. The forest reserve boundaries provided by the Sabah Forestry Department is essential for identifying the source of fire and consistently calculating the area of land destroyed. Ultimately, we examined the impact of the fires on the current protective forest reserve.

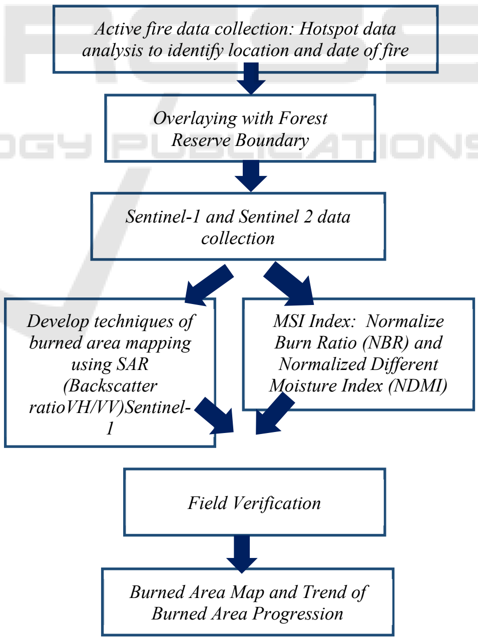

Figure 1: Workflow of Burned Area Mapping.

2.1 Area of Interest

The research was carried out in Binsuluk Forest Reserve which is a protected forest reserve on the Klias Peninsula, in Beaufort District of Interior

Division, Sabah, the Sabah Forestry Department in 1992. Its area is 12,106 hectares (121.06 km^2). The reserve is mostly flat, consisting mostly of peat swamp forest, with a small area of mangroves. The forest type here is peat swamp forest over soils of the Klias Association. Most of the FR was badly burnt during the long drought of 1997-1998. Of the remaining trees, *Dryobalanops rappa* is the most dominant canopy tree species. Most of the burnt areas are dominated by small shrubs. The Binsuluk Forest Reserve Boundary was overlaid with the images as shown in Figure 2 to identify the actual AOI of the study area

Figure 2: Sentinel-2 true colour composite on April 24, 2024, of the study area. Sentinel-2 image available at https://scihub.copernicus.eu/.

Previously in 2016 large fires in peat bogs occured, which were caused by fires spread to Binsuluk and other forest reserves from nearby open burning had contributed to the 2016 Malaysian haze. Over half of the reserve were burnt during this event. Open burning caused yet another forest fire in 2020, this time burning 274 hectares (2.74 km2). However, after some action and enforcement from the government, the trend of hotspots kept decreasing over the years as a result of mitigation action from Malaysia via the National Haze and Dry Weather Committee and ASEAN Agreement on Transboundary Haze Pollution.

2.2 Active Fire Data Collection

First, peat fires were identified by overlaying active fire data from from NASA Fire Information for Resource Management System (FIRMS) data catalog. FIRMS distributes Near Real-Time (NRT) active fire data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites, and the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA 20 satellitesTerra/Aqua MODIS hotspots onto the existing peatland map. Fire and Thermal Anomalies algorithms are automated pre-processed utilising Python scripts and ArcGIS software to input administrative boundary information such as division, district, and city. Next, the NRT data from these four sensors from 2020 to 2024 are utilised to calculate the total number of hotspots, illustrate the hotspot distribution, and certify the high fire prone area.

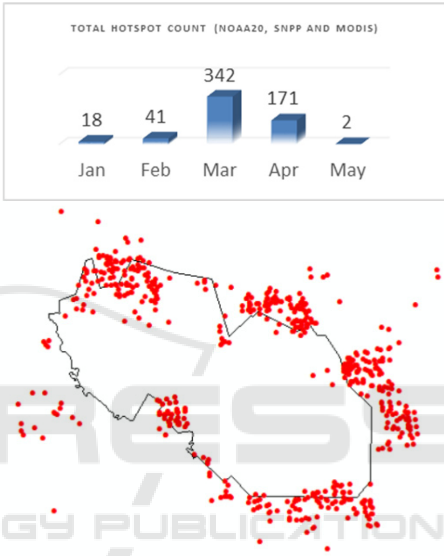

Figure 3: The distribution of hotspot in FR Binsuluk within January- May 2024.

In this study, the daily hotspot is downloaded from NASA Fire Information for Resource Management System (FIRMS) data catalogue. FIRMS distributes Near Real-Time (NRT) active fire data from the Moderate Resolution Imaging spectroradiometer (MODIS) aboard the Aqua and Terra satellites, and the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA 20 satellites. Combined (Terra and Aqua) MODIS NRT active fire products (MCD14DL) are processed using the standard MOD14/MYD14. Fire and thermal anomalies algorithms are automated pre-processed utilising Python scripts and ArcGIS software to input administrative boundary information such as division, district, and city, which is then merged into the ForFIS database for user access. Next, the NRT data from these four sensors for year 2024 are plotted to get the distribution as shown in Figure 3.

2.3 Sentinel Data Collection and Pre-Processing

Sentinel SAR and optical satellite images of Binsuluk Forest Reserve, acquired from January to April 2024, were retrieved from the ESA Copernicus Data Space Ecosystem portal. The dates picked are based on the existence of hotspot in continuous cycle of fire event. Basically, Sentinel-2 and Sentinel-1 are two key missions in a series of satellite missions initiated by the ESA to support global environmental monitoring and resource management. Sentinel-1 mission consists of a pair of polar-orbiting satellites that provide high-resolution, all-weather imaging of the Earth's surface. It includes C-band imaging operating in four modes with different resolutions (up to 5 m). ESA S1 mission provides global coverage of freely available dual polarization C-band SAR images with a repeat cycle at 6-days and revisit frequencies at 1–3 days taking into account of ascending and descending orbits and overlaying. Two bands of Sentinel-1 were used as SAR features, including VH and VV bands. The SAR images were exported from Sentinel-1 SAR GRD (Ground Range Detected) image collection named "COPERNICUS/ S1_GRD" in the Copernicus Platform. Major pre-processing step are running using The Sentinel Application Platform (SNAP). The software is developed by Brockmann Consult, Skywatch, Sensar and C-S. SNAP software.

Table 1: Dates of satellite acquired in a descending pass, by Sentinel-1 (s1) and Sentinel- 2 (s2).

Acquisition Date	*Imagery*	*Acquisition Date*	*Imagery*
5 Jan 2024	*S2*	*5 March 2024*	*S2*
10 Jan 2024	*S1 and s2*	*10 March 2024*	*S1 and s2*
15 Jan 2024	*S2*	*15 March 2024*	*S2*
20 Jan 2024	*S2*	*20 March 2024*	*S2*
22 Jan 2024	*S1*	*25 March 2024*	*S2*
25 Jan 2024	*S2*	*30 March 2024*	*S2*
30 Jan 2024	*S2*	*3 April 2024*	*S1*
3 Feb 2024	*S1*	*4 April 2024*	*S2*
4 Feb 2024	*S2*	*9 April 2024*	*S2*
9 Feb 2024	*S2*	*14 April 2024*	*S2*
14 Feb 2024	*S2*	*19 April 2024*	*S2*
19 Feb 2024	*S2*	*24 April 2024*	*S2*
24 Feb 2024	*S2*	*27 April 2024*	*S1*
27 Feb 2024	*S1*	*29 April 2024*	*S2*
29 Feb 2024	*S2*		

Sentinel-2 is a multi-spectral imaging system that provides high-resolution imaging of the Earth's surface with 13 bands. It also comprises two satellites, each with a spatial resolution of up to 10 m. These two satellites can be combined to provide full coverage of the surface of the earth every five-day interval. Sentinel-2 images were atmospherically corrected. Table 1 shows the total images used for tracking the forest fire. In the normal condition of monitoring peatland areas in Malaysia, only 12 out of a total of 24 S2 images have less than 30% cloud cover and can be used to generate the burnt area. The remaining S1 images totally can be utilized to complete the cycle.

2.4 Techniques of Burned Area Mapping

2.4.1 Multi-Spectral Burned Area Index

Ten bands of Sentinel-2 were selected as spectral features, including three visible bands, one Near-Infrared (NIR) band, four Red-edge bands, and two short-wave infrared (SWIR) bands. The raw image from band 2,3,4,8 and 12 were selected for displaying the burned area. The responses of these features in various spectral bands will shows specific character during the visualization of burned area.

In the context of identifying burn areas in dense cloud cover area, we apply various indices like Normalized Difference Moisture Index (NDMI) and Normalized Burn Ratio (NBR) are utilized, each offering unique benefits and facing specific limitations. NBR generates values ranging from -1 to 1. Intense green vegetation will exhibit a high NBR value, whereas charred vegetation will have a low value. Regions characterized by dry, brown vegetation or exposed soil will have lower NBR values compared to green vegetation. Otherwise, NDMI is important in evaluating moisture levels in vegetation, which might indirectly reflect fire vulnerability or recovery; nevertheless, its efficacy may diminish in arid conditions or when distinguishing across vegetation kinds

2.4.2 Sentinel-1 SAR GRD Backscatter

SAR-based burnt area mapping mainly relies on the resultant changes in radar backscattering, which depend on the modification degree caused by fire events in backscattering mechanisms. The total amount of energy scattered back to radar sensor can be influenced by sensor characteristic (signal wavelength and polarization), target properties (including vegetation structure, dielectric permittivity, canopy and water content, soil moisture and dielectric properties, and surface roughness) and observation geometry (Imperatore et al., 2017).

2.5 Field Verification

Using a mobile GPS device, we conducted an aerial survey in Binsuluk FR to validate the burned area.

The geographic coordinates and land cover categories are included in each sample point. In addition to the burned area, the image captures the nearly identical features of cleared land as a result of agricultural activities and flooded wetlands. In addition to aerial surveys, verification of the hotspot's status as an active fire was conducted using multispectral higher-resolution satellites, such as SPOT and Pleiades. We collaborate with the Sabah Forestry Department to conduct airborne surveys for field verification at 40 locations throughout the Binsuluk FR zone as shown in Figure 4.

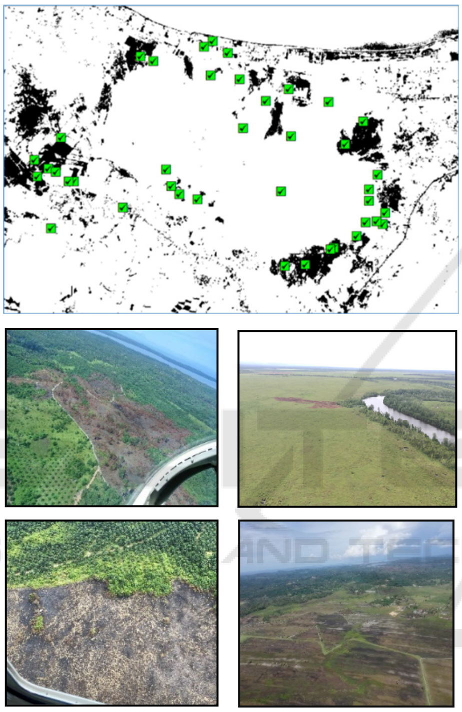

Figure 4: Location of aerial survey and sample of photos of burnt areas.

2.6 Multi-Temporal of Burned Area Progression

Considering the difference in acquisition time of SAR and optical observation, we assessed the initial until final stage of the progression maps, which mean assessing the full progressions of each fire event. This is deemed as unsuitable for validation since the fire could progress very fast during that period. In the normal condition of monitoring peatland areas in Malaysia, only 12 out of a total of 24 S2 images have less than 30% cloud cover and can be used to generate the burnt area. The remaining S1 images totally can be utilized to complete the cycle.

3 RESULTS AND DISCUSSION

3.1 Multi-Spectral Indices in Burned Area Mapping

The multi-spectral image was studied with three well-known band combinations which is true colour composite, near infrared (NIR) false colour composite image and shortwave infrared (SWIR) false colour composite image to decide which combination best to highlight the burned areas. Figure 5 shows SWIR colour composite that act as the best band combination to visualize the burned areas.

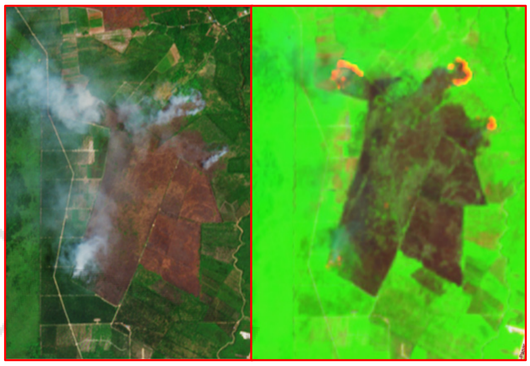

Figure 5: SWIR false colour composite (a) enhances the burned area features and active fire location in Sentinel-2 MSI dated 27 April 2024 compared to (b) true colour composite

NBR excels at assessing burn intensity and outlining burn scars; however, its efficacy diminishes in areas with sparse vegetation or in identifying early post-fire regrowth. Using +0.1 as a criterion produces false positives on unburned cleared land and forest areas where foliage has dried prior to the fire. A far more cautious criterion (+0.3) produces a better outcome. Rahman et al. (2018) discovered that a dNBR threshold value of +0.1 is adequate for distinguishing burnt from unburnt areas using Sentinel-2.

This study indicates that specific conditions may result in false positives, since significant smoke in the post-burn image can distort the dNBR value. Regions that have had vegetation removal through alternative methods (logging, harvesting, and landslides) at the conclusion of the baseline period may erroneously appear as scorched.

The Normalized Difference Moisture Index (NDMI) is employed to assess vegetation water content and monitor drought conditions. Figure 6 indicates that the red and yellow regions are classified as burned areas. NDMI can distinguish between clouds and shadows when identifying burned areas compare to NBR. The NDMI value range is from -1 to 1. Negative NDMI values (approaching -1) indicate infertile soil. Values near zero (-0.2 to 0.4) typically indicate water stress. Elevated, positive values indicate substantial canopy coverage without water stress (about 0.4 to 1).

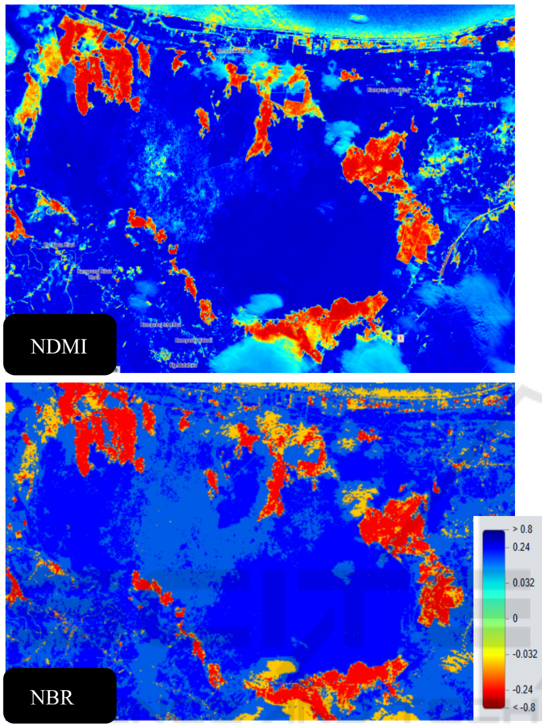

Figure 6: Comparison on Burned Area mapping on S2 imagery dated 24th April 2024 using difference indices NDMI and NBR.

3.2 SAR-Based Burned Area Mapping

Figure 7 illustrate that VV and VH polarizations can be display into a false colour visualization. It uses the VV polarization in the red channel, the VH polarization in the green channel, and a ratio of VH/VV in the blue channel. It shows water areas in dark red (black), urban areas in yellow, vegetated areas in turquoise, and bare ground and burned area in dark purple The grayscale visualization of the gamma0 of the VH polarization also can be displayed. The values for the cross polarization (VH) are generally lower (darker visualization) than for the co-polarization (HH, VV). The VH polarization has higher values for surfaces characterized by volume scattering, e.g., branches, dry coil bodies, or canopies (lighter color in the visualization) and lower for surfaces

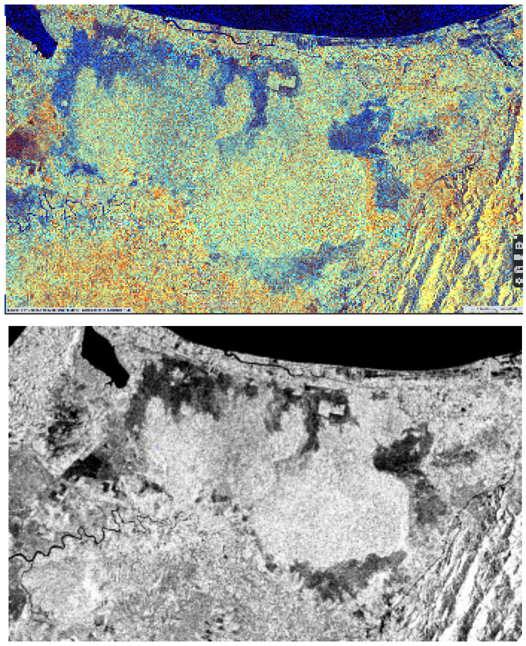

Figure 7: Visualisation of Sentinel-1 SAR false colour composite VV:VH:VH/VV enhance the burned area features and grayscale VH.

3.3 Tracking Burned Area Progression by Combination of Optical and SAR

Taking advantage of the equivalent spatial and temporal resolutions of radar and optical information is facilitated by the availability of near-concurrent active (Sentinel-1) and passive (Sentinel-2) datasets. Figure 8 shows the comparison of trends of SAR false colour composite VV:VH:VH/VV and SWIR colour composite in monitoring forest fire progression within four month periods. Sentinel-2 images were matched to the Sentinel-1 dates for each detection period as follows when there was not any temporally coincident image: for the pre-fire date, the closest Sentinel-2 image acquired before was selected. Based on observation, SWIR colour composite shows higher percentage of cloud cover that distract burned area delineation. While the delineation of burned areas using SAR images can provide more information on the area due to cloud penetration but still limited for some landscapes, since the radar signal reflected from the burned surface may be similar in intensity to the signal from other components of the landscape for example, areas of open ground.

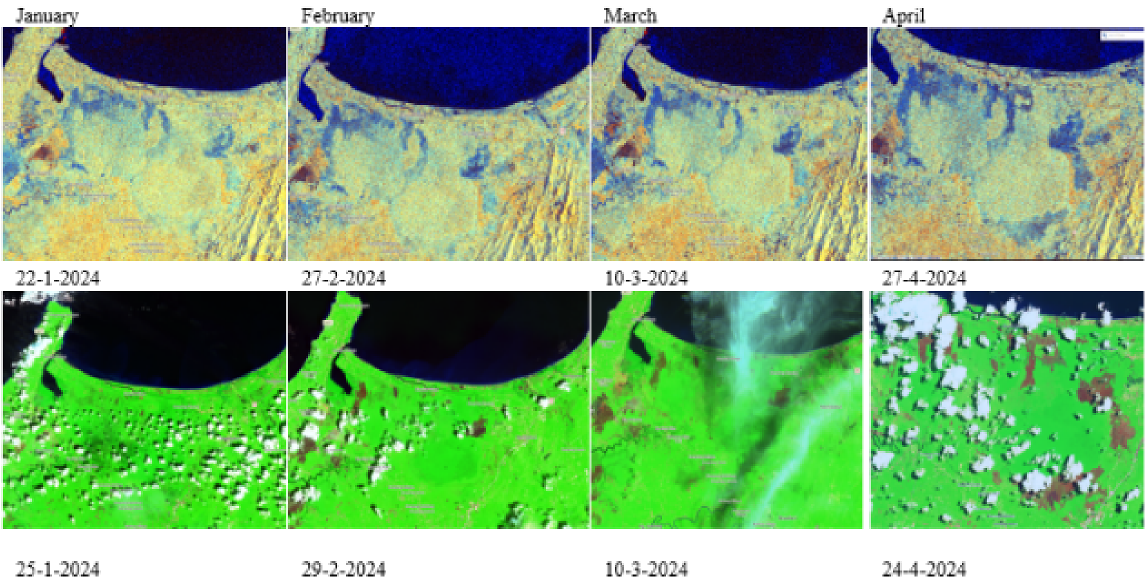

Figure 8: Comparing Burn Area Propagation visualized by SAR and SWIR false colour composite within January-April 2024.

3.4 Incorporation of Burned Area Map into WebGIS Database

The validated burned area maps will be used in iForSABAH system which is an innovative application webGIS system that aims to address these challenges by using space technology and remote sensing to monitor the forest areas in Sabah, Malaysia. iForSABAH stands for Integrated Forest Resource Information System for Sabah, and it is a collaboration between the Malaysian Space Agency (MYSA) and the Sabah Forestry Department. The system uses Geographic Information System (GIS) technology and high-resolution satellite images to detect any changes in permanent forest reserves, and provide information on forest cover, forest type, forest degradation, forest fire, forest restoration, forest carbon stock, and forest biodiversity.

The system also supports the empowerment of indigenous peoples and local communities who depend on the forest resources for their livelihoods. iForSABAH is a cutting-edge solution that leverages the power of space technology to enhance the management of forest resources, support the implementation of the Sabah Forest Management Plan, and contribute to the national and international commitments on forest conservation and climate change mitigation. By using iForSABAH, users can access reliable, timely, and accurate information on the status and trends of the forest areas in Sabah, and make informed decisions for the benefit of the environment and the society.

4 CONCLUSION

In conclusion, the combining of Sentinel-1 and Sentinel-2 facilitates a higher frequency of data collecting and enhances the detection of burned areas, particularly in regions with significant cloud cover. The Sentinel-2 SWIR and NIR bands have demonstrated effectiveness in defining burned areas, in conjunction with the temporal backscatter patterns using Sentinel-1 SAR for forest fire propagation analysis. The multi-date of prefire and postfire data are crucial due to the characteristics of burned areas, which are often linked to agricultural clearance activities that precede the fire event, potentially resulting in misclassification between burned land and cleared land. Future research may demonstrate that NBR and NDMI differencing can yield a more effective methodology. Additionally, noise reduction techniques, such as cloud masking, are essential for improving detection outcomes. Information regarding the progression of burned areas, including segmented areas and hectares, can also be obtained from the final map.

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