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Mapping Red Dust Dispersion in Saldanha Bay: Machine Learning Classification Using Open-Source Geospatial Tools

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Abstract: Saldanha Bay, situated on South Africa's West Coast, faces persistent environmental challenges due to red dust pollution from industrial activities, including operations at Transnet's iron ore terminal and the former Saldanha Steel Plant. This study examined the spatial and temporal distribution of iron ore dust between June 2017 and December 2024 using Sentinel-2 satellite imagery and machine learning classification through the Dzetsaka plugin in QGIS. By applying Random Forest (RF) classification across five distinct land cover classes, this study identified significant seasonal variations in dust dispersion, driven by climatic factors such as strong coastal winds and the Mediterranean climate's dry summers and wet winters. Although RF was the primary classification method employed in this study, its selection was informed by extensive literature highlighting its robust performance in classifying complex land cover types using Sentinel-2 imagery. Compared to other classifiers such as Support Vector Machines (SVM) and k-Nearest Neighbour (k-NN), RF is recognised for its resilience to overfitting, robustness to noisy data, and ability to generalise well in heterogeneous urban-industrial landscapes. These documented advantages in recent studies support the adoption of RF as the most suitable classifier for this research context, particularly given the diverse spectral characteristics of the Saldanha Bay region. The findings highlight the environmental impact of industrial activities and demonstrate the practical application of Free-and-Open-Source GIS (FOSSGIS) tools in environmental monitoring, contributing to effective industrial pollution control in coastal regions.

Keywords: red dust pollution, geospatial analysis, Random Forest classification, QGIS, Free-and-Open-Source GIS (FOSSGIS)

1. Introduction

The industrial port zone of Saldanha Bay, located on South Africa's west coast, has been a focal point of economic activity and industrial expansion, largely driven by the transportation and processing of iron ore. One of the steel plants in the area, the Saldanha Steel Plant (hereafter known as the 'plant'), was previously owned by a South African steel company originally formed as a partnership between Iscor Limited and the Industrial Development Corporation (IDC). In 2002, ArcelorMittal South Africa gained full control of the plant after the company underwent a series of changes in the company's ownership structure. The plant was established to capitalise on the region's proximity to the Sishen-Saldanha railway line and played a pivotal role in the region's industrial development before its closure in February 2020. While the plant bolstered local economic growth, the handling, processing, and transportation of iron ore contributed to air quality concerns due to the dispersal of iron ore dust, commonly referred to as "red dust." This dust has long been a point of contention, particularly regarding its impact on the surrounding environment and public health (Banerjee et al., 2006; Singh and Gautam, 2024). Although various studies have examined industrial emissions in Saldanha Bay (Garland et al., 2019; Kangueehi, 2021; Venture and Steffani, 2008; Vos et al., 2024), limited research has focused on the geospatial and temporal distribution of iron ore dust using remote sensing technologies and Free-and-Open-Source GIS software (FOSSGIS). This study aims to fill this gap by providing a geospatial analysis of iron ore dust distribution through industrial activities in the Saldanha Bay area from 2017 to 2024, utilising satellite imagery and open-source tools.

Iron ore dust emissions have become a persistent environmental challenge in the Saldanha Bay area, exacerbated by industrial activities such as stockpiling, transportation, and ship loading processes at the port (Hendrich, 2021). The closure of the plant in 2020 created an opportunity to assess how industrial shutdowns affect the spatial and temporal dynamics of dust emissions. Understanding these dynamics is essential for improving air quality management strategies and mitigating environmental risks (Munsif et al., 2021). Moreover, the availability of high-resolution satellite imagery, coupled with advancements in FOSSGIS tools, provides researchers with new avenues for monitoring and mapping environmental changes over time (Rustanto et al., 2024). This study builds on the findings of Vos et al. (2024), who highlighted the multifaceted nature of dust sources in the region by exploring natural and anthropogenic drivers, assessing health and environmental impacts, and evaluating the effectiveness of current monitoring efforts to enhance public health risk assessment.

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Previous studies on industrial air pollution in Saldanha Bay have predominantly relied on ground-based monitoring stations and traditional air quality assessment methods (Burger and Petzer, 2023; Probyn et al., 2023; Vos et al., 2024). However, these methods often lack the spatial coverage needed to fully understand dust distribution patterns across large regions. Remote sensing and GIS offer a complementary approach by enabling researchers to capture large-scale environmental data over time, and in terms of this study, will offer insights into the spatial extent of iron ore dust emissions before and after the closure of the Saldanha Steel Plant. Although the temporal analysis captured data from both the operational and post-closure phases of the Saldanha Steel Plant, this study did not solely attribute the red dust distribution to the plant's operations. Other industrial activities in the region, particularly at the Transnet Port Terminal and surrounding facilities, contribute to dust dispersion. This broader industrial context was considered to provide a comprehensive understanding of the environmental impact of red dust in the Saldanha Bay. This study addresses a critical gap in the existing literature by applying a geospatial and temporal approach to assess the iron ore dust distribution in Saldanha Bay from June 2017 to December 2024. Using FOSSGIS software to compare satellite imagery over time, this study aimed to identify spatial trends in dust distribution and assess the environmental impact of the plant's closure. This approach offers a cost-effective and replicable method for monitoring industrial pollution in similar settings, contributing to the fields of environmental management and geospatial analysis.

The findings of this study highlight the potential of FOSSGIS tools for environmental monitoring, demonstrating their utility in providing accessible and accurate geospatial data for decision-making processes (Ciolli et al., 2017). In a context where air quality concerns are becoming increasingly urgent, particularly in industrial regions, this study offers a timely and relevant contribution to understanding and managing the environmental impacts of industrial activities.

2. Industrial Development and Environmental Impacts in Saldanha Bay

Saldanha Bay, located on South Africa's West Coast (Figure 1), has long been recognised for its economic and strategic significance, particularly because of its deep natural harbour and industrial activities (Moses, 2017; Welman, 2018; Welman and Ferreira, 2014). The region's economic growth has been driven by the iron ore export industry, facilitated by the Transnet Port Terminal and Sishen-Saldanha railway line. However, this industrial development has not come without environmental costs (Bartlett et al., 2022; Garland et al., 2019). The pervasive issue of iron ore dust, colloquially referred to as "red dust", has become a pressing concern for both residents and environmental supporters (Mail & Guardian, 2024).

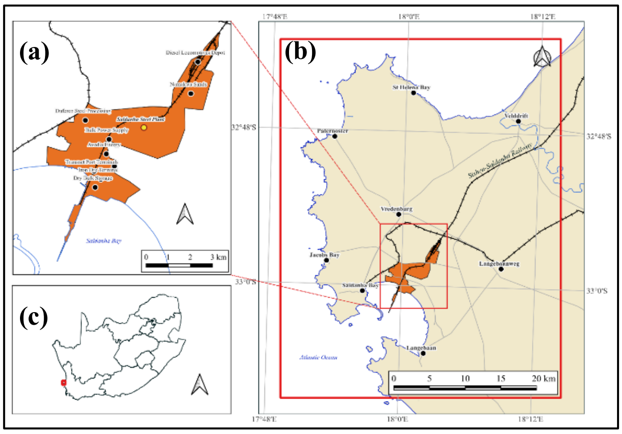

Figure 1: Study Area of Saldanha Bay and Surrounding Region. Panel (a) highlights the key industrial sites, including the Transnet Iron Ore Terminal, Saldanha Steel Plant, Dry Bulk Storage, and Diesel Locomotive Depot. Panel (b) depicts the broader geographical context, showing major towns (Jacob Bay, Langebaan, Langebaanweg, Paternoster, Saldanha Bay, St Helena Bay, and Vredenburg), key transport routes, and the Sishen-Saldanha railway line. Panel (c) shows the study area in South Africa (source: Author created).

The primary sources of red dust pollution in Saldanha Bay are iron ore handling activities at the Transnet terminal and the now-defunct Saldanha Steel Plant, which ceased operations in February 2020. Iron ore transported from the Sishen mines in the Northern Cape is loaded onto ships at the port for export. Although Transnet has implemented measures to mitigate dust emissions, residents have consistently reported issues with dust settling on homes, vegetation, and infrastructure, leading to the formation of advocacy groups, such as the Red Dust Action Group (RDAG) (Red Dust Revolution, 2024; Transnet Port Terminals, 2015). Industrial operations in Saldanha Bay date back to the early 1970s, with the construction of the Saldanha Steel Plant and development of the port to accommodate iron ore exports. The iron ore terminal has since become Africa's largest iron ore exporter, handling an average of 58,000 tonnes per year (Githahu, 2023). Despite efforts by Transnet to suppress dust through water spraying, chemical dosing on conveyor belts, and dust extraction systems, the dust problem persists, particularly during the dry summer months when wind patterns exacerbate dispersion (GroundUp, 2024; Jones and Dalgliesh, 2009; P.D. Naidoo & Associates & SRK Consulting, 2008).

For this study, the area of interest included key towns surrounding the Port of Saldanha, including Vredenburg, Langebaan, Langebaanweg, St. Helena Bay, Velddrift, Paternoster, Jacobs Bay, and Saldanha Bay (Figure 1b). This buffer selection ensures comprehensive spatial coverage of areas likely to be affected by red dust pollution, considering both residential and natural regions. Research indicates that particulate matter can travel significant distances under favourable wind conditions, necessitating a broader geographical scope for the analysis (Chen et al., 2021; Elmes and Gasparon, 2017).

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2.1 Climatic and Environmental Context

Saldanha Bay's climate plays a crucial role in the dispersion of iron ore dust. The region experiences a Mediterranean climate, characterised by hot, dry summers and cool, wet winters (Read et al., 2025). During the summer months, the prevailing winds predominantly (Figure 2) come from the southwest, with speeds exceeding 30 km/h for more than 20% of the time. In winter, the prevailing winds shift to the north and southwest, although they are generally less intense than in summer and are occasionally influenced by the berg wind conditions. These seasonal wind patterns significantly affect the distribution of red dust, carrying it across residential, industrial and natural areas (Garland et al., 2019). The combination of strong summer winds and minimal vegetation cover during the dry months increases the susceptibility of the landscape to dust deposition, underscoring the need for effective dust management (Vos et al., 2024).

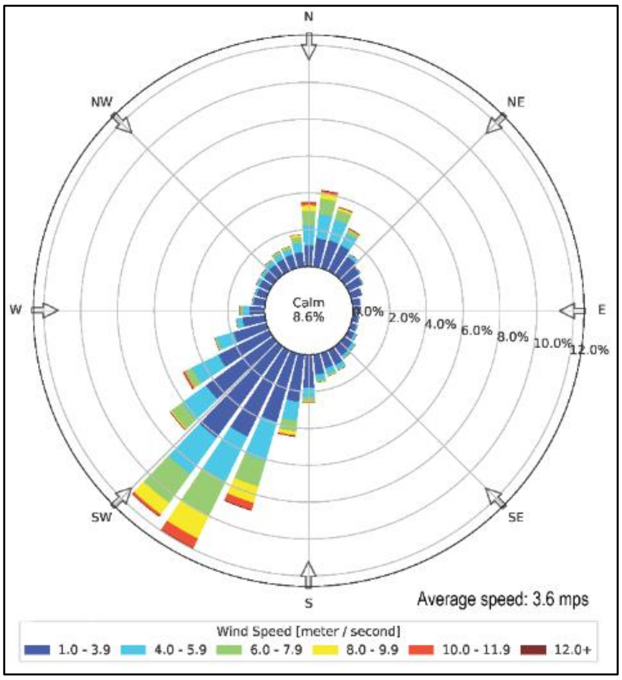

Figure 2: Wind Rose for Saldanha Bay Region. The wind rose illustrates the prevailing wind directions and speeds in Saldanha Bay, with dominant southwesterly winds in summer (4.0–7.9 m/s) and lighter northwesterly winds in winter. Calm conditions occurred 8.6% of the time (source: Iowa Environmental Mesonet (IEM), 2024).

The Langebaan Lagoon, located south-east of the port, is a registered Ramsar site[1] and a key environmental feature of the region. The lagoon's proximity to industrial activities has raised concerns about potential ecological impacts, particularly because dustfall rates near industrial facilities often exceed guideline limits for particulate matter (PM_{10} and $PM_{2.5}$) (Garland et al., 2019). Studies have shown that dust particles settle on various surfaces, including homes, roads, and vegetation, staining them with a rust-red hue (Figure 3) and potentially impacting biodiversity (Red Dust Revolution, 2024; Transnet Port Terminals, 2015).

Figure 3: The impact of red dust pollution is clearly visible in the Saldanha Bay region. The images showcase the abandoned steel plant (top) with surrounding vegetation, road signage, and building facades stained by iron ore dust. Persistent dust deposits illustrate the environmental footprint left behind by industrial activities, affecting both natural landscapes and infrastructure (image credit: Authors, taken 10 January 2025).

2.2 Industrial Activities and Air Quality

Air quality in Saldanha Bay has been a topic of concern for both residents and environmental specialists. The Saldanha Iron Ore Handling Facility, operated by Transnet, is a significant contributor to airborne particulate matter. According to air quality assessments conducted by SRK Consulting, dust emissions from the facility were monitored for compliance with the National Environmental Management: Air Quality Act (NEM:AQA). Despite measures to mitigate dust, monitoring data suggest that certain areas, such as Blue Water Bay, experience higher-than-acceptable dust levels during peak operational periods (P.D. Naidoo & Associates & SRK Consulting, 2008; Venture and Steffani, 2008). However, Transnet and the Saldanha Bay Municipality's Ambient Air Quality Monitoring Report for Saldanha Bay and Vredenburg Sites stated that dust levels currently remain within lawful boundaries as defined under NEM:AQA standards (GroundUp, 2024; Ravenscroft, 2024), reflecting the efficacy of the implemented dust control measures. Garland et al. (2019) highlighted the potential health impacts of iron ore dust

[1] "The Ramsar Convention on Wetlands, also known as the Ramsar Convention, is an intergovernmental treaty that provides the framework for national action and international cooperation to conserve and wisely use wetlands and their resources". It was signed in the city of Ramsar, Iran in 1971. Source: https://www.nextias.com/blog/ramsar-convention-on-wetlands/

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on local communities. This study noted that particulate matter (PM_{10}) can contribute to respiratory illnesses, particularly during periods of high dust emissions. Effective dust mitigation measures, such as maintaining ore moisture content and implementing dust suppression systems, are recommended to reduce health risks (Garland et al., 2019).

3. Methodology

This study spanned from December 2017 to December 2024, capturing the temporal distribution of red dust before and after the closure of the Saldanha Steel Plant. Imagery from both summer (December) and winter (June) was selected to account for seasonal climatic variations, particularly the influence of strong winds and dry conditions on dust dispersion. The specific dates of 23 June 2017 20 December 2017 26 June 2024 and 23 December 2024 were used to ensure consistent seasonal coverage for temporal comparison.

3.1 Tool, Data and Processing

The geospatial analysis conducted in this study relied on a combination of free and open-source software tools to ensure the accessibility and replicability of the methods used. QGIS, an open-source geographic information system, served as the primary platform for processing satellite imagery and performing machine learning (ML) classification. The software facilitated the digitisation of training samples, application of the ML classification algorithm, and visualisation of classified outputs. QGIS has a user-friendly interface, and its compatibility with various plugins makes it a practical choice for conducting comprehensive geospatial analyses (Henrico et al., 2022).

The primary data source for this study was Sentinel-2A multispectral imagery provided by the European Space Agency (ESA) and acquired from the Copernicus Open-Access Hub[2]. Sentinel-2A imagery was particularly advantageous because of its 10–20 m spatial resolution and frequent revisit times, enabling fine-scale monitoring of seasonal dust dispersion. Spectral richness, including bands in the red, near-infrared (NIR), and shortwave infrared (SWIR) regions, provides critical information for distinguishing between vegetated areas, bare soil, and red dust deposits. These bands were used as input features in the RF classifier, where the SWIR (B11 and B12) bands were particularly valuable for detecting iron oxide-rich dust based on its unique spectral signature (Yuan et al., 2022). Sentinel-2A data were pre-processed, including radiometric and geometric corrections, and for Level-2A products, atmospheric corrections were applied to produce Bottom of Atmosphere (BOA) reflectance values. Therefore, no additional atmospheric correction or pre-processing was required for this dataset. The accessibility and reliability of Sentinel-2 imagery make it an ideal dataset for conducting a temporal and spatial analysis (Yuan et al., 2022) of dust dispersion in the Saldanha Bay region.

3.2 Machine Learning Classification

The Random Forest (RF) algorithm was selected as the primary classification method for this study because of its robust performance, interpretability, and practicality for land cover classification using Sentinel-2 imagery. RF is a widely recognised ensemble machine learning technique that constructs multiple decision trees and aggregates their predictions to improve classification accuracy and reduce the risk of overfitting (Khatami et al., 2016; Rodriguez-Galiano et al., 2012). One of the core advantages of RF is its non-parametric nature, which enables it to effectively handle complex, high-dimensional datasets without requiring strict assumptions regarding data distribution (Belgiu and Drăguţ, 2016; Pal, 2005). This is especially relevant in the present study, where the land cover types impacted by red dust in the Saldanha Bay region produced diverse and heterogeneous spectral responses in Sentinel-2 imagery. The intricate spatial patterns and varied surface materials, including urban infrastructure, bare soil, vegetation, and areas with dust deposition, create a classification environment in which traditional parametric methods may struggle to model the data effectively. The flexibility of RF thus aligns well with the challenges posed by the spectral and spatial complexities inherent in this research.

Recent comparative studies have demonstrated that RF consistently produces high classification accuracy in various land cover and land use mapping scenarios using Sentinel-2 data. For example, Thanh Noi and Kappas (2017) found that RF, along with Support Vector Machines (SVM) and k-Nearest Neighbour (k-NN), delivered high overall accuracies, with SVM performing marginally better under certain conditions. Importantly, RF was shown to be relatively robust to variations in training sample size, especially when the training data were moderately abundant, and maintained strong accuracy in complex, heterogeneous environments. Similarly, Abdi (2020) reported that RF performed comparably to other leading machine learning classifiers, including SVM and Extreme Gradient Boosting, in a boreal landscape using Sentinel-2 imagery. RF was particularly valued for its ability to handle noise, computational efficiency, and the insight it provides into variable (band) importance, which is useful for interpreting the influence of spectral bands on classification outcomes. While some studies indicate that SVM or gradient boosting methods may outperform RF under specific circumstances or with fine-tuned parameters (Abdi, 2020; Zhang et al., 2021), RF remains a compelling choice for practical land cover mapping. This is because of its ease of implementation, strong generalisation ability, and proven performance across a wide range of environments. Additionally, the ability of RF to assess variable importance aids in understanding which Sentinel-2 bands most effectively discriminate between land cover types, which is an asset when focusing on features such as red dust dispersion (Zhang et al., 2021).

[2] Copernicus Open Access Hub is available at: (https://data-space.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2).

Supervised learning requires training data to guide the classification. In this study, five distinct land cover classes were identified based on field knowledge and visual interpretation of the Sentinel-2 imagery (Table 1). These classes included water bodies, bare areas, urban areas, healthy vegetation, and areas affected by red dust. Among these classes, only vegetation (bare areas, bare vegetation, and healthy moderate vegetation) and those affected by red dust were presented to ensure relevance to the study's objectives and simplify the analysis for targeted insights. Training polygons were manually digitised within QGIS to represent each class, ensuring that the RF model had sufficient labelled data for accurate classification.

Class #	Class Name	Colour
1	Water Bodies	
2	Bare Areas & Bare Vegetation	
3	Urban Areas & Roads	
4	Healthy & Moderate Vegetation	
5	Red Dust Covered Areas (Urban & Vegetation)	

Table 1: Land cover classification scheme used in the geospatial analysis of the Saldanha Bay region, detailing the assigned class numbers and corresponding surface types

The RF model was trained on these classes and then applied to classify the entire study area. The algorithm's ability to handle multiple raster bands, including Blue, Red, NIR, and SWIR, made it ideal for this study. It also performed well in dealing with noisy data and required less extensive training data than other machine learning algorithms.

After classification, a temporal change detection analysis was conducted to evaluate shifts in the extent of red dust-affected areas over the study period. This involved calculating the area covered by each land cover class at different time points and assessing the changes between 2017 and 2024. The change detection results were further analysed to understand the seasonal and long-term trends in dust dispersion.

4. Results

The results of the RF classification highlighted the spatial distribution of red dust deposits across various land cover types (Figure 4). Areas close to industrial sites showed higher instances of dust-covered urban areas and vegetation.

4.1 Land Cover Classification

The classification identified significant land cover (LC) changes influenced by the red dust deposition. The red dust-covered areas (Class 5) were the most impacted, particularly in areas closest to Transnet's iron ore terminal and the former Saldanha Steel Plant.

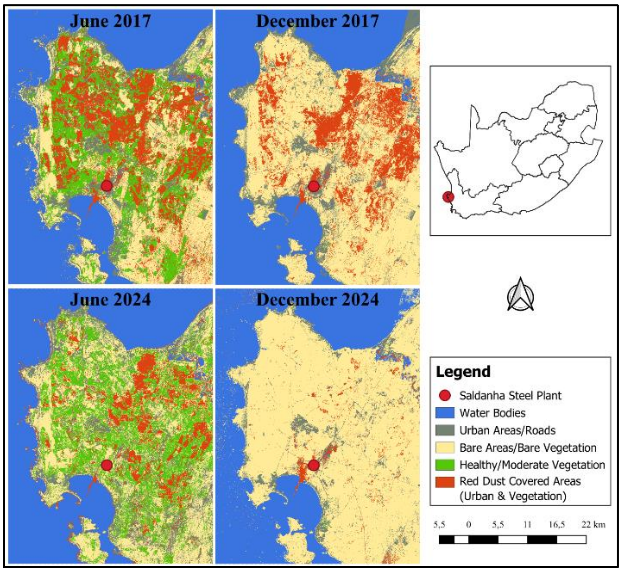

Figure 4: Temporal geospatial classification of the Saldanha Bay region, illustrating the distribution of land cover classes in June 2017 (top left), December 2017 (top right), June 2024 (bottom left), and December 2024 (bottom right). The maps display water bodies (blue), urban areas and roads (grey), bare areas/bare vegetation (beige), healthy/moderate vegetation (green), and red dust-covered areas (orange) in both the urban and vegetated zones. The Saldanha Steel Plant is marked with a red dot, and a location inset shows its position in South Africa. The maps revealed seasonal variations in red dust dispersion, with more extensive dust coverage observed during the dry summer months. These classifications were derived using Sentinel-2 imagery and Random Forest classification in QGIS. This analysis provides insights into the environmental impact of industrial dust over time.

4.2 Raster layer unique values report

The Raster layer unique values report tool available in QGIS was used to calculate the pixel counts, area sizes, and land cover percentages for all classes (see Table 1); however, only vegetation and red dust-covered areas are presented in Table 3 to highlight the key factors relevant to the study objectives. The analysis highlights both temporal changes over the seven-year period and seasonal differences between the wet winter months (June) and dry summer months (December).

June 2017			
Classes	**Pixels (Count)**	**Area Size (km²)**	**LC Coverage (%)***
Bare Areas & Bare Vegetation	4 550 561	455.06	22.43
Healthy & Moderate Vegetation	3 205 887	320.59	15.8
Red Dust Covered Areas	3 352 952	335.3	16.53
December 2017			
Bare Areas & Bare Vegetation	8 456 099	845.61	41.69
Healthy & Moderate Vegetation	6 460	0.65	0.03

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Red Dust Covered Areas	2 645 520	264.55	13.04
June 2024			
Bare Areas & Bare Vegetation	4 884 130	488.41	21.53
Healthy & Moderate Vegetation	4 085 203	408.52	18.01
Red Dust Covered Areas	1 874 855	187.49	8.27
December 2024			
Bare Areas & Bare Vegetation	11 523 900	1 152.39	50.81
Healthy & Moderate Vegetation	13 204	1.32	0.06
Red Dust Covered Areas	405 065	40.51	1.79
** Note that the percentage land cover values in the table reflect the distribution of each class relative to the total study area, which can make changes appear less dramatic when viewed as a proportion of the overall landscape.*			

Table 3: Land Cover Classification Results for Saldanha Bay from June 2017 to December 2024

Figure 5 displays the percentage coverage of the three land cover classes across the four time periods. The top graph compares June 2017 with June 2024, and the bottom graph compares December 2017 with December 2024. Notable changes included a reduction in red dust-covered areas and an increase in bare areas and bare vegetation during the dry season, indicating environmental recovery following the closure of the Saldanha Steel Plant.

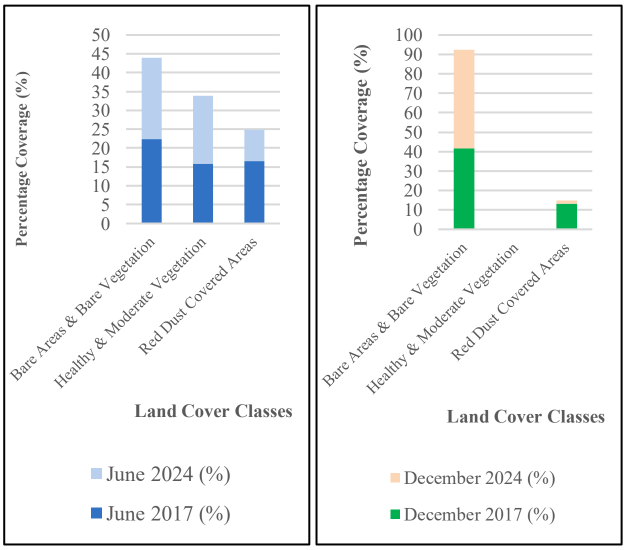

Figure 5: Comparative Land Cover Class Percentage Coverage for the periods under investigation

The bare areas and bare vegetation classes experienced significant increases, particularly during the dry season (December). Between June 2017 and June 2024, this class increased by 7.33%, from 455.06 km² to 488.41 km². However, a much more dramatic increase was observed during the dry season, with bare areas expanding by 36.30% from 845.61 km² in December 2017 to 1 152.39 km² in December 2024. This increase is likely due to persistent drought conditions coupled with ongoing soil degradation and vegetation stress during the summer months. The sharp seasonal increase also suggests that the vegetation recovery observed during winter months is not sustained through the dry season.

One of the most positive trends observed was an increase in healthy and moderate vegetation. Between June 2017 and June 2024, healthy vegetation increased from 320.59 km² to 408.52 km², representing a 27.43% increase. This indicates a recovery in vegetation health following the reduction in industrial emissions after the closure of the Saldanha Steel Plant. During the dry season, healthy vegetation remained minimal but showed a small increase from 0.65 km² in December 2017 to 1.32 km² in December 2024, a 103.08% increase. Although the overall area remains low, this suggests that even during dry periods, some pockets of vegetation are recovering.

The most significant change observed in this study was the reduction in red dust-covered areas. Between June 2017 and June 2024, red dust-covered areas decreased from 335.30 km² to 187.49 km², representing a 44.09% decrease. An even more dramatic change was observed during the dry season. Between December 2017 and December 2024, red dust-covered areas decreased from 264.55 km² to 40.51 km², reflecting an 84.68% decrease. This significant reduction indicates that the cessation of dust-generating activities allowed the environment to recover, with previously dust-covered areas now showing improved vegetation health and reduced dust deposition. This reduction highlights the positive environmental impact of reduced dust emissions, which is most likely due to several contributing factors. Improved handling practices at the Transnet Port Terminal, such as enhanced dust suppression systems during loading and offloading processes, may have played a role. A quicker turnaround time for moving iron ore from the dry bulk storage area to ships could also reduce dust dispersion. Additionally, advancements in dust containment measures, such as conveyor covers and chemical treatments, may have been implemented. Finally, the closure of the Saldanha Steel Plant in 2020 reduced local dust-generating activities, further contributing to the observed decline. While these factors provide plausible explanations, further research is necessary to determine the exact reasons for this decrease.

From the descriptions above, Figure 6 shows the percentage changes in the three land cover classes over two time intervals: June 2017 to June 2024 and December 2017 to December 2024. The graph highlights significant increases in bare areas and bare vegetation, particularly during the dry season (December 2017 to December 2024), whereas red dust-covered areas showed a notable decrease in both time periods. Healthy and moderate

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vegetation slightly increased during the June comparison, indicating seasonal recovery during the wet period.

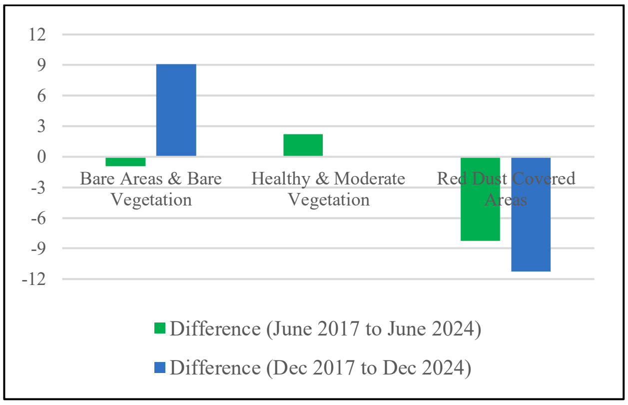

Figure 6: Percentage Coverage Differences in Land Cover Classes

4.3 Dust Dispersion Patterns

With strong southwesterly winds during the summer months and weaker north-to northwesterly winds during the winter months (Figure 2), these seasonal patterns play a significant role in dust dispersion in the Saldanha Bay region. Vos et al. (2024) further emphasised the role of industrial activities in contributing to dust dispersion. In addition to the Saldanha Steel Plant and Transnet Port Terminal, other industrial operations in the region, including bulk cargo handling and construction activities, contribute to the overall dust load. These activities create a complex and multifaceted dust source, where particles are dispersed not only by direct emissions but also by secondary processes, such as vehicle movement on unpaved roads, stockpile erosion, and ship-loading operations (GroundUp, 2024).

Wind modelling studies and experimental research have shown that dust particulates from industrial sites can travel significant distances under favourable wind conditions. The topography and open landscapes of this region amplify the effects of wind-driven dispersion, allowing dust to spread across a broader area that can impact vegetation, infrastructure, and air quality over both short and long distances from the source (Marzen et al., 2016; Yang et al., 2024).

The combination of wind-driven dispersion and industrial activities presents a unique challenge in managing dust pollution in Saldanha Bay. Mitigation strategies must consider both primary sources of dust and environmental factors that influence its spread. Understanding these dust dispersion patterns is essential for developing targeted measures to reduce dust exposure in affected communities and protect the region's natural and built environment (Garland et al., 2019; Vos et al., 2024).

5. Conclusion

This study provides a geospatially driven assessment of red dust impacts in Saldanha Bay, highlighting the utility of remote sensing technologies and machine learning classification in environmental impact assessments. By employing the Random Forest (RF) algorithm through the Dzetsaka plugin in QGIS, this study successfully identified the spatial distribution and temporal trends of red dust dispersion across the region. The analysis captured the impact of dust before and after the closure of the Saldanha Steel Plant in February 2020, shedding light on the ongoing environmental challenges posed by industrial activities at the Transnet Port Terminal.

The findings confirmed that dust dispersion is heavily influenced by both industrial activities and natural climatic factors, with significant impacts on local communities and ecosystems in the region. Southwesterly winds during the summer months carried dust inland, affecting residential areas in towns such as Vredenburg and Langebaan, whereas northwesterly winds in winter dispersed dust towards coastal areas. This highlights the interplay between human activities and natural processes in shaping the environmental landscape of the region. Despite the partial environmental recovery observed after the steel plant's closure, the continued transport and handling of iron ore by Transnet remains a significant contributor to dust pollution in the area. This aligns well with the statement made by Vos et al. (2024) that identifying a single source of dust in such a diverse industrial area is challenging.

Areas with the highest dust deposits were near industrial sites, particularly near the Transnet Port Terminal. However, the impact of dust extends beyond immediate industrial zones, affecting residential areas and natural landscapes. This underscores the need for a comprehensive approach to dust management that addresses both point-source emissions and the broader environmental factors that facilitate dust dispersion. The reduction in red dust-covered areas, such as the 44.09% decrease observed between June 2017 and June 2024, highlights the positive environmental impact of improved dust control measures and closure of the Saldanha Steel Plant. However, further research is required to identify the specific factors driving this reduction, including potential improvements in handling practices, quicker turnaround times, and enhanced dust suppression systems.

This study demonstrates the value of remote sensing and open-source GIS tools in environmental impact assessments, providing a replicable framework for future studies. The use of open-source GIS tools and machine learning classification provides a cost-effective and scalable approach that can be adopted by local municipalities, environmental agencies, and industrial operators to assess and manage dust impacts more effectively. These insights can inform targeted dust mitigation strategies, such as the implementation of dust suppression systems, creation of vegetation buffers, and establishment of comprehensive air quality monitoring programs. Such measures are essential to protect the health and well-being of local communities and preserve the natural environment of Saldanha Bay.

Beyond its practical outcomes, this study illustrates the strategic value of integrating machine learning into environmental monitoring frameworks. Algorithms such as RF do not merely enhance classification accuracy; they enable efficient, scalable, and cost-effective assessments of pollution patterns, particularly in data-scarce or resource-constrained settings. Their interpretability and compatibility with open-source GIS tools, such as QGIS, make them accessible to municipal and regional authorities who may lack proprietary software or extensive computing power. As Belgiu and Drăguţ (2016) argued, machine learning not only streamlines analysis but also supports robust decision-making in environmental planning. Future applications could further expand the role of these tools by incorporating automated time-series analyses, ensemble modelling, or real-time classification for dynamic dust monitoring.

Although this study provides valuable insights into dust dispersion patterns in Saldanha Bay, several gaps remain that warrant further investigation. Although effective, reliance on satellite imagery and machine learning classification does not capture ground-level dust concentrations or specific health impacts on local communities. Future research should incorporate in-situ air quality measurements and epidemiological studies to assess the direct health effects of exposure to red dust. Additionally, this study primarily focused on red dust dispersion from industrial activities, whereas other sources of particulate matter, such as vehicle emissions and agricultural activities, were not addressed. A more holistic approach to air quality assessment would provide a comprehensive understanding of the contributing factors. Finally, the temporal analysis was limited to specific dates in the summer and winter months. A continuous temporal analysis over multiple years would offer a deeper understanding of the long-term trends in dust dispersion and its environmental impacts.

Recent air quality assessments conducted by Transnet indicate that the iron concentrations in the ambient air around the Saldanha Port Terminal are within the permissible limits established by South Africa's National Ambient Air Quality Standards (NAAQS) (Mail & Guardian, 2024). These limits, which set an annual average of 40 $\mu g/m^3$ and a 24-hour average of 75 $\mu g/m^3$ for particulate matter (PM_{10}), aim to protect public health and the environment. Transnet's compliance with these standards demonstrates its commitment to regulatory requirements; however, continued monitoring and mitigation efforts are essential to address community concerns regarding dust exposure.

In conclusion, this study assessed the spatial and temporal distribution of red dust in Saldanha Bay using geospatial technologies and machine learning classification. While it has achieved its primary objectives, it also highlights the need for continued research and monitoring to address remaining gaps. A more integrated approach that combines geospatial analysis with ground-level measurements and community engagement is necessary to develop effective and sustainable solutions for dust pollution in industrial regions. By building on the foundations laid in this study, future research can further enhance our understanding of dust dispersion patterns and contribute to the development of the best practices for environmental management in Saldanha Bay and similar regions worldwide.

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