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Environmental Contamination of a Biodiversity Hotspot—Action Needed for Nature Conservation in the Niger Delta, Nigeria

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Abstract: The Niger Delta belongs to the largest swamp and mangrove forests in the world hosting many endemic and endangered species. Therefore, its conservation should be of highest priority. However, the Niger Delta is confronted with overexploitation, deforestation and pollution to a large extent. In particular, oil spills threaten the biodiversity, ecosystem services, and local people. Remote sensing can support the detection of spills and their potential impact when accessibility on site is difficult. We tested different vegetation indices to assess the impact of oil spills on the land cover as well as to detect accumulations (hotspots) of oil spills. We further identified which species, land cover types, and protected areas could be threatened in the Niger Delta due to oil spills. The results showed that the Enhanced Vegetation Index, the Normalized Difference Vegetation Index, and the Soil Adjusted Vegetation Index were more sensitive to the effects of oil spills on different vegetation cover than other tested vegetation indices. Forest cover was the most affected land-cover type and oil spills also occurred in protected areas. Threatened species are inhabiting the Niger Delta Swamp Forest and the Central African Mangroves that were mainly affected by oil spills and, therefore, strong conservation measures are needed even though security issues hamper the monitoring and control.

Keywords: nature conservation; NDVI; pollution; remote sensing; species; vegetation indices; oil spill

1. Introduction

The Niger Delta is one of the largest wetlands in the world with huge biodiversity [1,2]. It has the largest river delta and mangrove extension in Africa [3–5]. The International Union for Conservation of Nature (IUCN) rated this region as one of the highest conservation priority areas in West Africa [5–8]. In contrast, it has also become one of the most vulnerable biodiversity hotspots in Africa. It has lost large portions of its protected areas over the years due to overexploitation, deforestation and pollution [3,5,9,10]. Oil exploration has become a curse rather than a blessing because of the numerous adverse effects on people and nature resulting from oil production. Large amounts of oil were discovered in 1956 under the Delta surface [5,11]. In 2020, Nigeria's crude oil reserves were estimated to be 36.9 billion barrels, making it the second-largest reserve in Africa after Libya [12,13]. In 2015, Nigeria was the world's fourth-largest exporter of liquefied natural gas and Africa´s major oil producer [14–16]. Even though about 86% of the country's exports and foreign exchange earnings come from oil production, it constitutes only about 10% of the country's

gross domestic product (GDP) [17]. Therefore, the infrastructural development is low. The Niger Delta is facing conflicts between oil-producing communities and oil companies or the government with ethnic, economic and environmental concerns resulting from oil production [18]. The main environmental concerns in the region are gas flaring and oil spills. The gas flaring releases harmful gases such as sulfur dioxide that causes acid rain and breathing problems in the affected areas [18]. Oil spills contaminate soil, water, flora and fauna. Between 2007 and 2015, almost 90 million liters of oil were spilled in the Niger Delta and more than 1000 km^2 of the surface has been polluted [19]. In many selected areas, the soil was polluted to a depth of more than 5 m and the mangroves were destroyed. The study also revealed that restored spill sites remained extremely contaminated [20]. According to Obida et al. [19], about 1160 km^2 of, mainly, broadleaved forest, mangroves and croplands have been affected by oil spills between 2007 and 2015. Sabotage (theft) was the primary cause of oil spills in the Niger Delta ([19]; see also Appendix A, Figure A2).

The severe pollution not only causes difficulties for flora and fauna but also for local people. Approximately 565,000 people are at high exposure to oil spills because they live in close proximity [19]. The majority of the residents are directly dependent on the (polluted) environment by farming, fishing and other resource usages [9]. In addition, sources of potable water are polluted. Crude oil contains benzene, toluene, ethylbenzene and xylenes (BTEX), among others. Prolonged exposure to BTEX can affect the liver, kidney and blood system. For instance, long-term exposure to benzene, which evaporates quickly into the air, reduces the red blood cells and leads to anemia. Its short-term symptoms include headaches, irregular heartbeats, convulsion and skin irritations [21,22]. Furthermore, a higher child mortality rate was detected in the Niger Delta region [23].

Remote sensing can support the detection, mapping and monitoring of oil spills. In most cases, remote sensing is used to detect oil spills on water surfaces [24–26], as, for example, assessing the impact of one of the largest oil spills in history—BP's Deepwater Horizon spill in 2010 [27,28]. The emissivity property of oil makes identification of oil easier on water surfaces. In contrast to active (radar) remote sensing data, passive (optical) remote sensing, visible, infrared and thermal infrared bands can be used to detect oil on the surface of water. A study by De Kerf et al. [29] detected oil spill on the surface of water using a combination of the visible bands from an unmanned aerial vehicle (UAV) and thermal infrared band. The thermal infrared images were able to detect oil spill on the water because the emissivity of oil is greater than water. The oil absorbs visible light and re-radiates some of that light in the thermal infrared spectrum which makes it appear warmer than water [30,31]. Xing et al. [28] also detected oil spills of the Deepwater Horizon (Gulf of Mexico) using Landsat thermal infrared imagery. From their research, thermal images of an oil slick usually show hot slicks when the oil absorbs the heat during the day. The high emissivity of oil as a result of the sun heating the oil on the surface of water enabled the detection of oil slicks since it was warmer than the surrounding water surface.

The use of radar imagery (active remote sensing) to monitor oil spills is also possible because oil slicks reduce the surface roughness on water and appear darker in the radar imagery. Brekke and Solberg [32] concluded in their research that the use of Synthetic Aperture Radar (SAR) was the most applicable when it comes to oil-spill detection due to its wide coverage and ability to capture data despite the weather. It can penetrate clouds and capture data both during the day and at night. Hyperspectral sensors have also been used by some authors to explore the spectral signature of oil-polluted environments [33–35]. Furthermore, the spectral signature of vegetation is dependent on the physiological state of the vegetation at a particular time. Stressed vegetation gives a different spectral signature in comparison to healthy vegetation due to the reduction in the leaf chlorophyll content and its absorption properties [36,37]. Therefore, vegetation indices have been used by various authors to detect oil spills (e.g., [38–40]).

Our objective was to detect the land use/land cover types and protected areas that have been affected by oil spills between 2016–2020 in the Niger Delta. In addition, we estimated the potentially affected species indirectly by location information by IUCN. We

used remote sensing techniques in combination with vegetation indices to identify polluted surfaces. The subordinated research questions were:

- Which vegetation indices are most suitable to detect oil spills in the Niger Delta?
- Where are the hotspots (accumulation) of oil spills located in the Niger Delta?
- Which species, land cover types and protected areas/ecosystems are most threatened by oil spills in the Niger Delta?

2. Materials and Methods

2.1. Study Area

The Niger Delta is located in southern Nigeria along a 450-km coastline of the Gulf of Guinea and covers approx. 7.5% of Nigeria's surface [41]. The Niger Delta is highly populated. In our study area (Figure 1), approx. 43 million people were living in 2020 [42]. The most densely populated state is Imo State with 600–800 people/km^2. Therefore, high pressure on the environment is caused by urbanization, agriculture and resource extraction [3].
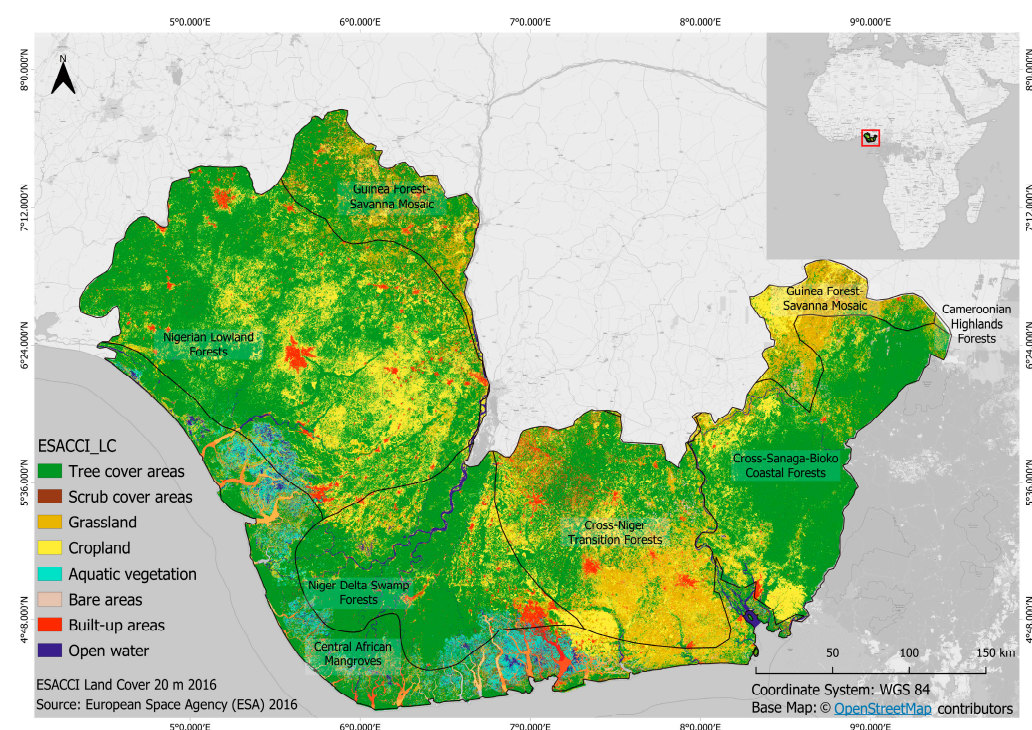

Figure 1. The study area Niger Delta in Nigeria with ecoregions and land use types. The pipelines are shown in Appendix A, Figure A1.

Seven ecoregions cover the Niger Delta (see Figure 1): Cameroonian Highlands Forests; Central African Mangroves; Cross-Niger Transition Forests; Cross-Sanaga-Bioko Coastal Forests; Guinea Forest-Savanna Mosaic; Niger Delta Swamp Forests; and the Nigerian Lowland Forests. The ecoregion with the largest extent of mangroves is the Central African Mangroves, which covers about 30–40 km in the south of the Niger Delta and contains all the mangrove species found in Nigeria. In addition to the loss of mangroves due to industrialization, urbanization, timber exploitation and agriculture, oil exploitation is also posing a threat to this region [43]. Located between the biogeographic areas of the Cross River and the Niger River is the Cross Niger Transition Forests ecoregion. This ecoregion is confronted with a high agricultural intensity that has caused the removal of most of the natural tree cover [44]. The Cross-Sanaga-Bioko Coastal Forests ecoregion has the highest number of forest birds and mammal species in Africa [45]. The highly threatened Cross River population of the lowland gorilla is living in this ecoregion in Nigeria and Cameroon [46]. The ecoregion of the Guinean Forest-Savanna is located in the northern part

of the Niger Delta and forms a mosaic of different ecosystem types and, therefore, a high variety of habitats and species. The main threats to its biodiversity are hunting, agriculture and deforestation [47]. The Niger Delta Swamp Forest is Africa's largest swamp forest after the Congo Basin Swamp Forests. For many years, it escaped habitat degradation because it was less populated and had less socioeconomic activity. It was the discovery of oil that opened the region for development at the expense of its environment.

The Nigerian Lowland Forest ecoregion remains one of the densely populated areas with a lot of anthropogenic activities. The high exploitation of the region's forests has led to fragmentation and reduced forest connectivity. Almost all reserves were converted to rubber plantations and crops [48]. The Cameroonian Highland Forest is the smallest ecoregion in our study area and forms part of the Cross River State where no oil spills have been recorded.

Over 90% of the region's protected areas are nationally designated forest reserves [49]. Only a few protected areas have internationally acknowledged protection status. The Urhonigbe Protected Area is a strict nature reserve according to IUCN (protection category Ia). Human activities are very limited and the primary aim is the protection of nature. The Gilli-Gilli Game Reserve has IUCN protection category IV, which is a habitat/species management area. This category aims to protect specific species or habitats by actively managing the protected area [50]. The Apoi Creek Forest is a lowland swamp-forest and since 2008 a Ramsar Site (Wetlands of International Importance [51])—especially for the protection of the endemic and endangered Niger Delta Red Colobus Monkey [52]. Other internationally designated protected areas are the Oban Biosphere Reserve and Okwangwo Biosphere Reserve which were assigned as biosphere reserves within the Man and Biosphere program of UNESCO [53,54]. The Oban Biosphere Reserve covers the Oban Forest Reserve, the Cross River National Park and the Obudu Plateau. The Okwangwo Biosphere Reserve is located north of the Cross River National Park [54].

The oil facilities in the Niger Delta cover an area of about 31,000 km^2 with oil and gas flow lines stretching over 45,000 km [7,55]. The Niger Delta has 500 oil fields, with more than 55% onshore. The remaining oil fields are found less than 500 m in shallow waters (offshore; [56]). Among the oil facilities, there are higher rates of oil spills linked to the pipelines [19]. Pipelines have experienced regular leaks and ruptures since their invention in the late 19th century [57,58]. They transport crude oil at a high pressure, over 1000 pounds per square inch (psi), which can result in oil spills when the pipelines are not well maintained [11]. Furthermore, oil facilities are often attacked and sabotaged by local and militant groups trying to obtain a share of the oil wealth [59]. According to Onuoha [59], over 10% of stolen oil is exported every year in the country. Between 2009 and 2018, Nigeria lost USD38.5 billion due to crude oil theft [60]. In addition, some oil spills were caused by equipment failure, operational/maintenance error and corrosion after abandonment [20,61]. In Nigeria, there are serious concerns regarding the age and condition of pipelines in light of industrial standards and international guidelines [20,62].

It happens that some pipelines (see Figure A1), oil fields and terminals are located within protected areas. This increases the vulnerability of protected areas being affected by oil spills. Several species in the Niger Delta are under severe threat. Near-threatened (NT) species had the highest count—with birds being the most threatened species in the region (Appendix A, Figure A3; [63]). Species such as the Mona Monkey (*Cercopithecus mona*, NT), West African Black Mud Turtle (*Pelusios niger*, NT), Niger Delta Red Colobus (*Piliocolobus epieni*, critically endangered—CR), Red-Eared Monkey (*Cercopithecus erythrotis*, vulnerable—VU) and Cape Gannet (*Morus capensis*, endangered—EN) have significantly declined over the years.

2.2. Data

We used different datasets for land use/type, biodiversity and oil spills (see Table 1). The land use data used in this study include the European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover 20 m Map of Africa 2016 [64], a Sentinel-2 prototype land cover of 20 m, from which the training data for the classification were obtained. A composite of the datasets at a resolution of 20 m was used for the classification. Due

to its location with high cloud coverage [65,66], Sentinel-2 MSI, Level-1C and Sentinel-1 SAR GRD were used for the Niger Delta. Auxiliary variables used to enhance the classification included WorldPop Global Project Population Data [67], Hansen Global Forest Change v1.8 [68] and the 2015 30 m Global Food Security-support Analysis Data (GFSAD) Cropland Extent of Africa (GFSAD30AFCE v001; [69]). Excluding the GFSAD cropland extent data [70], all the other datasets were obtained from Google Earth Engine.

The ecoregions (RESOLVE Ecoregions; [71]) and protected areas (World Database on Protected Areas; [49]) data were also obtained from Google Earth Engine. The RESOLVE Ecoregions dataset constitutes 846 terrestrial ecoregions of which 7 can be found in the Niger Delta. With the protected areas, less than 5% of the protected areas in the Niger Delta have reported IUCN categories. The IUCN classifies protected areas based on their management objectives, with different levels of restrictions [50]. Data on the conservation status of species were obtained from the IUCN Red List of Threatened Species [63]. Location data of species from the near-threatened (NT) to critically endangered (CR) were used for this study the from Global Biodiversity Information Facility (GBIF) [72].

The oil spill incident data used for this study were obtained from the National Oil Spill Detection and Response Agency (NOSDRA) website [73]. Information provided in the data includes the spill date, when it stopped, reported date, causes of the oil spills, type of facilities affected, affected states, geographic coordinates and the quantity of the spill. A total of 2704 oil-spill incidents were used for this study. These are oil spills that occurred between 2016 and 2020. These are visible on the readily available Google Earth Pro Landsat imagery.

Table 1. Data used for the study.

Data	Resolution	Year	Data Source
European Space Agency Climate Change Initiative Land Cover 20 m Map of Africa	20 m	2016	[64]
Sentinel-2 MSI, Level-1C	10 m	2016–2020	[74]
Sentinel-1 Synthetic Aperture Radar Ground Range Detected	10 m	2016–2020	[75]
WorldPop Global Project Population Data	100 m	2016–2020	[67]
Hansen Global Forest Change v1.8	30 m	2016–2020	[68]
Global Food Security-support Analysis Data Cropland Extent of Africa	30 m	2015	[69]
RESOLVE Ecoregions	-	2017	[71]
World Database on Protected Areas	-	2021	[49]
Species occurrence data	-	2010–2021	[72]
Oil spill incident data	-	2016–2020	[73]

2.3. Methods

The aim was to assess the impact of oil spills on the land cover from 2016–2020 and to detect the affected biodiversity areas in the Niger Delta by using remote sensing techniques and vegetation indices. The analyses were completed using Google Earth Engine, R studio, ArcGIS Pro and QGIS.

2.3.1. Vegetation Indices for Remote Sensing

Vegetation indices (VIs) give information on vegetation cover, vigor and its growth dynamics [26] and can track the changes in the leaf chlorophyll content (LCC) of vegetation [37]. According to Xue and Su [26], monitoring vegetation conditions and mapping land cover changes has increasingly relied on VIs derived from satellite data. Moreover, many studies have examined vegetation by using individual or grouped spectral bands (e.g., [38–40]). The VIs are a mathematical combination of several spectral bands, designed to maximize sensitivity to the vegetation characteristics [76,77]. For example, a study by Mishra et al. [78] revealed that stress on salt marshes—caused by an oil spill—led to a considerable decrease after the oil spill in the biomass and chlorophyll content of the plants during the growing season of 2010. With remote sensing, the spectral signatures of vegetation can be assessed and the use of vegetation indices has proved to be a successful strategy in detecting and assessing the impact of spilt crude-oil on vegetation [79]. Another example is the study by Lassalle et al. [39] who employed 14 VIs to monitor oil pollution in a vegetated industrial site and which had high levels of total petroleum hydrocarbons (TPH) contamination, stressing the vegetation.

The visible bands are still widely used in oil-spill detection by remote sensing, even though they have many shortcomings [24]. Sensors of this type are poor at detecting oil, as they find it difficult to separate oil from the normal background interference. In general, the use of remote sensing to assess vegetation health is based on the following light spectra: ultraviolet (UV) region (10 to 380 nm); visible spectra, consisting of blue (450–495 nm), green (495–570 nm) and red (620–750 nm) wavelength, and the near and mid-infrared (850–1700 nm) bands [80,81]. Following the approach of Adamu et al. [82] who utilized 20 VIs to compare the vegetation health of oil-polluted areas with unpolluted areas, we selected five VIs for this study: Enhanced Vegetation Index (EVI); Normalized Difference Vegetation Index (NDVI); Soil-Adjusted Vegetation Index (SAVI); Normalized Green Red Difference Index (NGRDI) and Green Leaf Index (GLI). EVI and GLI are the two VIs that expressed the highest differences between polluted and unpolluted sites. NDVI and SAVI are commonly used in vegetation studies and NGRDI has been integrated to gain new insights on the usefulness of this index in vegetation pollution studies.

The overview of equations and references is given in Table 2. NDVI is an indicator for photosynthetic activities in plants and it helps in detecting the health of a plant [83–85]. It is widely used for vegetation studies due to its responsiveness to green vegetation [26]. Nonetheless, it can be biased in sparsely vegetated areas due to its sensitivity to background variations [26,86]. In order to address the limitations of the NDVI, EVI was developed, incorporating both background adjustment and atmospheric resistance concepts [26]. It helps correct the influence of soil and the atmosphere when studying vegetation, where the constants C1 and C2 are 6 and 7.5, respectively, and L_E is the soil adjustment parameter, equivalent to 1. Huete [87] also proposed SAVI as an improvement on the sensitivity of NDVI to background soil. Background variations such as soil color, brightness and moisture content do not have much of an effect on the SAVI. L_S is the soil conditioning index, with the value 0.5. NGRDI is another index for vegetation monitoring [88]. However, it is based on the visible spectral bands, green and red. GLI was initially developed by Louhaichi et al. [89] for the use of the digital RGB camera. The camera was used to monitor wheat cover using the visible spectral bands: red, green and blue. These indices are broadband greenness VIs that measure the quantity and vigor of green plants and help to assess the impact of the oil spills on vegetated areas in the Niger Delta.

Table 2. Vegetation indices used in this study.

Name	Abbreviation	Equation	Reference
Enhanced Vegetation Index	EVI	$2.5(\text{NIR} - \text{Red})/$ $(\text{NIR} + \text{C1}\cdot\text{Red} - \text{C2}\cdot\text{Blue} + L_E)$	[90]
Green Leaf Index	GLI	$(2\cdot\text{Gren} - \text{Red} - \text{Blue})/$ $(2\cdot\text{Green} + \text{Red} + \text{Blue})$	[89]
Normalized Difference Vegetation Index	NDVI	$(\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$	[88]
Normalized Green Red Difference Index	NGRDI	$(\text{Green} - \text{Red})/(\text{Green} + \text{Red})$	[88]
Soil Adjusted Vegetation Index	SAVI	$(1 + L_S)(\text{NIR} - \text{Red})/$ $(\text{NIR} + \text{Red} + L_S)$	[87]

2.3.2. Assessing the Impact of Oil Spills on Land Cover

The Sentinel-2 MSI Level-1C image collection for each year was filtered for scenes with less than 10% cloud cover and then cloud-masked. The other data used were Sentinel-1 Synthetic Aperture Radar (SAR) Ground Range Detected (GRD) yearly median image; WorldPop Global Project Population Data; Hansen Global Forest Change v1.8 and the GFSAD Cropland extent data. All data were stacked as bands into the resulting raster stack for the classification. A pixel-based classification was completed in Google Earth Engine using Random Forest (RF) classifier and the training data were obtained from ESA CCI Land Cover 20 m Map of Africa using the stratified random sampling technique: Tree cover areas (number of training pixels: 450); Shrub cover areas (200); Grassland (300); Cropland (350); Aquatic vegetation (150); Bare areas (100); Built-up areas (300) and Water (150). Hyperparameter tuning was used for determining the Number of Trees that resulted in the highest accuracy.

One of the benefits of using RF is its ability to rank the importance of the variables used for the prediction. The variable importance of the bands used in the classification was computed, as well as the confusion matrix, Kappa coefficient, overall, producer and user accuracy (resubstitution accuracy). After the classification, post-classification using a moving window (3×3 pixel) was completed to reduce the salt and pepper effect in the final classification maps. Figure 2 contains the steps used in obtaining the land use/land cover (LULC) maps of the Niger Delta, from 2016 to 2020.

After obtaining the LULC maps for each year, land cover information was assigned to the spill incidences as shown in Figure 3. This provided data on the oil spill-affected land cover in the region. Then, the oil-spill incidents within vegetation cover areas were selected (spill sites—SS). These are tree cover areas, croplands, grassland, scrub cover areas and aquatic vegetation. An equivalent number of points were also randomly selected in areas that had not experienced any oil spill. To avoid the non-spill points overlapping with the spill points, a 30 m buffer around each spill point was clipped from a bounding shape file of areas where the oil spills occurred. Then, using stratified random sampling, the non-spill points were generated with a count matching the affected land cover types (NSS; Appendix A, Figure A4: Comparison of data count within selected SS and NSS). The five VIs (EVI, NDVI, SAVI, NGRDI and GLI) to assess the impact of oil spills on the vegetation cover were then calculated. The VIs were assigned to the SS and NSS for each year. A buffer of 30 m around each SS and NSS point was used for the analysis because oil spills may migrate from the point of source and affect neighboring surroundings. With 30 m, we ensured that the spill sides are covered in case of potential errors in the geolocation of the utilized datasets. The average vegetation indices for each point were then used to generate a boxplot to compare the performances of the indices with oil-polluted and unpolluted vegetation cover areas and the significance level of the selected indices were computed.
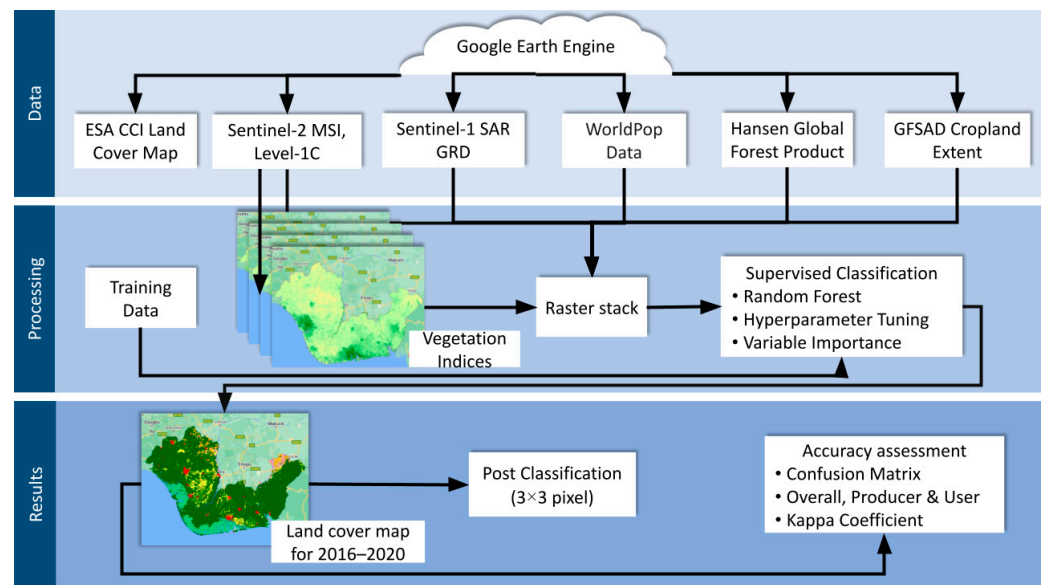
Figure 2. Showing the steps used in obtaining the land use/land cover (LULC) maps of the Niger Delta, from 2016 to 2020. Abbreviations: ESA = European Space Agency; CCI = Climate Change Initiative; GFSAD = Global Food Security-support Analysis Data; GRD = Ground Range Detected; SAR = Synthetic Aperture Radar.
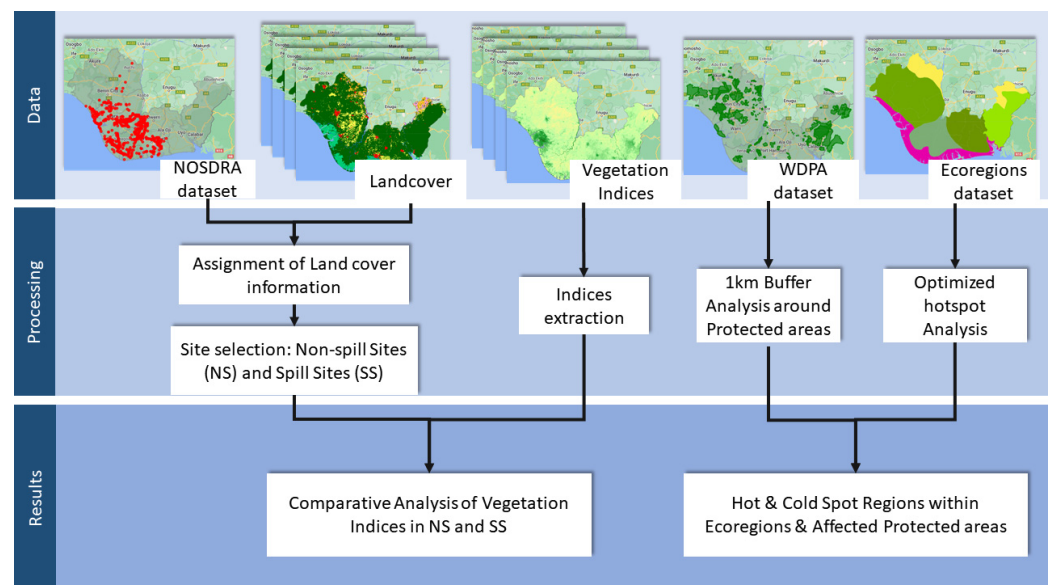

Figure 3. Methodological framework for the impact of oil spills on the land cover using vegetation indices. Abbreviations: NOSDRA = National Oil Spill Detection and Response Agency; WDPA = World Database on Protected Areas.

2.3.3. Assessing the Impact of Oil Spills on Biodiversity Areas

Figure 3 shows the framework that was used to detect the affected ecoregions and protected areas, with spill count, within the oil-spills' hotspot (high density of oil spills) and cold spot regions (low density of oil spills) in the Niger Delta. The ecoregion data were used to assess the oil spills that occurred within each region and to detect the most impacted ecoregion. Spills within and around protected areas were also assessed, using a 1 km buffer around the boundaries of the protected areas. Spatial join was also used in this analysis to obtain the spills within and around the protected areas. Getis and Ord's G_i^* spatial statistic was used for the hotspot analysis. It was used to analyze spatial association

in relation to distance [91,92] in ArcGIS Pro: Optimized hotspot analysis (Getis-Ord G_i^*). In addition, Obida et al. [19] used this approach to identify the main areas of oil spills in the Niger Delta in 2007–2015. The Getis-Ord G_i^* statistic used in ArcGIS are given as:

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - \overline{x} \sum_{j=1}^n w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^n w_{ij} - (\sum_{j=1}^n w_{ij})^2}{n-1}}}$$

where the attribute value for the feature j is x_j; the spatial weight between feature i and j is w_{ij}; the total number of features is equal to n.

$$\overline{x} = \frac{\sum_{j=1}^n x_j}{n} \qquad S = \sqrt{\frac{\sum_{j=1}^n x^2{}_j}{n} - \overline{x}^2}$$

This formula generates positive and negative G_i^* statistics (Z-value) that give information on the spatial clustering of oil spills within the context of neighboring features. For statistically significant positive Z-values, the larger the Z-value, the more intense the clustering of oil spills (hotspots). Whereas oil-spill cold spot regions are areas with statistically significant negative Z values, indicating low spatial clustering of oil spills. Values close to zero imply the oil-spill points are randomly distributed [93]. The aggregation method used in obtaining spill point counts to be used in the analysis was to count incidents within the hexagon grid. This generates a hexagonal polygon mesh which is positioned over the spill points to count points within each polygon cell. Ecoregions and affected protected areas within cold and hotspot regions in the Niger Delta were detected from the results of the optimized hotspot analysis.

The devastating state of the Niger Delta threatens several species as well as their habitats. The selection of the species was based on the IUCN Red List of Threatened Species which is a critical indicator of the health of biodiversity worldwide. The geolocation of species that are near threatened, vulnerable, endangered and critically endangered in the Niger Delta was downloaded from the GBIF website [72]. Although water bodies are not excluded when it comes to oil pollution, the assessment of the impact of oil spills on land cover excluded that of the water class, hence fishes were not part of the species used for this study. Water bodies were excluded from the core analysis (even though part of the results in Appendix A, Figure A5) because oil spreads more easily on water surfaces than on land. Therefore, assessing the impact of oil spills on water surfaces involves taking into consideration when the oil spilt, the direction of flow of the water and the quantity spilled since the water will transport the oil on the water surface. This is not feasible considering the temporal scale of this study.

3. Results

3.1. Vegetation Indices and Land Cover Types Affected by Oil Spills

Figure 4 shows the vegetation greenness distribution within the selected spill sites and non-spill sites. The five vegetation indices were able to distinguish between vegetation spill sites (SS) and non-spill sites (NSS). The index values of polluted vegetated areas were lower than unpolluted vegetation (see also Appendix A, Figure A4). This means vegetation within NSS was greener than that of SS. All vegetation indices were able to distinguish between SS and NSS. However, three of the indices—EVI, NDVI and SAVI—were very sensitive to the effects of oil spills on the different vegetation cover areas.

The majority of the oil spills occurred within tree cover areas (848 oil spills) whereas the least incidence was recorded within shrub cover areas (45 oil spills). Oil spills that occurred in water were 610, cropland and grassland recorded 367 oil spills each, 201 oil spills occurred within aquatic vegetation and 266 oil spills occurred within built-up areas (Appendix A, Figure A5). However, in assessing the impact of oil spills on land cover, only vegetated areas were selected for this analysis. The results shown in Figure 4 show that the oil spill has stressed the vegetation at the spill sites.
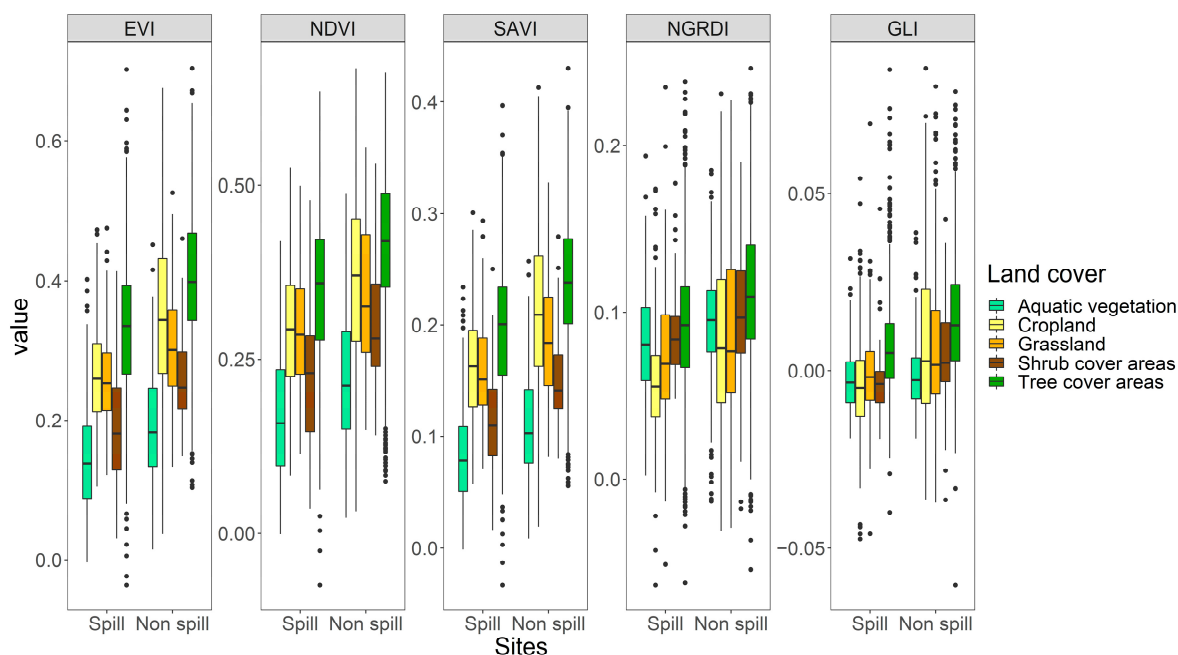
Figure 4. Vegetation indices showing the effect of oil spills on five vegetation types.

3.2. Hotspots of Oil Spills and Threatened Biodiversity

The spatial distribution of the oil spills was not random, rather they were clustering along the pipelines. Amongst the seven ecoregions of the Niger Delta, the one that is threatened the most by oil spills is the Niger Delta Swamp Forest (Figure 5, oil-spill hotspot with the highest range of Z-score: 9.62 < Z-score ≤ 17.33). Between 2016 and 2020, 1289 oil spills were recorded in this ecoregion. The Niger River is also located in this oil-spill hotspot. Furthermore, the Central African Mangroves and the Cross-Niger Transition Forest are affected by oil spills. The Niger Delta Swamp Forest serves as habitat for some of the IUCN red list species. The threatened endemic mammals found in this ecoregion include: Niger Delta Pygmy Hippopotamus (*Choeropsis liberiensis*, EN); Red-Bellied Monkey (*Cercopithecus erythrogaster*, EN) and Sclater's Monkey (*Cercopithecus sclateri*, EN; IUCN [63]). One of the world's 25 most endangered primates, the Niger Delta Red Colobus (*Procolobus epieni*, CR), is also found in this ecoregion. It has a decreasing population due to threats from hunting and a continual decrease in the extent of its habitat due to logging. The threats facing this species and others have intensified over the years since the habitat quality is also hampered by the oil spills. The region which provides habitat for threatened species such as the West African Manatee *(Trichechus senegalensis*, VU) recorded the second largest number of oil spills during the study period. Specific species within the oil-spill hotspot with the highest range of Z-scores (9.62 < Z-score ≤ 17.33) were the Sclater's Monkey (*Cercopithecus sclateri*, EN) and the Hooded Vulture (*Necrosyrtes monachus*, CR) but due to mobility, species also occur in different oil-spill hotspots (Table 3).

Due to the fact that some pipelines are located within nature reserves, protected areas are also affected by the oil spills. From the NOSDRA oil-spill incident data, between 2016 and 2020, 18 protected areas were affected with 322 oil spills within the protected areas in the Niger Delta. A total of 130 oil spills were also captured within a buffer of 1 km around protected areas. The most affected protected areas were Apoi Creek Forest and the Uremure-Yokri Forest Reserve (Figure 6). More than 45 oil spills were detected inside these two protected areas, respectively. In the Gilli-Gilli Game Reserve (habitat/species management area by IUCN category), only one oil spill occurred. No spills were detected in the Oban and Okwangwo Biosphere Reserves.
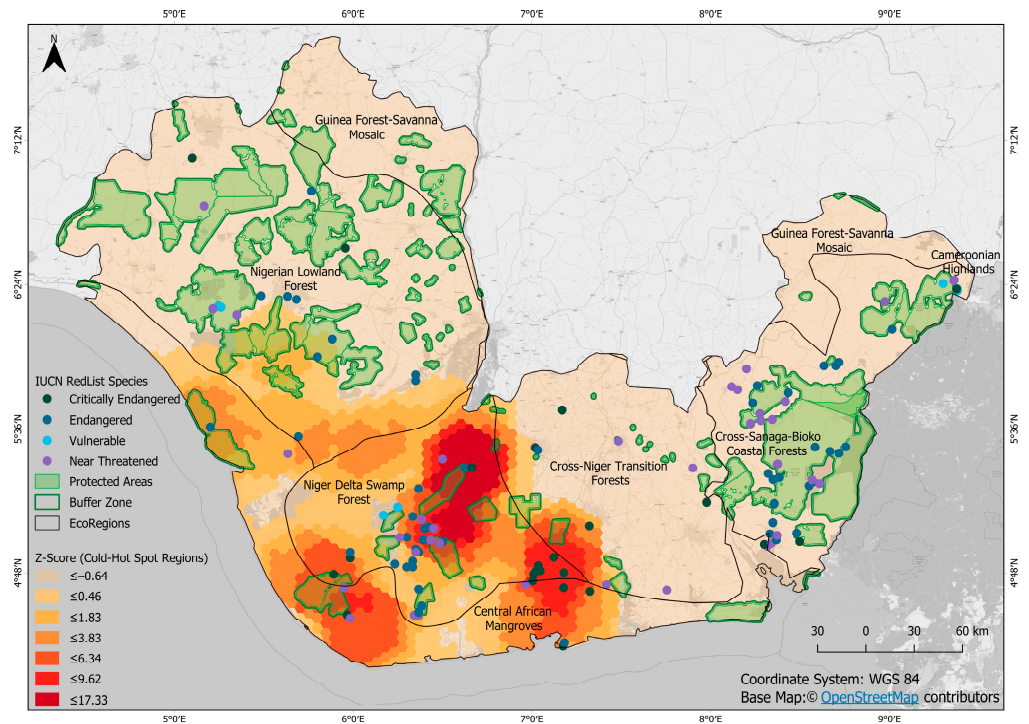
Figure 5. Oil spill areas (in red), protected areas (in green), IUCN Red List Species and ecoregions in the Niger Delta, 2016–2020. Data and sources are shown in Table 1. The specific species that were found in the oil-spill hotspots are shown in Table 3.
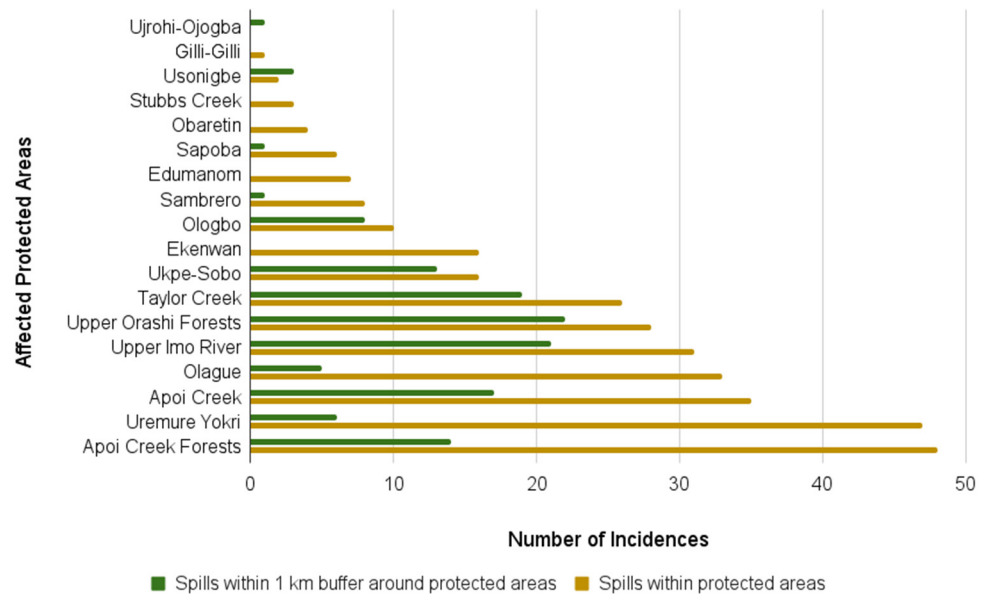

Figure 6. Oil spills within and around protected areas in the Niger Delta between 2016 and 2020.

Table 3. The endangered species (from GBIF occurrence/point data [72]) within the Niger Delta oil-spill hotspot regions and according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species [63]. Due to mobility, species also occurred in different oil-spill hotspots. More species could be potentially affected since point data of real occurrence and not potential distribution data were used. Abbreviations: Near threatened (NT); endangered (EN); critically endangered (CR) species.

	Hotspot Regions of Oil Spills		
	Highly Clustered Spills (9.62 < Z-Score ≤ 17.33)	Medium Clustered Spills (6.34 < Z-Score ≤ 9.62)	Low Clustered Spills (3.83 < Z-Score ≤ 6.34)
Species names	Sclater's Monkey (*Cercopithecus sclateri*, EN)	Calabar Angwantibo (*Arctocebus calabarensis*, NT)	Western Red Colobus (*Procolobus badius*, CR)
		Putty-Nosed monkey (*Cercopithecus nictitans*, NT)	Poto (*Perodicticus potto*, NT)
		Sclater's Monkey (*Cercopithecus sclateri*, EN)	Red-Bellied Monkey (*Cercopithecus erythrogaster*, EN)
	Hooded Vulture (*Necrosyrtes monachus*, CR)	Red-Bellied Monkey (*Cercopithecus erythrogaster*, EN)	Sclater's Monkey (*Cercopithecus sclateri*, EN)
		Hooded Vulture (*Necrosyrtes monachus*, CR)	Mona Monkey (*Cercopithecus mona*, NT)
		Poto (*Perodicticus potto*, NT)	
		Bioko Squirrel Galago (*Sciurocheirus alleni*, NT)	

4. Discussion

4.1. Performance of Vegetation Indices

According to the National Aeronautics and Space Administration [94] and Rieser et al. [95], analyzing the absorption and reflection of plants within both the visible and infrared wavelengths helps determine the health status of plants. The health status of plants within oil spill and non-spill areas were assessed using VI and the findings on the performance of VI to detect the impact of oil spills revealed that EVI, NDVI and SAVI were more sensitive to the effects of oil spills on the different vegetation cover areas than the other tested VI (GLI and NGRDI). These indices include the NIR band in their calculation, which is an indicator for the health of plants. Unhealthy and stressed plants and in this case oil-polluted vegetation tend to reflect less NIR which makes their identification with the use of spectral information easier [96]. The low reflectance of NIR in the oil-polluted (stressed) vegetation contributed to the SS having lower index values than the NSS. Studies by Bulgarelli and Djavidnia [97], Pisano et al. [27] and Adamo et al. [98] have proved the importance of NIR in monitoring the health of vegetation. The detection of plant greenness significantly improves by combining visible and near-infrared bands in calculating VIs [26].

Oil spill is a controversial topic in the Niger Delta, and backed by the unrest within the region, a field study would have been impossible. Collecting ground truth data such as soil samples and biomass which will then be analyzed in the lab would have been a risk-it-all research as well as capital intensive and time-consuming; in particular, considering the huge area in question. With remote sensing, the impact of oil spills on vegetation was assessed for a period of five years over an area of about 70,000 km^2. Although with the help of remote sensing vegetation indices, the impact of oil spills on vegetation was detected, different plants react differently to the stress from oil spills [82]. The quantity of oil spilt and duration of contact with vegetation till clean-up also plays a role in the extent of the stress. Including such differences to analyze the impact of oil spills on vegetation in the future will be beneficial and more detailed. This analysis could however be executed on a smaller scale using remote sensing imagery with a higher resolution, preferably an unmanned aerial

vehicle. The use of hyperspectral imagery instead of optical imagery is also recommended for detailed identification and quantification of the volume of oil spilt.

4.2. Oil Spills as a Threat for a Biodiversity Hotspot

As the literature has already stated, e.g., [4,5,9,20,58], oil spills caused high losses in ecosystems, ecosystem services and biodiversity in the Niger Delta. The majority of oil spills occurred in forests. Linking this finding to the main cause of oil spills in the Niger Delta, which is sabotage/theft, it is realistic that the majority of the spills occurred within tree cover areas. As stated earlier, sabotage is a punishable offence under the Petroleum Production and Distribution (Anti-Sabotage) Act of 1990. Therefore, tree cover areas provide a hidden place to facilitate illegal oil refineries.

These spills affect vegetation as proven by this study and if the necessary measures are not taken, many more ecosystems and habitats for species will be lost in the near future. Mangroves are especially affected by the pollution caused by oil spills but also deforestation and land conversion cause a threat. Between 2007 and 2017, approx. 12% of mangrove cover were lost in the Niger Delta [99]. Mangroves provide important ecosystem services such as flood control, salinity control, purification, food, water and materials, among others [9]. Local communities highly depend on these ecosystem services. For example, the destruction of mangroves would cause economic losses in the fish catch because mangroves serve as an important habitat and nursery of different fish species. In addition, mangroves are relevant in the context of climate change because they can store a lot of carbon [5].

Even though we did not analyze the direct effects on species in this study, it can be said that wildlife within an oil-polluted ecosystem is at threat because of oil-contaminated food, animals' polluted coats and the environment. Oil-contaminated vegetation can be passed on to different levels of consumers. According to IUCN [100], based on the 2013 internal report of the Shell Petroleum Development Company (SPDC), there were functional wellheads, pipelines, manifolds and flow stations, amongst others, within the protected areas such as Apoi Creek Ramsar Site, Olague, Urhonigbe, Ukpe Sobo and Uremure-Yokri Forest Reserves. To date, some oil facilities are still within protected areas. In general, there are almost no protected areas in the Niger Delta that are really protected [101]. In our analysis, the Apoi Creek Forest was the reserve with the highest oil-spill occurrence in our study even though it is a Ramsar site and has an internationally high protection status (strict nature reserve by IUCN category). The endemic and critically endangered Niger Delta Red Colobus Monkey (*Piliocolobus epieni*), living in the Apoi Creek Forest, might be highly at risk even though the results in Table 3 did not show that this species is affected; this could be related to the fact that we used point data (occurrence of the species) and not the potential distribution range of species. Between 1994–1997, the population of the Niger Delta Red Colobus Monkey was less than 10,000 individuals and is now expected to be only a few hundred [102]. Even though many bird species are endangered in the Niger Delta (Appendix A, Figure A3), they were less reflected in our results as an oil-spill affected species (Table 3). In contrast to mammals, bird species might be more mobile but they use the swamp area as an important breeding and feeding ground. For example, the Upper Orashi Forest Reserve, located in the Niger Delta Swamp Forest and also affected by oil spills, hosts the Grey Parrot (*Psittacus erithacus*), the Congo Serpent Eagle (*Dryotriorchis spectabilis*) and more than 90 other bird species [103]. Some mammal species have just been discovered in the area (that are new to Nigeria), such as the Black-Fronted Duiker (*Cephalophus nigrifrons*), the Pygmy Scaly-Tailed Flying Squirrel (*Idiurus* sp.) and the Small Green Squirrel (*Paraxerus poensis*).

4.3. Implications for Nature Conservation and Environmental Policy

Oil spills were clustered along the pipelines. Furthermore, the oil facilities being sabotaged depended on the level of accessibility of the facilities to people [19,59,104]. Therefore, highly accessible facilities and regularly sabotaged pipelines can be surveyed and monitored more often using digital techniques such as the remote oil and gas pipeline

integrity monitoring systems. Oil facilities such as pipelines must be in good condition, inspected and serviced regularly to help early detection of potential spills. Otherwise, pipelines could also be replaced with new, concrete-encased pipes sunk 3–4 m underground.

Regarding environmental policy implications, if the contamination that is longstanding in the Niger-Delta region is to be fully addressed, environmental policies such as the NOSDRA enabling laws need to be revised and amended so that nature conservation clauses are fully mainstreamed to expand the scope of the agency. This would help to address remediation, reclamation and restoration aspects of the oil-spill management value-chain. In addition, the proposed policy update and upgrade need to encourage adoption of space-dependent technologies such as integrated Remote Sensing and Geographic Information Systems to facilitate the continuous mapping and monitoring of the regions with oil-spill occurrence and impacts. This will enable Nigeria to build on the recommendations made in the assessment report issued in 2012 by the United Nations Environmental Programme (UNEP) on the petroleum hydrocarbon pollution in Nigeria with a focus on the 69 oil-impacted sites in various parts of Ogoniland [96], an area currently remediated under the Hydrocarbon Pollution Remediation Project (HYPREP), which is supervised by NOSDRA. However, beyond the Ogoniland, the project needs to be expanded to areas deserving urgent attention reflecting on the data published in the Oil Spill Monitor [73] managed by the lead oil-spill management agency and environmental regulator on oil and gas pollution matters in the petroleum sector in Nigeria, NOSDRA.

The implication of persistent oil spills in the environment is a challenge to the effectiveness of policies enacted to manage oil spills in Nigeria. Strict measures and control must be put in place to avoid further oil spills (as well as hunting and deforestation) but due to security reasons, conservation measures could not be implemented so far [102]. Scientific investigations and monitoring of threatened species on site were impossible. In addition, measures of environmental education and awareness are not conducted [103]. The prevailing insecurity for on-site observations poses the need for systematic and remote initiatives of developing and utilizing up-to-date and accurate map tools showing oil-sensitive features within oil and gas assets. For example, the utilization of Environmental Sensitivity Index (ESI, e.g., [105]) maps is a proactive tool for smart oil-spill preparedness and responses that must be instilled and enforced by NOSDRA, the environmental regulatory agency of the Federal Government of Nigeria for oil companies operating in the upstream and downstream sectors of the petroleum sector in Nigeria, to ensure environmental sustainability. Beyond oil spills, gas flaring, venting and emissions' detection and measurement from the petroleum sector are significant oil and gas pollution that should be investigated within the context of nature conservation and policy efficiency in the oil and gas sector and progress can be presented regularly in the Conference of the Parties (COP) of the Convention on Biological Diversity. This approach will help to amplify environmental accountability efforts in conservation in oil-producing regions globally.

5. Conclusions

Oil spills have a massive negative impact on local species, ecosystems, ecosystem services and people. The effects of persistent un-remediated oil-spill sites are measurable decades after the occurrence of the spill incidence. With the support of remote sensing and vegetation indices, this study has shown that oil impacts on vegetation and passes through protected areas, potentially threatening species. The vegetation indices EVI, NDVI and SAVI are more suitable to identify the impact of oil spills on different vegetation cover than the other vegetation indices.

The results of this study serve as a wake-up call for the Federal Government of Nigeria, oil companies and all parties benefiting from the oil production at the expense of the environment. The identified accumulation of oil spills is located in the heart of the Niger Delta—the Central African Mangroves and the Niger Delta Swamp Forest. These areas are of international relevance since they host many endemic and endangered species and provide important ecosystem services for local livelihoods, e.g., flood protection, climate

regulation and the provision of food, materials and water. Largely unprotected but sensitive ecosystems in the Niger Delta are at risk but also protected areas, such as the Apoi Creek Forest and Uremure-Yokri Forest Reserve. We argue that a special remediation, reclamation and restoration project should be commissioned to conserve nature, halt threats and avert the long-term implications of oil spills on species, ecosystems and people.
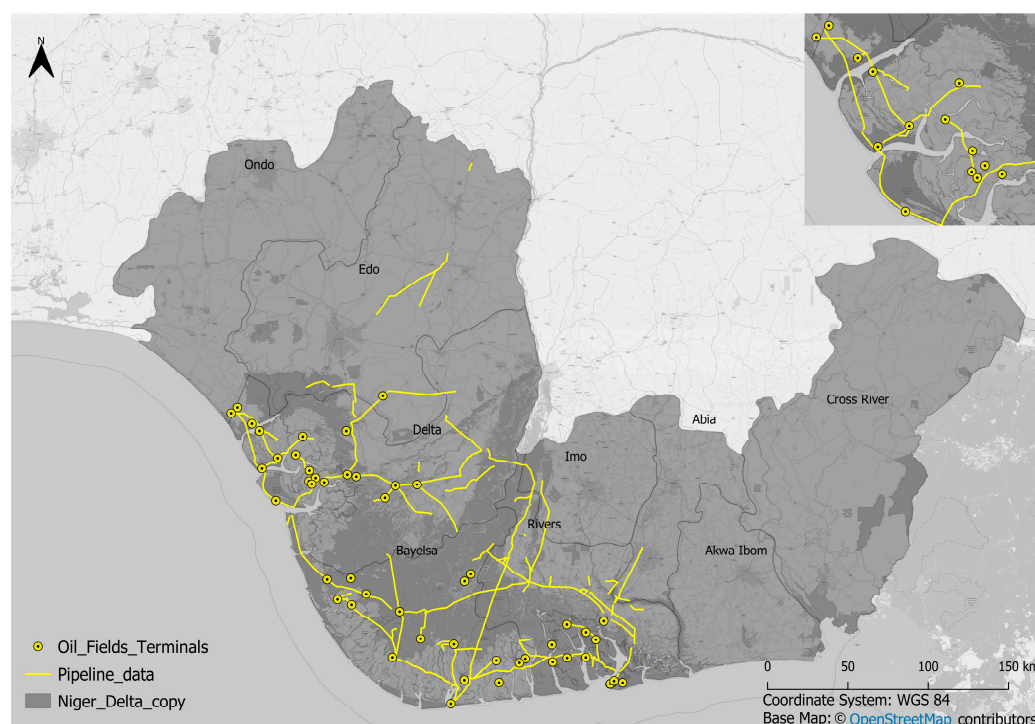
Appendix A

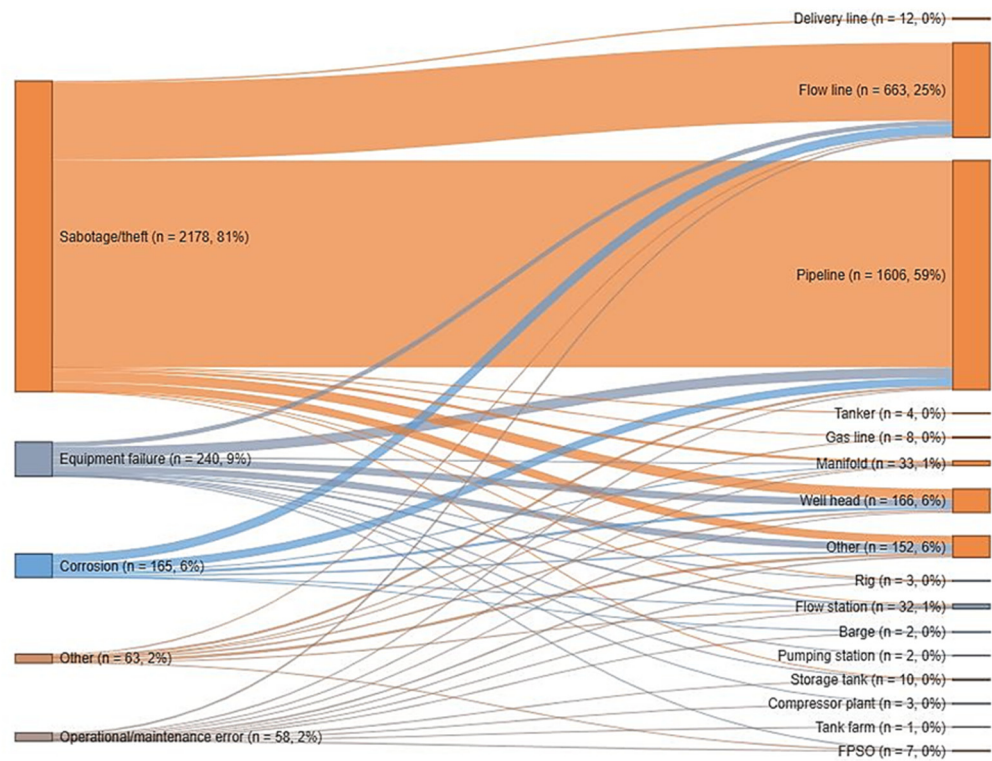**Figure A1.** Map of Niger Delta showing the distribution of some oil facilities.

Figure A2. Sankey diagram showing the causes of spills and the facilities affected (own compilation and representation; NOSDRA data from 2016–2020).
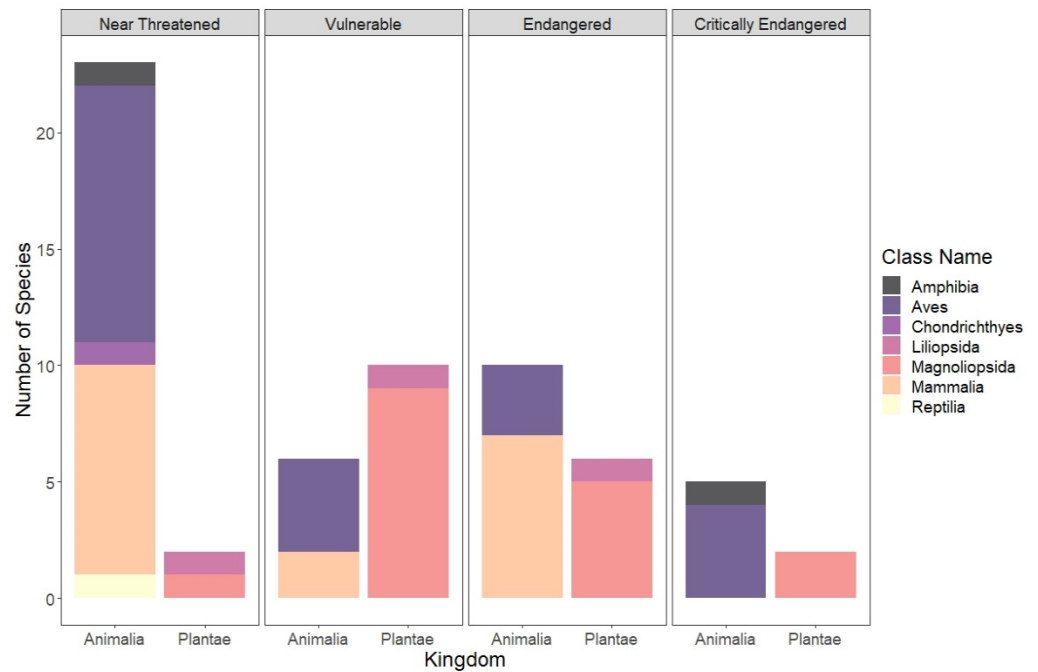
Figure A3. Distribution of near threatened, vulnerable, endangered and critically endangered IUCN Red List species in the Niger Delta (compilation based on data from IUCN [63] and GBIF [72]).

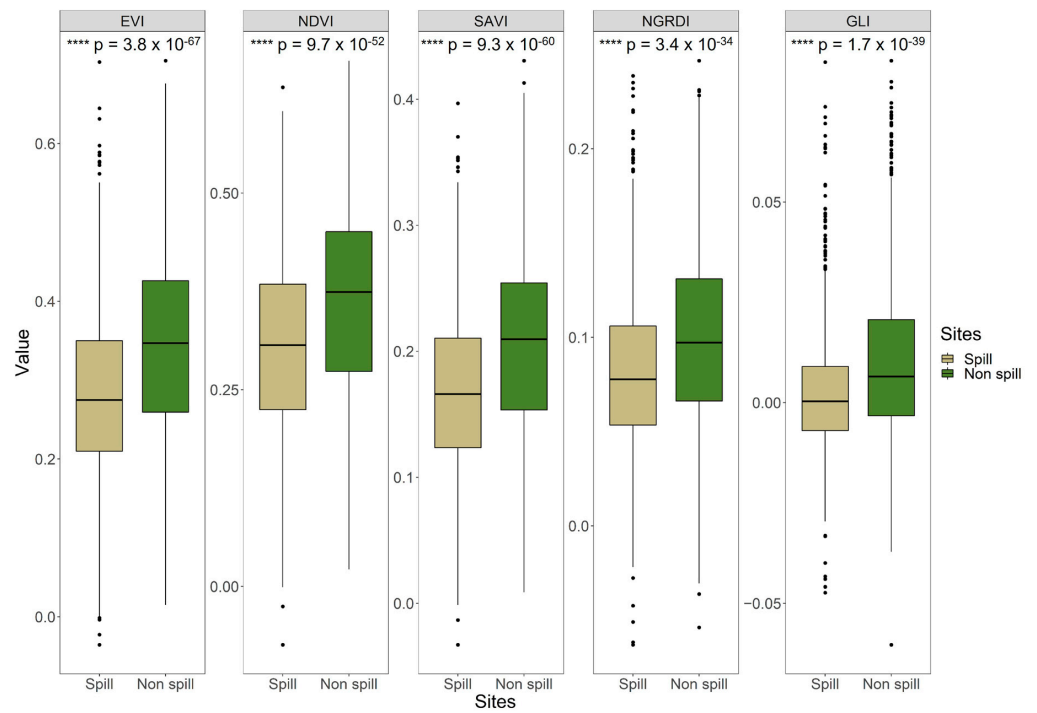**Figure A4.** The performance of the vegetation indices displaying spill and non-spill land cover. All five vegetation indices were significant at *p*-value less that 0.0001 (****).
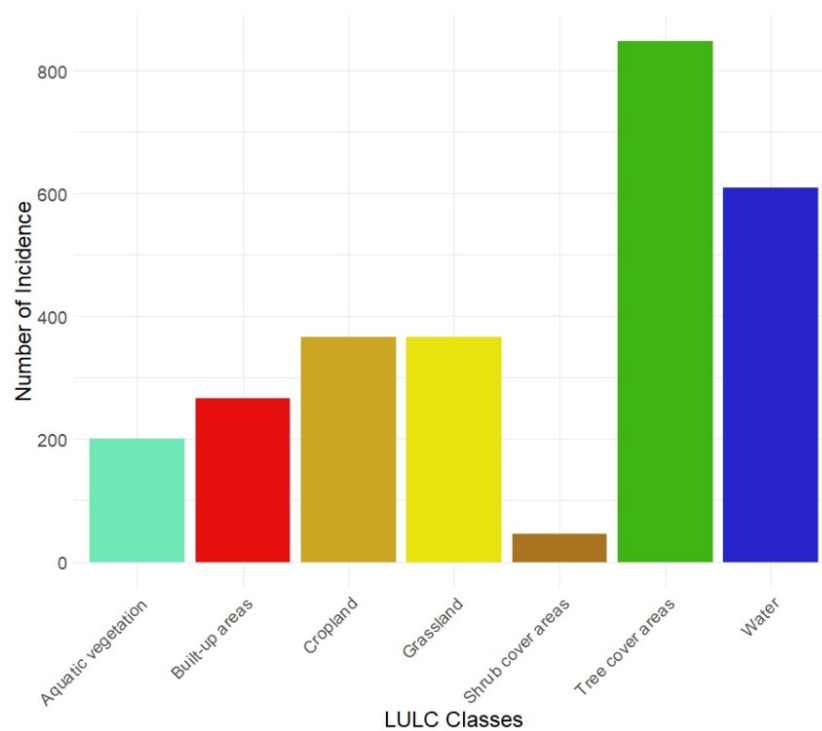

Figure A5. Land use/land cover (LULC) impacted by oil spills.

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