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Remote Monitoring of the Impact of Oil Spills on Vegetation in the Niger Delta, Nigeria

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Abstract: The widespread oil extraction in the Niger Delta and the impacts on different types of vegetation are poorly understood due to lack of ground access. This study aims to determine the impact of oil spills on vegetation in the Niger Delta using a Landsat satellite-derived normalised difference vegetation index (NDVI). The impact of oil spill volume and time after an oil spill on the health of different types of vegetation were evaluated, and the time series of the changes in NDVI were analysed to determine the medium- and long-term responses of vegetation to oil spill exposure, using a combination of linear regression and paired *t*-tests. With regards to the relationship between spill volume and NDVI, a moderate correlation (R^2 = 0.5018) was observed for spill volumes in the range of 401–1000 barrels for sparse vegetation, for volumes greater than 1000 barrels for dense vegetation (R^2 = 0.4356), whilst no correlation was found for mangrove vegetation at any range of spill volume. Similarly, the results of the paired *t*-test confirmed a significant difference (p-value < 0.05) between the change in NDVI values for spill sites and non-spill sites for all vegetation types, with the sparse vegetation being the most affected of the three types. However, the impact of the oil spill on vegetation over a period is not statistically significant. The outcomes of this study provide insights into how different types of vegetation in the Niger Delta respond to oil spills, which could ultimately help in designing an oil spill clean-up program to reduce the impact on the environment.

Keywords: normalised difference vegetation index (NDVI); vegetation health; vegetation degradation; mangrove; sparse vegetation; dense vegetation; paired *t*-tests

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1. Introduction

The impact of oil production activities on vegetation cover can be particularly devastating, resulting in either its degradation or complete destruction. This can occur due to changes in vegetation health and vigour following exposure to oil pollution [1–3], therefore necessitating effective monitoring of vegetation health to help identify and mitigate the impact of oil releases on the environment. The two main approaches for assessing and monitoring the health of vegetation are field-based [4] or through satellite remote sensing [5]. Key advantages of the field-based approach include the ability to acquire measurements at fine (i.e., leaf) scale and obtain under-canopy measurements and the flexibility in obtaining measurements whenever required. Despite these advantages, field-based approaches can consume considerable time, effort and resources, typically restricting their application to small areas and rendering them unsuitable for regional, national and global monitoring [6].

In addition, field-based approaches are challenging to implement in inhospitable locations, whether due to security concerns or inaccessible terrain.

Progression in optical sensor technology has facilitated a great opportunity to understand vegetation health/quality at various spatiotemporal scales previously regarded as complex [7]. Remote sensing of vegetation has advanced significantly over the past half-century due to advances in technology and analyses improving the ability to retrieve useful plant biochemical, physiological and structural quantities across a range of spatial and temporal scales [8]. Satellite remote sensing has become an essential tool in vegetation health status monitoring because it provides a means of overcoming the limitations of field-based approaches [9]. For instance, it provides routinely acquired remote measurements over large areas, which permits regional, national and global monitoring, whilst overcoming the challenges of working on the ground [9] in inhospitable locations. Moreover, several satellite missions exist, e.g., Landsat, meaning that the vast historical archives of data that have been acquired enable long-term spatiotemporal analysis of vegetation health and other land cover changes. Accordingly, satellite remote sensing can play an important role in detecting and responding to oil spills and assessing the impact they have on the environment [1,10–14]. More broadly, satellite remote sensing data have been used to forecast crop yield and assess natural forest expansion [15], biodiversity and conservation [16], and drought monitoring [17,18] among other vegetation-related applications.

Vegetation indices derived from remotely sensed (satellite) data can be an efficient tool for measuring vegetation status, growth, and biophysical parameters [19,20]. Among the algorithms developed for remote estimation of biophysical characteristics of vegetation, the mathematical combination of visible and near-infrared reflectance bands is the most widely used [21]. These indices involve measuring electromagnetic energy reflected from vegetation canopies using optical sensors [19,22]. These sensors can be either multi- or hyperspectral sensors, with the indices computed from the reflectance measured at specific wavelengths. In the case of the former, these indices can be grouped into broadband multispectral vegetation indices (BMVIs) and narrow-band multispectral vegetation indices (NMVIs), depending on the wavebands they use [23]. Time series of vegetation indices like the normalised difference vegetation index (NDVI) can be used to study vegetation dynamics [24], as they have proven to be a robust indicator of terrestrial vegetation productivity [25]. Such time series, therefore, provide a straightforward means of remotely determining and monitoring vegetation health and change from space [14], which is especially beneficial for assessing the impact of oil pollution in areas that are difficult to access on the ground. Among authors that have used remotely sensed vegetation indices to monitor the impact of oil spills on the vegetation area [2,26].

The Niger Delta region has experienced oil production-related vegetation degradation through two main pathways: oil spills onto the land and gas flares into the atmosphere. For more than four decades, oil exploration and production activities have left a severely degraded environment in the Niger Delta region [27]. However, in recent times, the issue of oil spills in the Niger Delta was exacerbated due to militant activities in early 2006. A substantial amount of crude oil pipeline vandalism in the Niger Delta was carried out by militant groups with the excuse of fighting for better environmental management and development of the region [28]. Approximately 80,000–300,000 barrels (bbl)/day—valued at USD six billion—have been spilt into the environment in the Niger Delta in recent years [29]. Detecting oil spills and their impacts in polluted environs such as mangrove forests can be challenging using in situ measurements and laboratory-based analysis techniques due to security challenges and difficult terrain. As a more practical alternative, satellite remote sensing presents itself as an effective tool for assessing and monitoring vegetation health and status in polluted areas, especially over vast extents [30].

Despite the obvious potential offered, studies attempting to monitor the impact of oil spills in the Niger Delta region using satellite-derived vegetation indices are relatively scarce. Previous studies examining the effect of oil spills on the health of vegetation in this region using satellite-derived vegetation indices include Adamu Adamu [30] and Adamu et al. [1,31,32]. These studies investigated the influence of oil spill volume and time gap (i.e., number of days between oil spill events and subsequent satellite observations) on the condition of mangrove forests in the Niger Delta region using various vegetation indices, with the NDVI producing a stronger correlation between the volume of the oil spilt and the NDVI values. Similarly, the study by Ansah et al. [10] used the best five performing vegetation indices from [30] to compare the difference between vegetation at spill and non-spill sites. In addition, Ozigis et al. [13] identified oil-impacted land in the region by using a random forest classifier in conjunction with Landsat 8-derived vegetation health indices. Further, Onyia et al. [33] monitored the impact of oil pollution on plant species biodiversity at a regional scale by integrating a Hyperion satellite-derived normalised difference vegetation vigour index (NDVVI) and field data. However, these previous studies focus solely on detecting oil spills or determining the impact of oil pollution on the health of only a single vegetation species (i.e., mangrove) or used the absolute NDVI values. Thus, the impact of exposure to oil on the health of other types of vegetation found in the Niger Delta region is still poorly understood. Furthermore, the studies that focus specifically on the health of the vegetation in the region typically only compare the absolute NDVI values for groups of spill and non-spill sites before and after oil spills. However, comparing absolute values in this way fails to account for differences in the influence of other external factors on the health of vegetation that may vary naturally between sites, such as differences in soil nutrients and water availability. The novelty in this research is, to the best of our knowledge, that this is the first study to monitor the impact of the oil spill on three different types of vegetation and to use change-in-NDVI values.

Accordingly, there is a clear need for a more comprehensive understanding of the impact of oil spills on vegetation in the Niger Delta region. This study, therefore, aims to address this by determining the impact of oil spills on a range of vegetation types in the Niger Delta region by analysing location-specific changes in satellite-derived NDVI values at spill and non-spill sites. This will be achieved by (1) analysing the impact of oil spill volume and time after an oil spill on the health of three types of vegetation and (2) undertaking temporal monitoring of NDVI for the three types of vegetation to determine their medium- and long-term responses to oil spills. For this study, the vegetation types are divided into three broad categories: dense, sparse, and mangrove. The hypothesised result is that (1) the oil spill volume and the time gap after the oil spill determines the impact of the oil spill event on the vegetation; (2) there is a significant difference, as revealed by the NDVI, between the health of vegetation exposed to oil spill compared to the vegetation not exposed to oil spill and (3) different vegetation types will respond differently to the oil spill events.

2. Materials and Methods

2.1. Study Area

The Niger Delta region (Nigeria) comprises nine oil-producing states—sometimes called the political Niger Delta—hosting approximately 1500 communities and various oil and gas companies [34]. Traditionally, the Niger Delta comprises the three states of Rivers, Bayelsa and Delta States. These three states account for approximately 70% of Nigeria's oil spillage incidences [35]. The study area is located within longitudes 4°55′ E and 7°39′ E and latitudes 4°7′ N and 6°33′ N (Figure 1a). All three states are oil and agricultural-producing states. The climate in the Niger Delta region has been classified as a wet equatorial climate characterised by persistent cloud cover and few sunshine hours, which produces damp weather conditions for most parts of the year [36]. The annual rainfall ranges from 1500 to 2000 mm in the northwestern portions of the Niger Delta [37]. The average monthly temperature for the warmest months (from February to April) ranges from 28 to 33 °C, whilst the average monthly temperature for the coolest months (from June to September) ranges from 21 to 23 °C [38]. The Nigerian coastal geology is sedimentary, dominated by the geology of the arcuate Niger Delta [39]. The large amount of sediment carried by the river system over the centuries has resulted in a vast, relatively flat basin [40]. The river Niger forms a complex network of channels that drain into the Gulf of Guinea, characterised by rain-fed deltaic vegetation. The area is formed of fluvial and marine sediments built up over the past 50 million years since the upper Cretaceous period [32]. The natural delta of the Niger River is a vast sedimentary basin with deltaic deposits, which are comprised mainly of medium to coarse unconsolidated sands, silt, clay, shale, and peat [38]. The three lithostatic units in the Niger Delta were developed from the Akata Formation, Agbada Formation, and Benin Formation [41].

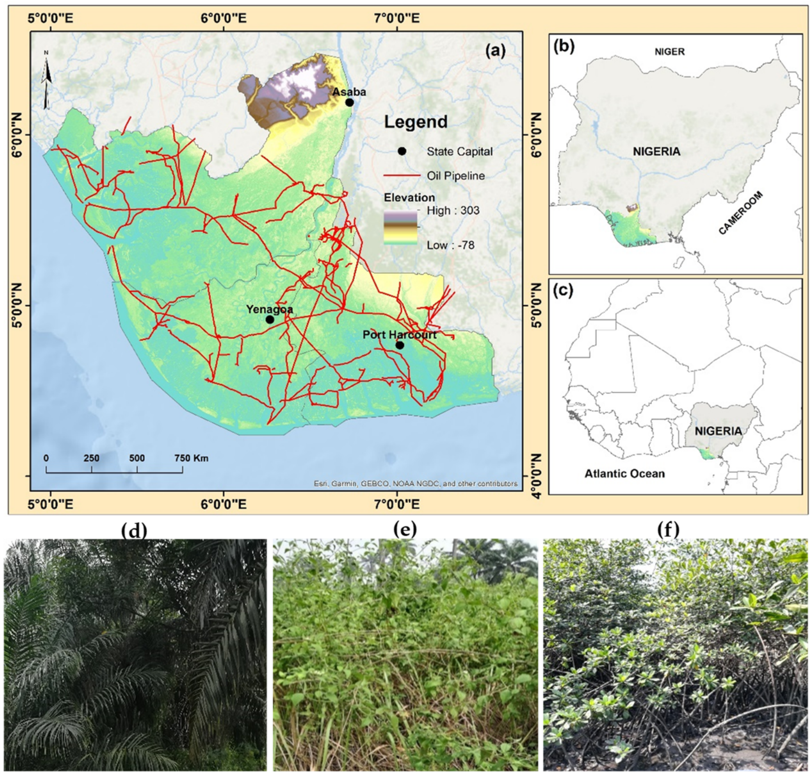

Figure 1. (**a**) Map of the study area (**b**) in relation to Nigeria and (**c**) in relation to West Africa, and field picture of dense vegetation (**d**), sparse vegetation (**e**), and mangrove vegetation (**f**).

However, the vegetation in the Niger Delta region was grouped into three primary types of cover for this study: (1) mangroves, which cover the coastal region of the delta, along with brackish lagoon and river systems, and freshwater swamp forest; (2) dense vegetation, which comprises rainforest; (3) sparse vegetation consisting of derived savannah grassland. The dominant mangroves are Red Mangroves (*Rhizophora* spp.), which comprise more than 90% of the vegetation in the mangrove zone [42]. Common species belonging to the dense vegetation category are Oil Palm (*Elaeis guineensis*) and mango trees (*Mangifera indica*), whereas the sparse vegetation category is dominated by Elephant grass (*Pennisetum purpureum*), Spear grass (*Panicum maximum*), and Awolowo grass (*Chromolaena odorata*). The sparse vegetation could be found in the seaward ecological zone, the outer edge of the mangrove ecosystem away from the oceans [43]. Field photographs of the three main types of vegetation found in the study area are shown in Figure 1d–f.

2.2. Data

2.2.1. Satellite-Derived Vegetation Index (NDVI)

Remote sensing Vegetation Indices (VIs) can be used to quantitative and qualitative evaluate vegetation cover, vigor, and growth dynamics [19]. The choice of vegetation index, the NDVI, was based on the result from Adamu [30], which shows that five spectral indices, namely, the normalised difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), adjusted resistant vegetation index (ARVI2), green near-infrared (G/NIR), and green shortwave infrared (G/SWIR), out of the twenty (20) VI tested, were consistently sensitive to the effects of oil pollution on vegetation in the Niger Delta. Similarly, the study by Ansah et al. [10] shows that three of the indices—EVI, NDVI, and SAVI—were very sensitive to the effects of oil spills on the different vegetation covers in the Niger Delta among five (5) vegetation indices. The NDVI has been demonstrated to be a robust vegetation index in monitoring the impact of oil spills on the health of vegetation [1,12,30,31,44] and is the most suitable index to detect the effects of petroleum pollution on vegetation [45]. The NDVI is an index of plant greenness as well as an indicator of the density of plants [46], which is based on the reflectance properties of the areas covered by the vegetation [47].

The launch of the Landsat (ERTS-1) mission in 1972 sparked investigations surrounding its capability for vegetation monitoring and categorisation [8]. The health of vegetation in the study area was determined using the Landsat collection 1 NDVI product, computed using Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite imagery for the period 2006–2018 via the EROS Science Processing Architecture (ESPA) on-demand interface. The Landsat 1 data collection comprises derived vegetation indices that are atmospherically corrected and orthorectified to provide an archive of consistent data for time-series analysis [48]. The ready-processed Landsat NDVI data were downloaded from https://espa.cr.usgs.gov/ (accessed on 22 December 2024). geometrically corrected, and projected to WGS84 Universal Traverse Mercator (UTM) projection Zones 31 and 32 (Table 1). For the period 2006–2018, a total of 22 NDVI images acquired around the timing of oil spill incidences were used in this study (Table 2). These images were selected to coincide with the most consistent weather conditions during the dry season from December to February to minimise cloud cover and temperature variability. Accordingly, the effect of meteorological conditions on the observed changes in NDVI is mitigated.

The NDVI in the ready-processed data is calculated from each Landsat 7 ETM+ according to Equation (1):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \tag{1}$$

where RED and NIR represent the spectral reflectance bands measurements acquired in the red (visible) and near-infrared regions with a wavelength range of 0.63–0.69 µm and 0.77–0.90 µm, respectively.

Table 1. Sensor and orbit path/row of the Landsat 7 ETM+ imagery.

Satellite	Sensor	Path/Row	UTM Zone
L7	ETM+	188/56	32
L7	ETM+	188/57	32
L7	ETM+	189/56	32
L7	ETM+	189/57	31
L7	ETM+	190/56	31

Table 2. Image acquisition dates and number of images acquired per year.

Year	NDVI Acquisition Dates		
2006	9 December 2006		
2008	14 February 2008	7 December 2008	30 December 2008
2010	2 January 2010	18 January 2010	
2011	11 January 2011	14 January 2011	21 January 2011
2012	17 January 2012	9 February 2012	
2013	10 January 2013	21 December 2013	
2014	13 January 2014		
2015	9 January 2015	16 January 2015	27 December 2015
2016	3 January 2016	29 December 2016	
2017	5 January 2017		
2018	1 January 2018	8 January 2018	

2.2.2. Oil Spill Data

Oil spill data obtained from the Nigerian Oil Spill Monitor website https://oilspillmonitor.ng/ (Accessed on 11 December 2017) were used to analyse the oil spill incidences recorded in Nigeria from 2006 to 2018. The data were compiled by the National Oil Spill Detection and Response Agency (NOSDRA), which relies on the voluntary support of oil companies to provide information on oil spills, such as their geographic coordinates, date and estimated spill volumes. The information on oil spills, which encompasses the dates, times, causes, magnitude, and GPS coordinates of oil spill locations, is determined through a process called Joint Investigation Visit (JIV), which includes the representatives of regulatory agencies, the oil company, the affected community, and the security forces [48,49]. The oil spill information is constantly validated and updated on the database as soon as an oil spill incident occurs [48]. The Nigerian Oil Spill Monitor website has been a source of data for research that utilises oil spill data in the Niger Delta [48,50–52]. However, no fieldwork was undertaken to collect ground data to validate the oil spill site or to collect soil samples. The Niger Delta is a challenging environment for field-based investigations due to the physical inaccessibility and security threats which makes it impossible to assess the spatial extent of oil spill impacts using traditional survey and sampling techniques [51], and it would have been capital-intensive and time-consuming, considering the huge area involved [10].

Figure 2 shows the distribution of oil spill occurrences within the study area that were used to determine the impact of oil spills on vegetation. In order to determine the vegetation-specific effects, the oil spills were split into categories according to the type of vegetation cover on which they occurred (Figure 2a). Additionally, a separate corresponding sample of sites not affected by oil spills was selected for each vegetation type for use as controls against which to compare the health of vegetation exposed to oil (Figure 2b).

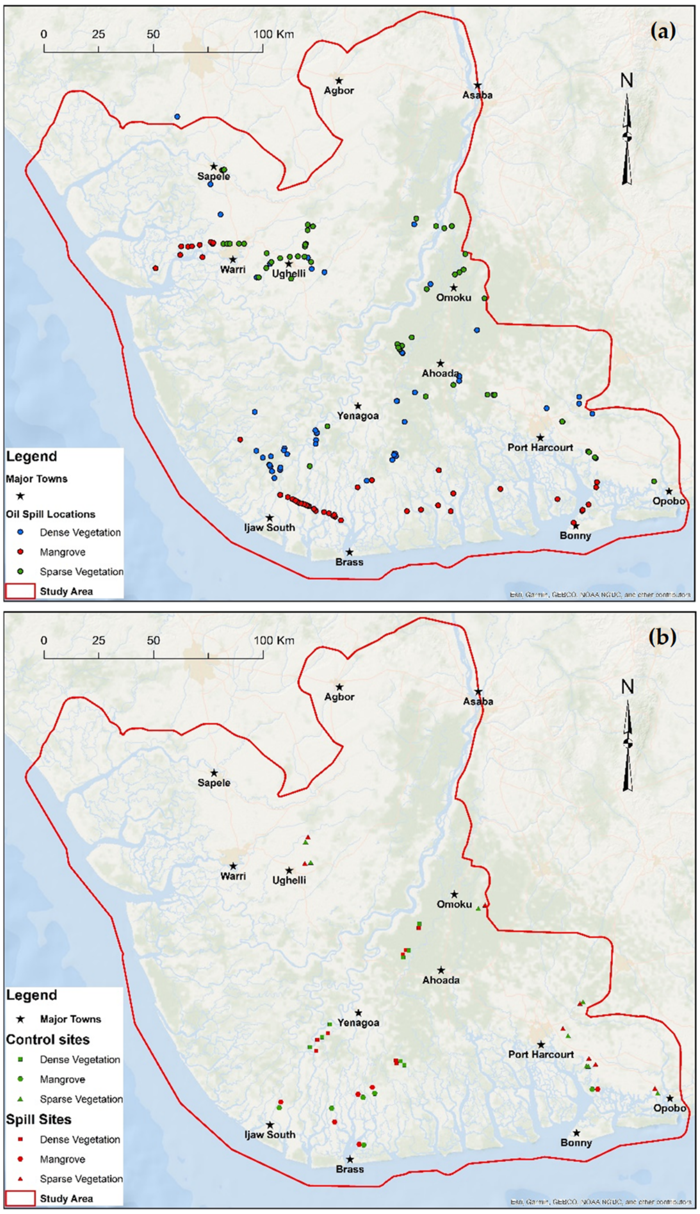

Figure 2. (**a**) Spatial distribution of oil spill sample points for determining the effect of oil spills on the different vegetation types and (**b**) locations of spills and no-spills sites for temporal monitoring of oil spill impacts on vegetation.

2.3. Methods

2.3.1. Data Pre-Processing and Plotting

The Landsat-generated NDVIs were already pre-processed, and no further processing was performed. However, the oil spill data were cleaned to remove some spill points with incomplete data, such as the lack of complete GPS coordinates (longitude and latitude) and spill volume. The oil spill data were plotted in ArcGIS 10.8.2 and overlaid on the NDVI map.

2.3.2. Selection of Oil Spill Sites and Determining the Impact of Oil Spills on Vegetation

The locations of the selected oil spill and non-spill control sites (see Figure 2) across the study area were used to extract the corresponding Landsat NDVI values for subsequent analysis. All the sites were selected to ensure they did not fall within the wedge-shaped scan-to-scan gaps caused by the Landsat 7 ETM+ Scan Line Corrector (SLC) failure on 31 May 2003 [53]. Firstly, to determine the impacts of both oil spill volume and the time gap between oil spills and subsequent observations on the vegetation health, oil spill sample sites totalling 55 for dense vegetation, 60 for sparse vegetation, and 61 for mangrove vegetation were identified with oil spill volumes ranging from 10 to 5000 bbl. The vegetation cover class for each spill sample site was determined using high-resolution Google Earth time series imagery to determine the oil spill point that fell on a particular vegetation type. The corresponding post-spill NDVI value was extracted (Figure 3) from within a 1×1 pixel window around each site from the first available Landsat image acquired after each spill. A 1×1 window was used since the areal extent of oil spills < 225 bbl is typically smaller than that of a single Landsat pixel (900 m^2). The extracted post-spill NDVI values for the sample sites were then correlated with both spill volume and time gap since the oil spill occurred in order to determine their effect on vegetation health. The time gap was computed as the difference between the date of a recorded oil spill and the date of the corresponding post-spill NDVI observation. Figure 3 shows Google Maps images of some oil spill sites with their corresponding control sites for some selected dense, sparse, and mangrove vegetation, respectively.

Secondly, to investigate whether the health of vegetation exposed to oil differs from vegetation at sites not exposed to oil, pair-wise comparisons of NDVI at spill sites (SSs) with those at no-spill control sites (CSs) were performed. Spill sites were selected for each of the three land cover types: eight for dense vegetation, eight for sparse vegetation, and six for mangroves (Figure 2b). Sites with oil spill volumes in the range of 225–2550 bbl were specifically selected for this analysis based on the minimum volume for which oil pollution is readily detectable in the region [32]. At each of the oil spill locations, the average NDVI value within a 3×3 pixel window around the site was calculated because oil from spills at this volume range may migrate from the point of source, thereby also affecting neighbouring surroundings [14,31] The same sampling approach was also used for no-spill sites. For each site, a time series of NDVI values was extracted for a period covering just before the spill and 4–10 years afterwards, depending on when the oil spills occurred. However, in this case, instead of using the absolute NDVI values to determine the temporal response in the health of the vegetation, changes in NDVI at SSs and CSs were calculated relative to the NDVI value just prior to the timings of spills. Utilising the change in NDVI accounts for the possibility that some sites may have inherently higher NDVI values than those at other sites if exposed to different health-affecting external factors. The potential effects of such external factors on the vegetation's health were further mitigated by carefully selecting SS and CS pairs with corresponding conditions, such as water availability, sunlight, soil composition, and climate (Figure 2).

The NDVI values at each site were used to derive a change in NDVI (ΔNDVI) time series using the following equation using Equation (2):

$$\Delta NDVI = NDVI_{AS}{}^{1} \ldots\ldots NDVI_{AS}{}^{s} - NDVI_{BS} \quad (2)$$

where $NDVI_{BS}$ is the baseline NDVI value before an oil spill occurs, whilst $NDVI_{AS}{}^{1}$ and $NDVI_{AS}{}^{s}$ are the first and subsequent NDVI values after the occurrence of a spill, respectively.

Table 3 shows the spill dates, volumes, and temporal coverage for the ΔNDVI time series for dense, sparse and mangrove vegetation sample spill sites. The oil spill volumes at the selected sites for each vegetation type are 280–1500 bbl for dense vegetation, 228–1500 bbl for sparse vegetation, and 264–2500 bbl for mangrove vegetation.

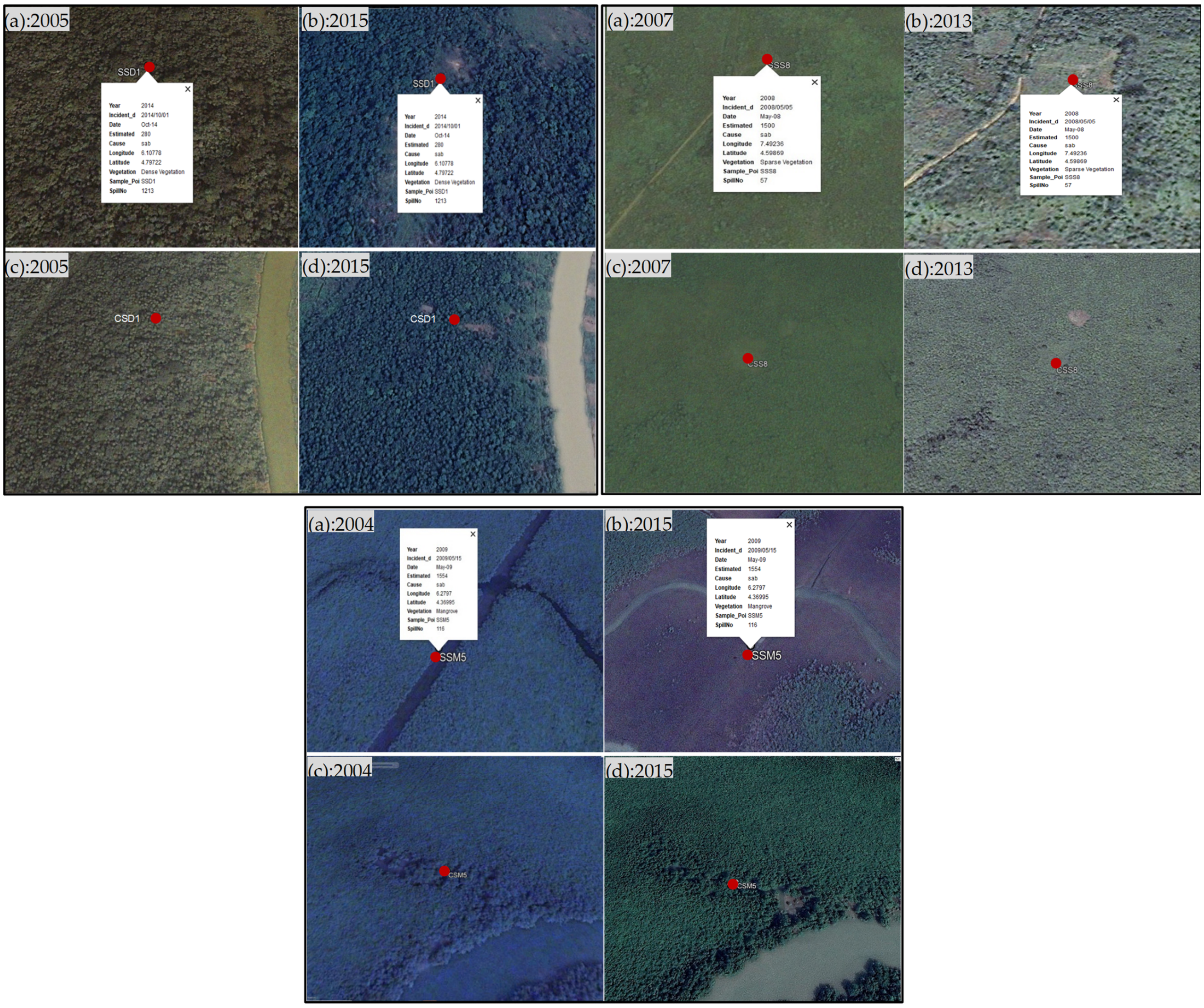

Figure 3. Vegetation sample points in red at the spill site, (**a**) before the spill, (**b**) after the spill, and control site, (**c**) before the spill, and (**d**) after the spill for dense vegetation (**Top left**), sparse vegetation (**Top right**), and the mangrove vegetation (**bottom**).

Table 3. The volumes of oil spills used to analyse the temporal ΔNDVI at the sample of spill sites.

Sample Points	Spill Date	Spill Volume (bbl)	ΔNDVI Coverage
D1	1 October 2014	280	2014 to 2018
D2	13 October 2011	346	2012 to 2018
D3	25 June 2014	367	2014 to 2018
D4	14 November 2014	367	2014 to 2018
D5	9 April 2011	429	2012 to 2017
D6	25 April 2010	1000	2011 to 2018
D7	31 October 2011	1430	2012 to 2018
D8	25 April 2010	1500	2010 to 2018
S1	19 January 2014	228	2013 to 2017
S2	17 September 2013	235	2012 to 2017
S3	24 June 2010	260	2010 to 2017
S4	8 August 2008	440.3	2008 to 2018
S5	22 January 2012	530	2011 to 2018
S6	23 December 2010	803	2010 to 2017
S7	25 September 2010	1000	2010 to 2016
S8	5 May 2008	1500	2008 to 2017

Table 3. *Cont.*

Sample Points	Spill Date	Spill Volume (bbl)	ΔNDVI Coverage
M1	14 August 2013	264	2013 to 2018
M2	26 June 2010	800	2010 to 2018
M3	1 February 2010	1020	2010 to 2018
M4	5 August 2010	1510	2009 to 2018
M5	15 May 2009	1554	2008 to 2018
M6	15 June 2009	2500	2008 to 2018

D—Dense vegetation sample site; S—Sparse vegetation sample site; M—Mangrove sample site.

2.3.3. Statistical Analysis

Statistical methods provide tools for making quantitative decisions about a process or processes [54]. Regression is a statistical technique used for prediction and causal inference to determine the linear relationship between two or more variables [55]. Here, regression analysis was carried out to determine the impact of oil spill volume, the time gap between oil spills and image acquisition date on vegetation health (i.e., NDVI), and the nature of any relationship between the variables and NDVI. Regression analysis was used by Adamu et al. [32] to determine the impact of oil spills on the vegetation. To analyse the effect of time on vegetation health recovery following exposure to oil, paired *t*-tests were used to compare ΔNDVI values from spill sites with those from non-spill sites [1,31,44] for a period of several years. A paired *t*-test is used to compare the two population samples; observations in one sample are paired with observations in the other sample [56] to determine the level of significance difference between any two observations.

3. Results and Discussion

Vegetation indices derived from remote-sensing images are an efficient tool for highlighting the spectral differences due to changes in leaf pigments and internal leaf structure, which are indicators of plant health [57]. The NDVI can detect changes in vegetation chlorophyll content, internal leaf structure, and water content that relate to stress [31]. The leaf chlorophyll content is sensitive to hydrocarbon pollution, and organic molecules from crude oil transported into the plant vascular system and intercellular spaces can lead to cell and tissue damage [58]. Accordingly, higher NDVI values would be expected for healthy vegetation with high chlorophyll content, whereas low values would be anticipated for vegetation whose health has been impacted by oil spills. The changes in vegetation health in oil-polluted sites may depend on the volume of a given oil spill because it is assumed that a larger volume of oil spills may have a greater impact on the surrounding vegetation [30]. In this study, we combined satellite base-derived NDVI with statistical analysis to determine the impact of the oil spill volume and the time after an oil spill using linear regression. We also determine the difference between the changes in the NDVI values of the spill site and their corresponding non-spill location using a paired *t*-test.

3.1. Post-Spill Impacts of Oil Spill Volume and Time Gap on Vegetation Health

Figure 4 summarises the post-spill NDVI value extracted for a sample of 176 spill sites from the first available Landsat satellite observation acquired immediately after oil spills that occurred during 2006–2018. From the results, the dense vegetation has the highest maximum post-spill NDVI values (~0.6), followed by the sparse vegetation (~0.55) and mangrove (~0.4). Similarly, the dense vegetation has the highest median value (~0.3). In contrast, mangrove has the lowest median NDVI (0.2) among all vegetation types, with over 75% of NDVI values being <0.3, making it the most degraded vegetation. Typically, the NDVI ranges from 0.2 to 0.5 for sparse vegetation, such as shrubs and grasslands, and from 0.6 to 0.9 for dense vegetation, such as that found in temperate and tropical forests or crops at their peak growth stage [59]. However, the post-spill minimum NDVI values are lower than the minimum NDVI values for typical healthy dense and sparse vegetation, whilst the maximum NDVI for dense vegetation is approximately the same as the minimum NDVI value for a typical healthy dense vegetation, which indicates the impact of oil spill on the health of the vegetation. Regarding healthy mangroves, Asian mangroves generally have the highest NDVI values, especially in Southeast Asia (0.80), whilst the average NDVI of African mangroves is typically 0.67 [60]. However, following exposure to oil, the highest NDVI values in the Niger Delta mangroves are 0.4 (~100%) and 0.2 (~50%) lower than those associated with Asian mangroves and typical West African mangroves, respectively, which also indicate the impact of oil spills on the health of the mangrove vegetation. The degradation of mangroves due to the oil spill could affect their sustainability. It may ultimately lead to the disappearance of the mangroves, which will have serious consequences for both the people and the fauna in the Niger Delta who depend on it. The Niger Mangrove ecosystem faces serious threats from crude oil spills [42]. Specifically, the degradation of mangrove forests will impact biodiversity and jeopardise the livelihoods of coastal communities that depend on them for food and resources, leaving them vulnerable to tidal inundation and extreme weather due to the loss of natural defences [43]. The study by Iliya et al. [61] discovered that, whilst healthy mangroves reported a net loss, degraded mangroves consistently reported a net gain between 1988 and 2013. To ensure the sustainability of the mangroves in the Niger Delta, there is a need for a policy that would mitigate the impact of the oil spill. Aransiola et al. [43] suggested that the enforcement of laws, public awareness campaigns, educational programs, and strategies for restoring and conserving the Niger Delta mangroves are crucial not only for safeguarding biodiversity but also for ensuring sustainable resource management practices and mitigating environmental threats.

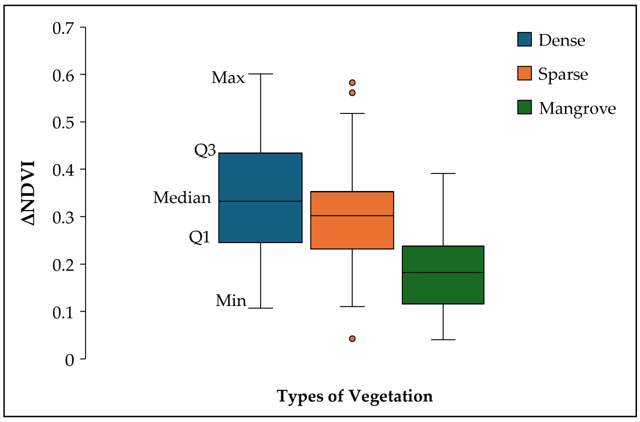

Figure 4. Box plot statistical summary of post-spill NDVI values for each vegetation type. Min and Max are the lowest and highest values of NDVI, respectively, excluding the outliers (diamond symbols). Q1 is the first quartile (25 percentile), and Q3 is the third quartile (75th percentile).

Figures 5–9 show the correlation between post-spill NDVI and oil spill volume for dense, sparse, and mangrove vegetation. The relationships are between all volumes of the oil spill (Figure 5), above 225 bbl (Figure 6), between 225 and 400 bbl (Figure 7), between 401 and 1000 bbl (Figure 8) and >1000 bbl (Figure 9). The oil spill volume ranges were determined based on the work by Adamu et al. [32], who investigated the factors influencing the detectability of oil spills using spectral indices in an oil-polluted environment in mangrove vegetation in the Niger Delta. From the results, the dense and sparse vegetation has the lowest spill points at volume >1000 (Figure 9a,b) due to the lack of available volume oil spills in that range. It can be observed that, for all volumes of spills and up to volumes >225–400 bbl, there was a weak relationship between the oil spill volumes and NDVI values for all the vegetation types with $R^2 < 0.03$. However, it can be observed that, though the relationship is weak, different vegetation types respond differently to the oil spill volume and the time interval between the oil spill dates. When the full range of oil spill volumes is considered, the relationship between the post-spill NDVI and the volume of oil spilt is weak for all vegetation types, with the highest $R^2 = 0.0107$ for mangroves (Figure 5). These results indicate a weak to no linear correlation between NDVI and oil spill volume, concurring with the lack of correlation ($R^2 = 0.0001$) found by Adamu et al. [32] when considering all spill volumes in the mangrove of the Niger Delta. However, when considering specific volume ranges, the NDVI for sparse vegetation is more negatively correlated ($R^2 = 0.5018$) to oil spill volumes in the range of 400–1000 bbl (Figure 8b). Similarly, the post-spill NDVI associated with dense vegetation is found to be more negatively linearly correlated with oil spill volumes >1000 bbl, with $R^2 = 0.4356$ (Figure 9a). Interestingly, at the same oil spill volumes >1000 bbl, the sparse vegetation is positively correlated with $R^2 = 0.9700$ (Figure 9b). Overall, the post-spill NDVI associated with mangrove vegetation is generally weakly correlated with spill volume, although a moderate positive correlation ($R^2 = 0.4520$) is observed for 401–1000 bbl (Figure 7c). However, the lack of a clear relationship between post-spill NDVI and oil spill volume for mangroves does not necessarily indicate that the oil spill does not impact the health of the mangroves. From Figure 4, it was observed that the mangrove is the most degraded type of vegetation. Much crude oil has been discharged into coastal environments, which makes mangroves extremely vulnerable to oil and industrial waste [62]. Therefore, the lack of correlation could arise because of difficulty quantifying the oil spill volume in the dynamic aquatic setting where mangroves are located, where waves and ocean currents can readily disperse the oil. Furthermore, the mangroves are often exposed to oil through runoff of spills inland, again making it difficult to reliably quantify the volume of oil originating at the mangrove sites. Similarly, the biota of mangroves exposed to oil pollution may experience increased mutation [63].

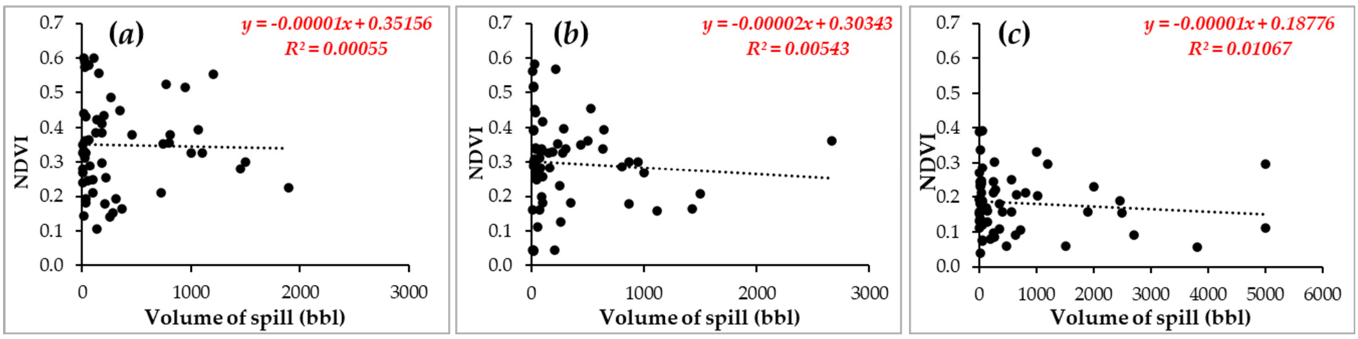

Figure 5. The relationship between post-spill NDVI and oil spill volume for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

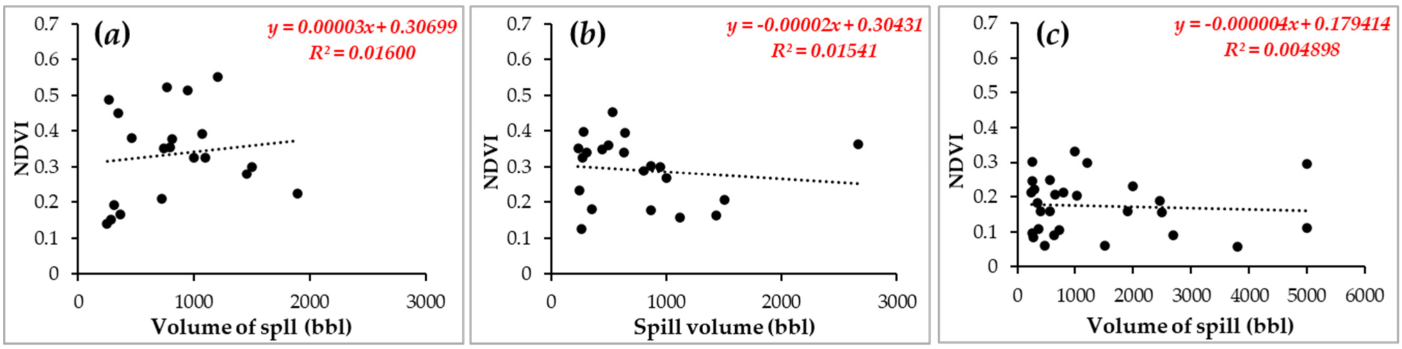

Figure 6. The relationship between post-spill NDVI and oil spill volumes greater than 225 bbl for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

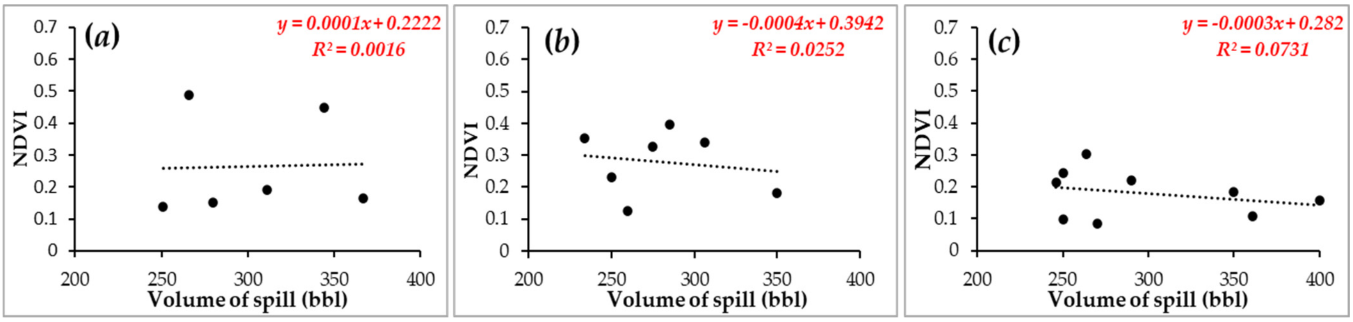

Figure 7. The relationship between post-spill NDVI and oil spill volumes of 225–400 bbl for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

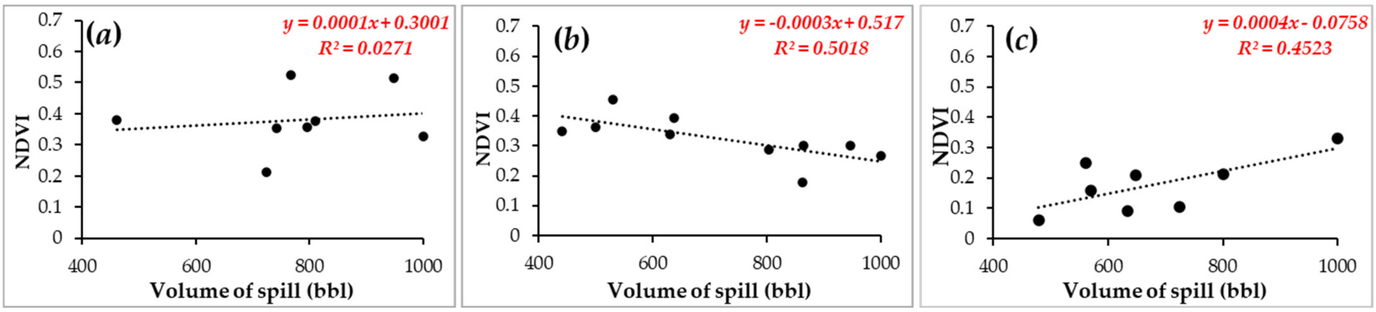

Figure 8. The relationship between post-spill NDVI and oil spill volumes of 401–1000 bbl for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

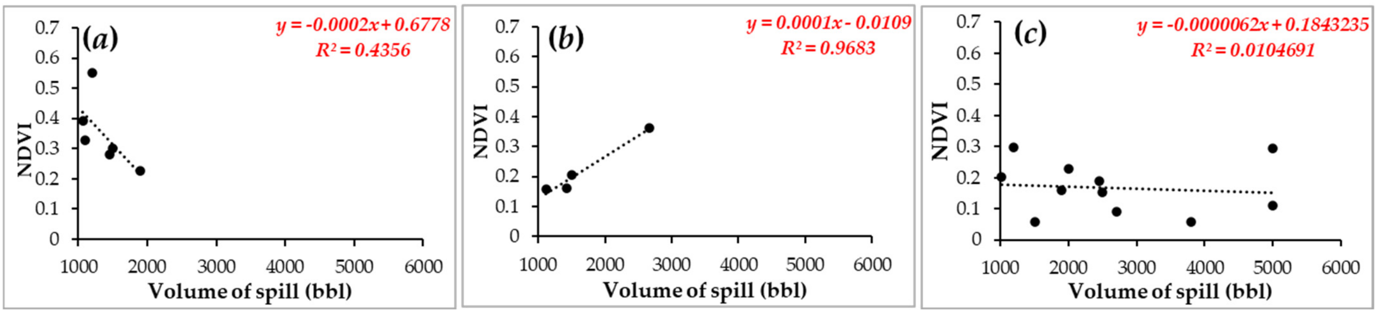

Figure 9. Relationship between post-spill NDVI and oil spill volumes greater than 1000 bbl for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

Similarly, Figure 10 shows the relationship between NDVI and time after the spill for the dense, sparse, and mangrove vegetation. In terms of the relationship between the post-spill NDVI and the time after the oil spill, the dense vegetation shows gradual signs of degradation through a weak decreasing trend in NDVI values following an oil spill (Figure 10a). This is because the full extent of the oil damage on dense vegetation may not be obvious until 6–12 months after a spill incident [64]. The sparse and mangrove vegetation appears not to show signs of degradation within 180 days and 90 days (Figure 10b and 10c, respectively). However, the dense vegetation tends to show non-significant signs of degradation. The possible reason for the lack of evidence of degradation could be that sparse vegetation and mangrove vegetation show signs of degradation a few days after an oil spill. Mangrove stress usually occurs within the first two weeks of an oil spill event, and these signs are visible in several ways, such as chlorosis and defoliation to tree death [65]. Mangroves are very sensitive to oil, partly because oil sediments thinly cover the highly sensitive fine-feeding roots of mangrove trees [66]. Additionally, visible oil stress symptoms of vegetation depend upon the plant species type and degree of stress [67]. Each vegetation type has different biophysical properties, so their levels of resistance vary.

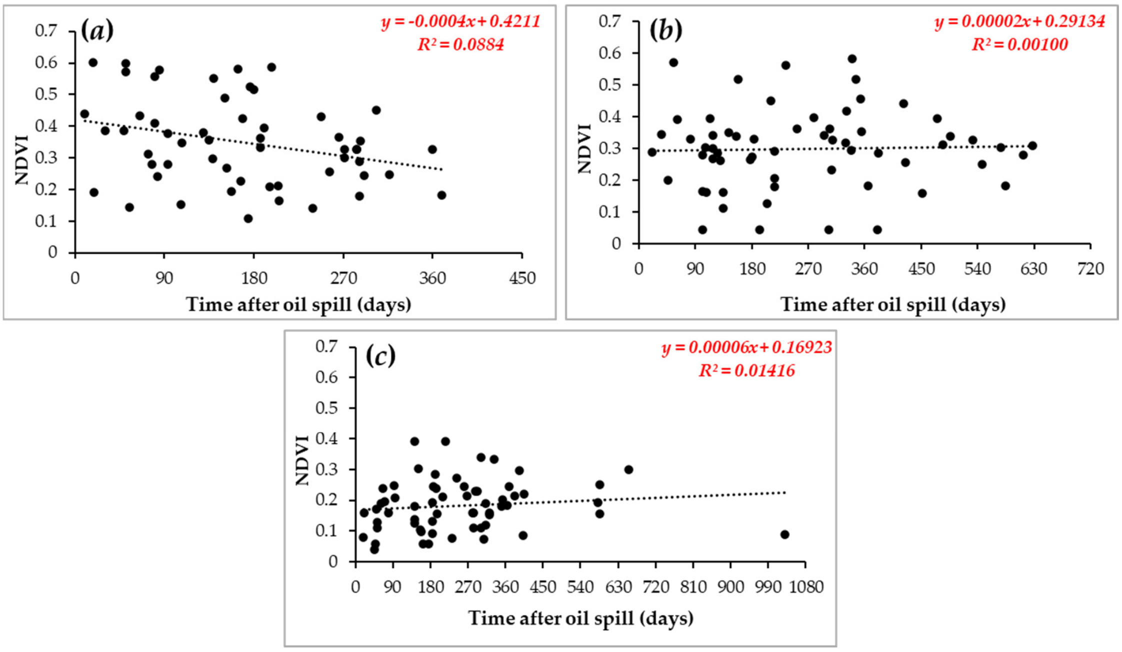

Figure 10. Relationship between post-spill NDVI and time after the spill for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangrove vegetation.

3.2. The Temporal Response of Vegetation Health to Oil Spill Exposure

Figure 11 shows the change in NDVI (ΔNDVI) at spill sites (SSs) with a spill volume above 225 bbl and their corresponding non-spill control sites (CSs), relative to a pre-spill baseline NDVI value, for a number of years after an oil spill occurrence for dense vegetation (Figure 11a), Sparse vegetation (Figure 11b) and Mangrove vegetation (Figure 11c). Additionally, Figure 11d presents a boxplot that summarises ΔNDVI for both SSs and their corresponding CSs for each vegetation type. A negative ΔNDVI suggests signs of degradation in vegetation's health condition (a sign of stress) relative to the condition prior to the occurrence of a spill. Both graphical and statistical analyses using paired *t*-tests were used to determine the significance of oil spill-induced differences in ΔNDVI values of SSs and CSs relative to a pre-spill baseline NDVI value for each site (Figure 11d). As previously mentioned, ΔNDVI was used instead of absolute NDVI values at different time points because the magnitude of NDVI at some sites may be inherently higher than at others due to the additional influence of other factors that affect vegetation health. These include soil type and both water and nutrient availability, among others [67]. For instance, vegetation at oil spill sites could be healthier (and, hence, have a higher NDVI) before a spill than vegetation not exposed to a spill if located in an area with better water and nutrient availability. Calculating the NDVI changes at a site relative to a pre-spill baseline NDVI, therefore, acts to isolate the effect of exposure to oil from the influence of these external factors. The influence of these factors was further mitigated by carefully selecting CS and SS pairs with corresponding conditions (e.g., sunlight, soil composition, climate).

The correlation between the ΔNDVI relative to pre-spill baselines for each site and the number of days after a spill shows that the vegetation health varied considerably during the study period at both the SSs and CSs (Figure 11). Although both positive and negative ΔNDVI values are observed at SSs and CSs for all vegetation types, the negative ΔNDVI values have a greater magnitude at the SSs, especially for sparse and mangrove vegetation. Dense vegetation at SSs exhibited 38% positive ΔNDVI values within the first 730 days (2 years) after a spill, sparse vegetation had 24% positive ΔNDVI values, whilst the mangrove vegetation displayed only negative ΔNDVI values within the first two years (Figure 10a–c). Dense vegetation at CSs exhibits a negligible decreasing trend in ΔNDVI during the time period, whilst the vegetation health at SSs remains stable following an initial decrease in NDVI (ΔNDVI = −0.05) immediately after oil spills. For the sparse vegetation (Figure 11b), the CSs exhibit an increasing trend in positive ΔNDVI during the entire time period, indicating that the vegetation health is improving over time. Although vegetation at the SSs shows signs of recovery through a similar increasing trend in ΔNDVI following exposure to oil, the vegetation health does not return to its pre-spill baseline condition until the ninth year (3285 days). The ΔNDVI trends for mangroves are similar to those observed for dense vegetation in that there is a negligible decrease in the vegetation health over time at CSs, whilst the vegetation health at SSs decreases (ΔNDVI = −0.1) immediately following exposure to oil and then remains consistent for the remainder of the time period.

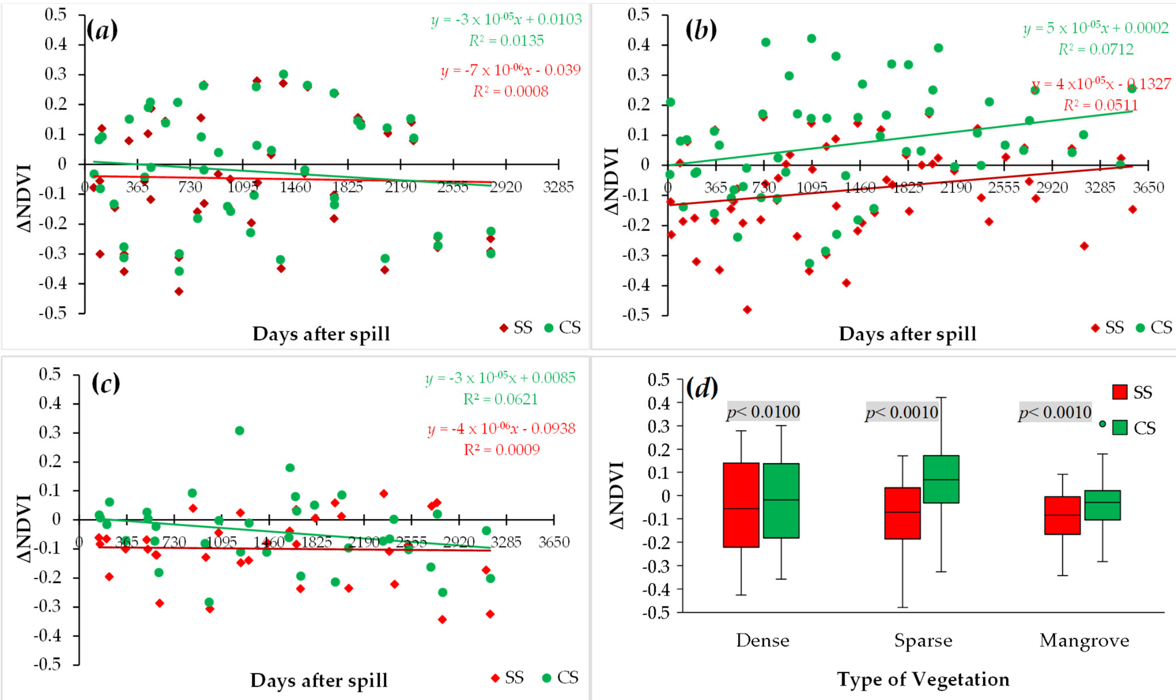

Figure 11. Relationship between ΔNDVI and number of days after a spill for volumes above 225 bbl and control sites for (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) Mangrove vegetation and (**d**) boxplot summary of ΔNDVI for spill sites (SSs) and control sites (CSs) for dense, sparse, and mangrove vegetation with the *p*-values from paired *t*-test analysis to determine the statistical differences in post-spill ΔNDVI for corresponding pairs of SSs and CSs located within dense ($n = 8$), sparse ($n = 8$) and mangrove vegetation ($n = 6$). Levels of significance: *p*-value < 0.0010 (highly significant); *p* value < 0.0100 (very significant); *p*-value < 0.0500 (significant); *p*-value ≥ 0.0500 (not significant) Figure 11d.

It can also be observed from the boxplot in Figure 11d that the median ΔNDVI is lower for SSs than CSs for all the vegetation types, with the biggest differences observed for sparse vegetation and mangroves. Moreover, the mangrove vegetation has more than 75% of ΔNDVI values below zero compared to less than 75% for the sparse and dense vegetation. Furthermore, Figure 11d shows that the ΔNDVI values at SSs are highly statistically different (*p*-value < 0.0010) from those at CSs for both sparse and mangrove vegetation and very significant (*p*-value < 0.0100) for dense vegetation. These observations concur with the findings of Adamu et al. [31], which found a significant difference with a *p*-value of <0.0050 between the NDVI values derived from the Landsat image of vegetation at spill sites and non-spill sites in mangrove vegetation in the Niger Delta. Also, Ozigis et al. [14] found a significant difference with a *p*-value < 0.0500 between the LAI, NDWI, and NDVI values derived from the Sentinel 2 multispectral bands for grassland in the Niger Delta. In summary, the statistical tests confirm that sparse and mangrove vegetation is most responsive to oil exposure in the region. Mangrove tidal wetland habitats are highly vulnerable to large and chronic oil spills [66]. Past oil spill events worldwide demonstrate that mangroves can suffer lethal and sublethal effects when exposed to oil, which can be impacted regardless of the distance from shore if oil reaches their roots and pneumatophores [68]. The presence of polynuclear hydrocarbons in the soil increases the incidence of a mangrove mutation in which chlorophyll is deficient or absent [69]. Also, continuous exposure of mangrove trees to high levels of pollution affects their health and productivity in the long term by imposing permanent stressful conditions [70].

3.3. The Response of Vegetation Health to the Volume of Oil Spills for Individual Locations

Table 4 presents a comparison of ΔNDVI for each pair of CSs and SSs for different oil spill volumes. Overall, this shows that oil spills, irrespective of volume, have less significant impacts on the health condition of dense vegetation than other vegetation types, with only one site (D1 at spill volume 280 bbl) experiencing significant differences in ΔNDVI values compared to its corresponding CS. The sparse vegetation has more impacted locations, with five out of eight spill locations exhibiting very significant differences in ΔNDVI compared to their SS, which indicates negative impacts on the vegetation health condition following exposure to oil spills. This is followed by the mangrove vegetation, with three out of six CS locations having a significant difference in their vegetation health condition compared to their SS counterparts. The results also show that the significant difference in ΔNDVI between SS and their CS is not directly positively correlated to the spill volume. For instance, the only significant difference for dense vegetation is observed for a spill volume of 280 bbl (p-value < 0.05), which is the smallest spill volume for such sample sites. A similar scenario is also observed for the mangrove vegetation for a spill volume of 1554 bbl, which has larger statistically significant differences in ΔNDVI than for a spill volume of 2500 bbl. One potential reason for this could be gas flaring from nearby refineries [67,71], which increases the temperature and affects the soil quality around SSs located closer to refineries. The impact of oil spills on vegetation is beyond the spill volume, though it is an important factor, as reported by [32]. However, Mohamadi et al. [67] reported that impacted area size, spilt oil volume, residual oil volume on-site, impacted area environment, and response, recovery, and clean-up timing are major determinants of oil spill influence on the Niger Delta's vegetation.

Table 4. Paired t-test analysis of ΔNDVI values after a spill between each spill site (SS) and control site (CS) at different volumes for dense, sparse, and mangrove vegetation.

Sample Points	Spill Volume (bbl)	p-Value	Sample Points	Spill Volume (bbl)	p-Value	Sample Points	Spill Volume (bbl)	p-Value
Dense Vegetation			Sparse Vegetation			Mangrove Vegetation		
D1	280	*	S1	228	*	M1	264	*
D2	346	ns	S2	235	ns	M2	800	ns
D3	367	ns	S3	260	**	M3	1020	ns
D4	367	ns	S4	440.3	ns	M4	1510	ns
D5	429	ns	S5	529.5	ns	M5	1554	**
D6	1000	ns	S6	802.5	**	M6	2500	*
D7	1430	ns	S7	1000	*			
D8	1500	ns	S8	1500	**			

Note: Levels of significance: ** p-value < 0.01 (very significant); * p-value < 0.05 (significant), ^{ns} p-value ≥ 0.05 (not significant).

3.4. Time Series Analysis of ΔNDVI for SS and CS

The graphs of the time series of ΔNDVI for the pairs of sites in dense, sparse, and mangrove vegetation are shown in Figures 12–14. Figures 12–14 show the temporal changes in NDVI values of each spill site (SS) with its corresponding control site (CS) from the values extracted from Table 4. Figure 12a–h is the graph for dense vegetation having several years ranging from 0–4 years (Figure 12a,c,d), 0–6 years (Figure 12e,f) and 0–7 years (Figure 12b,g,f) with the lowest and highest oil spill volumes of 280 and 1500 bbl, respectively, and with 4 and 7 years being the lowest and the highest number of years. The range of years for sparse vegetation in Figure 13a–h are 0–4 years (Figure 13a), 0–5 years (Figure 13b,g), 0–7 years (Figure 13e,f), 0–8 years (Figure 13c) and 0–10 years (Figure 13d,h), with the lowest and highest oil spill volumes of 234 and 1500 bbl and with the lowest and highest numbers of years of 4 and 10 years, respectively. For mangrove vegetation in Figure 14a–f, the years range from 0–5 years (Figure 14a,d), 0–6 years (Figure 14b,f) and 0–7 years (Figure 14c,e), with the lowest and highest oil spill volumes of 264 and 2500 bbl and with both the lowest and highest numbers of years being 5 and 7 years, respectively.

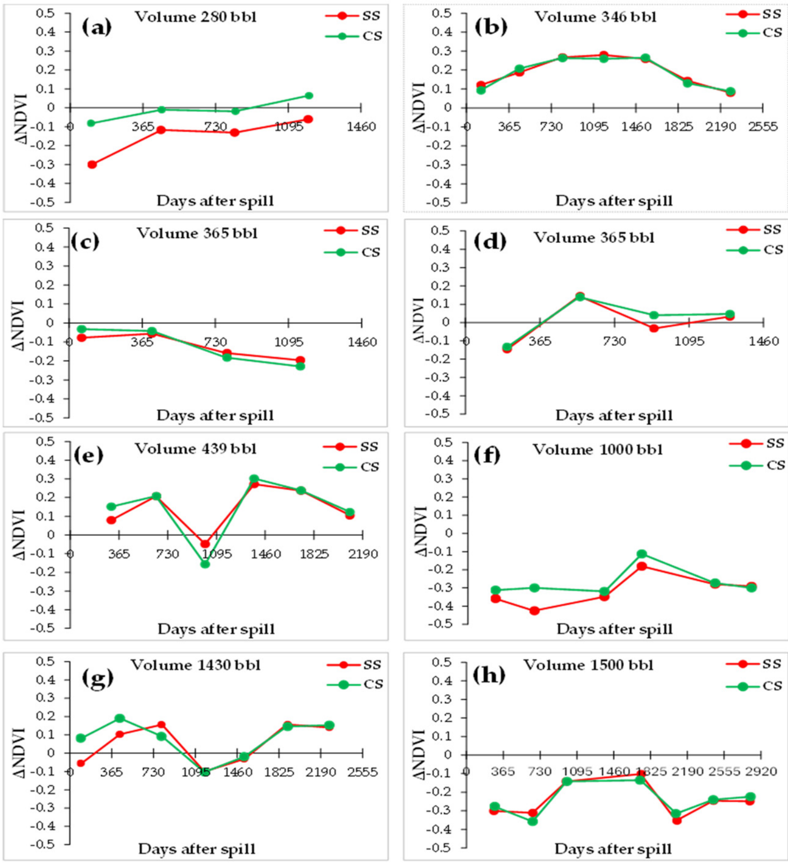

Figure 12. (**a**–**h**) Temporal changes in NDVI (ΔNDVI) for SS and CS pairs in dense vegetation for different oil spill volumes.

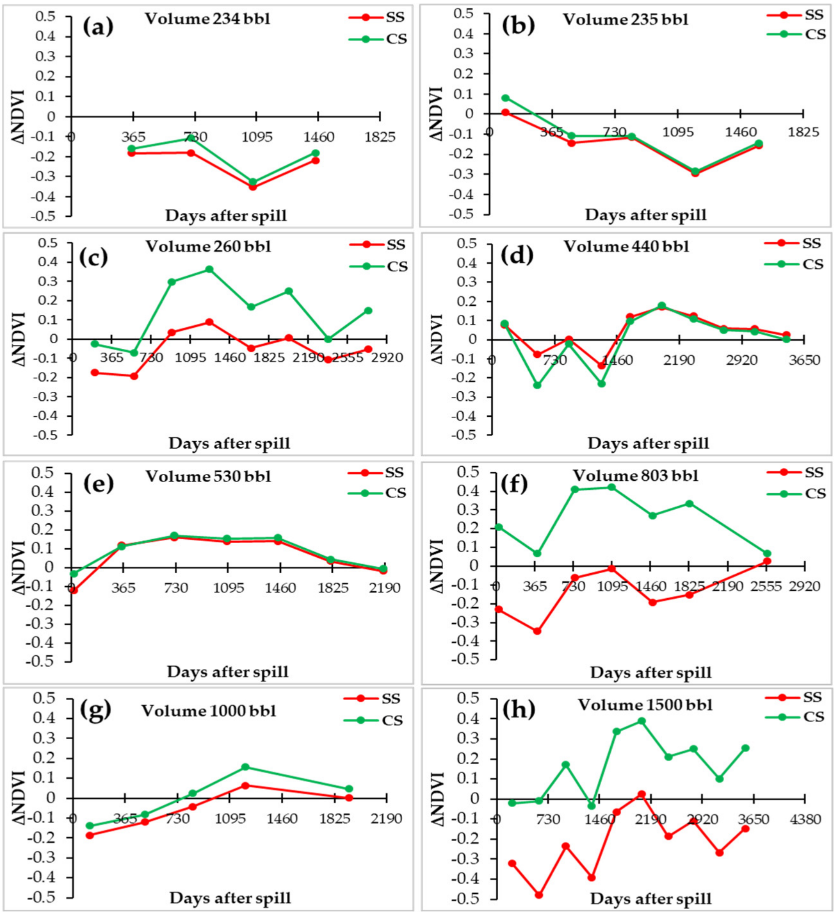

Figure 13. (**a**–**h**) Temporal changes in NDVI (ΔNDVI) for SS and CS pairs in sparse vegetation for different oil spill volumes.

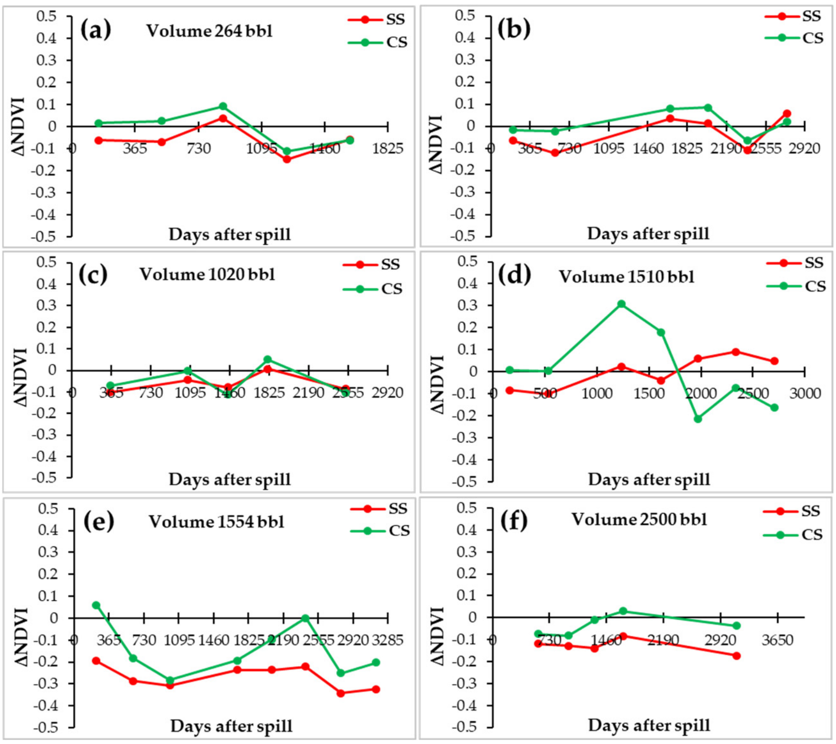

Figure 14. (**a**–**f**) Temporal changes in NDVI (ΔNDVI) for SS and CS pairs in mangrove vegetation for different oil spill volumes.

For most sites, the SSs and CSs exhibit the same underlying trend in ΔNDVI, likely due to the vegetation at those locations being exposed to the same inherent environmental conditions, such as water availability and soil type. However, the negative ΔNDVIs over time are generally of greater magnitude at SSs than at CSs. For example, the negative ΔNDVI values are all notably greater in magnitude at SSs than at CSs for dense vegetation at a spill volume of 280 bbl (Figure 12a), for sparse vegetation at spill volumes of 260 bbl (Figure 13c), 803 bbl (Figure 13f) and 1500 bbl (Figure 13h). Furthermore, for mangrove vegetation, negative ΔNDVI values are most notable at spill sites with volumes of 1554 bbl (Figure 14e) and 2500 bbl (Figure 14f). Nonetheless, several CSs exhibit negative ΔNDVI values despite not being exposed to an oil spill. In these cases, factors such as seasonal changes in rainfall and weather conditions could be responsible for affecting the condition of the vegetation. It is apparent that oil spills have clearly affected the recovery of some vegetation in the Niger Delta. Although the vegetation condition at some SSs appeared to recover after the oil spill (e.g., dense vegetation—Figure 12a; sparse vegetation—Figure 13c,e–h; mangrove vegetation—Figure 14b,d), it was not able to recover within the same period at other SSs (e.g., dense vegetation—Figure 12c; sparse vegetation—Figure 13b). Mangroves and rainforests affected by hydrocarbon have been shown to have reduced chlorophyll [1,45]. However, the oil pollution impact on adult trees is weak [71].

Figure 15 shows ΔNDVIs categorised according to spill volume for the different vegetation types. From the result, there is no apparent relationship between the health of vegetation at SSs and the volume of the oil spill. For instance, it can be observed that 100% of the ΔNDVI values for dense vegetation (Figure 15a) were negative at spill volumes 280, 1000, and 1500 bbl, whereas more than 75% were greater than zero at 346 and 429 bbl, with the most degradation occurring at spill volumes of 1000 and 1500 bbl. For sparse vegetation (Figure 15b), degradation during the time period overall appears to become less severe with an increase in spill volume of up to approximately 500 bbl before then increasing in severity again at higher spill volumes. Overall, some degradation of mangrove vegetation (Figure 15c) persists throughout the time period, although it is greatest at spill volumes of 1554 and 2500 bbl when 100% of ΔNDVIs are less than zero. Overall, vegetation degradation is not directly proportional to the oil spill volume. Possible reasons could be that some oil spills were remediated quicker than others or due to differences in the toxicity of the oil at some locations. Nevertheless, regardless of the vegetation type, the negative impact on the health was most prominent for oil spill volume above 1500 bbl. Another factor that could impact the impact of the oil spill in the Niger Delta is the topography and the relief of the spill site. High topography can influence the migration of large oil spills from the source [30]. Therefore, each spill site must be treated on an individual basis.

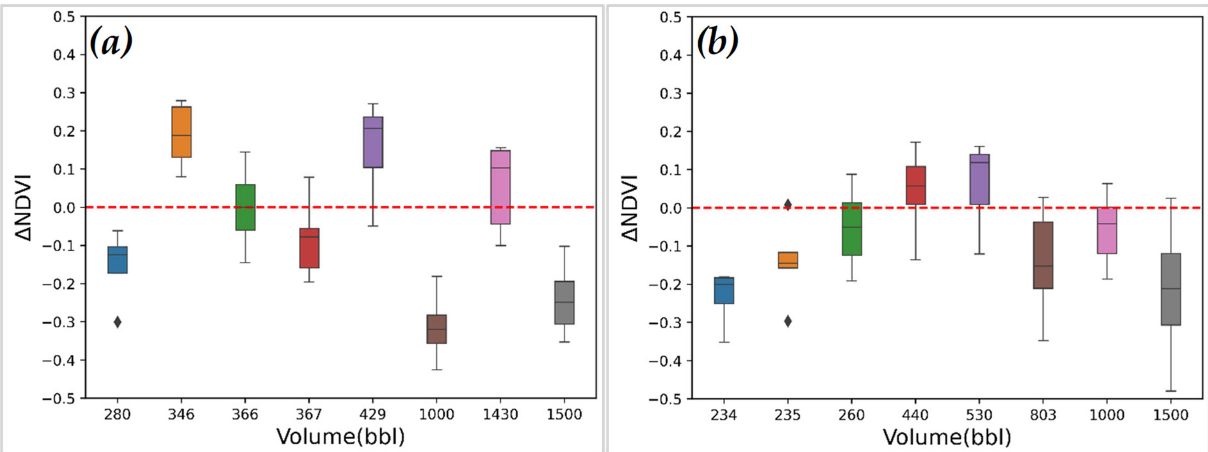

Figure 15. *Cont.*

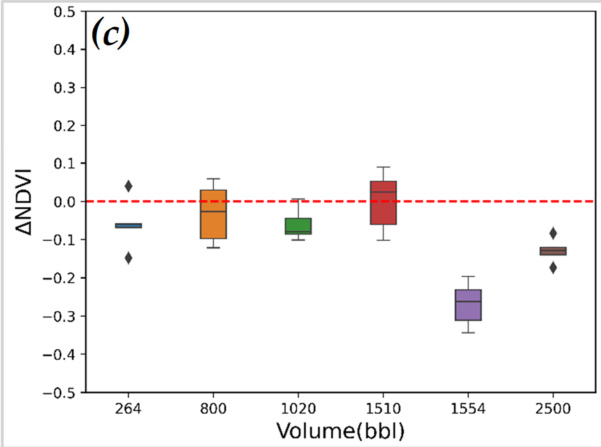

Figure 15. Temporal changes in NDVI (ΔNDVI) at spill sites (SSs) for different oil spill volumes in (**a**) dense vegetation, (**b**) sparse vegetation, and (**c**) mangroves.

3.5. Limitations of This Study

There are a few limitations to this study. One is that using only linear regression may not fully reveal the nonlinear relationship between the oil spill volume, the time gap after oil and the NDVI values for each vegetation. Secondly, there is a lack of soil and climatic data. However, the contributions of soil and climate on vegetation health were mitigated using pair-wise comparisons of spill and non-spill sites that are proximal to each other. Also, all the NDVI data were for the dry season (December and January), with similar weather conditions. Regarding the use of field data, that will be performed in future work.

4. Conclusions

This study utilised Landsat satellite-derived NDVI to determine the impact of oil spills on dense, sparse, and mangrove vegetation in the Niger Delta region using linear regression to determine the impact of oil spill volume and the time gap after an oil on the health of the vegetation, and, secondly, used Pared *t*-test determines the difference between the health of the vegetation exposed to an oil spill and the vegetation not exposed to the oil spill. The major findings are as follows:

- The mangrove and sparse vegetation are the most degraded vegetation in the Niger Delta, and the sparse vegetation is the most affected among the three vegetation types by oil spills between 401 and 1000 bbl, whilst the dense vegetation responds more at a higher volume >1000 bbl.
- The effect of the time gap after a spill is not statistically significant for all the vegetation types.
- There is a statistically significant difference in the health condition of vegetation affected by oil spills compared to the vegetation unaffected by the oil spill.

Despite the lack of a statistically significant relationship between the oil spill volume and time gap for most volume ranges, there is clear evidence that the health of vegetation in the Niger Delta is degraded when it is exposed to oil spills for all vegetation types. However, the result shows a statistically significant difference between spill sites and non-spill over time for all vegetation types. This has provided insight into how different types of vegetation respond to an oil spill, which could help in designing an oil spill clean-up program to reduce the impact of oil spills on different types of vegetation in the Niger Delta by prioritising oil spill clean-up based on the vegetation type that is most affected by the impact of the oil spill. The implication of the results is that the oil spill volume should not be the sole requirement when responding to or mitigating the impact of the oil spill on vegetation. Each site should be treated differently based on other factors such as the soil type, topography, etc. The long-term impact of oil spills on the vegetation could be mitigated by designing an early oil spill detection and clean-up response program to ensure that such vegetation recovers within the shortest period. The use of satellite-based-derived NDVI provides a unique option to monitor the health of vegetation in places like the Niger Delta. It provides spatiotemporal data without the need to visit the site due to security concerns. However, further research is recommended for the mangrove to investigate the lack of correlation between the oil spill and the NDVI value through ground visits and analysis of the leaf sample to determine if the mangrove has developed some form of resistance to the oil spill's impact due to constant exposure. Future work is being undertaken to understand vegetation impacts using leaf samples. In addition, other nonlinear regression analyses may be used since regression may not fully reveal a nonlinear relationship.

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Conflicts of Interest: The authors declare no conflicts of interest.

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