13 Oil-Related Mangrove Loss East of Bonny River, Nigeria

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Abstract

This study documents the largest cumulative loss of mangroves due to oil-related activities, including 4415 ha due directly to oil spillage (operational and illegal activities) and 105 ha due to pipeline corridors. Additionally, 217 illegal refinery sites are found which destroyed 116 ha of high ground habitat adjacent to mangroves. Source information utilized includes satellite imagery (1999–2016), aerial videography and photographs (2000, 2010, 2015), and field surveys (1983, 2013, 2015). Mangrove losses began in 2008/2009 due to four spills (three caused by corrosion, one from illegal activity) that caused ~2000 ha of damage. Two of these spills are part of a legal settlement with the resident Bodo community involving a mangrove loss of ~1000 ha. Illegal tapping of the major north-to-south oil-transport pipelines along with a concurrently large increase in illegal refineries became evident in the eastern part of the study area in 2010 and 2011, causing an additional ~1000 ha loss. In 2010, illegal activities also increased in the north causing >300 ha of mangrove loss. After 2013, mangrove losses are small as military operations substantially decreased but did not stop illegal activities. Field studies in 2015, designed to provide guidance to cleanup operations and mangrove restoration, found large areas with very high concentrations of surface and subsurface oil that will inhibit mangrove recovery. Indications are that natural recovery will take much longer than 30 years and, in some areas, may never occur without intervention due to substrate changes that now inhibit seed settlement and growth.

Keywords

Mangrove · GIS mapping · Oil spill impacts · Remote sensing · Bonny River · Niger Delta · Nigeria

13.1 Introduction

This paper analyses the cause, extent, and time-sequence of mangrove loss along the eastern side of the Bonny River, Rivers State, Nigeria. This information is critical for proper undertaking of remedial and restoration methods as described by UNEP (2011) and in process of implementation by the Bodo Mediation Initiative (BMI 2016) and the Hydrocarbon Pollution Remediation Project (HYPREP) under the Nigerian Ministry of Environment (MOE 2017).

The area of interest lies along the eastern part of the Niger Delta (Fig. 13.1). The Niger Delta includes waterways having water flow from the Niger River as well as adjacent areas having similar conditions. The Niger River distributary system is defined as extending from the Benin River (5.7364 N, 5.0636 E) in the west to the Imo River (4.4544 N, 7.5908 E) in the east (NDES 1997). Mangrove forests are located along the entire Niger Delta in areas of saline to brackish waters extending up to 40 km toward the mainland from a series of barrier islands fringing the Atlantic Ocean in the south. The Niger Delta contains the largest extent of mangroves in Africa. NDES (1997) using 1981 FAO data estimates the total Niger Delta mangroves at 966,676 ha, but this is likely a high value as UNEP (2007) suggests that Nigerian mangroves have reduced by 26% since the 1980s due to development.

13.1.1 Regional Overview

The study area extends from the Bonny River eastward to the furthest extent of observable mangrove loss, and from Bonny

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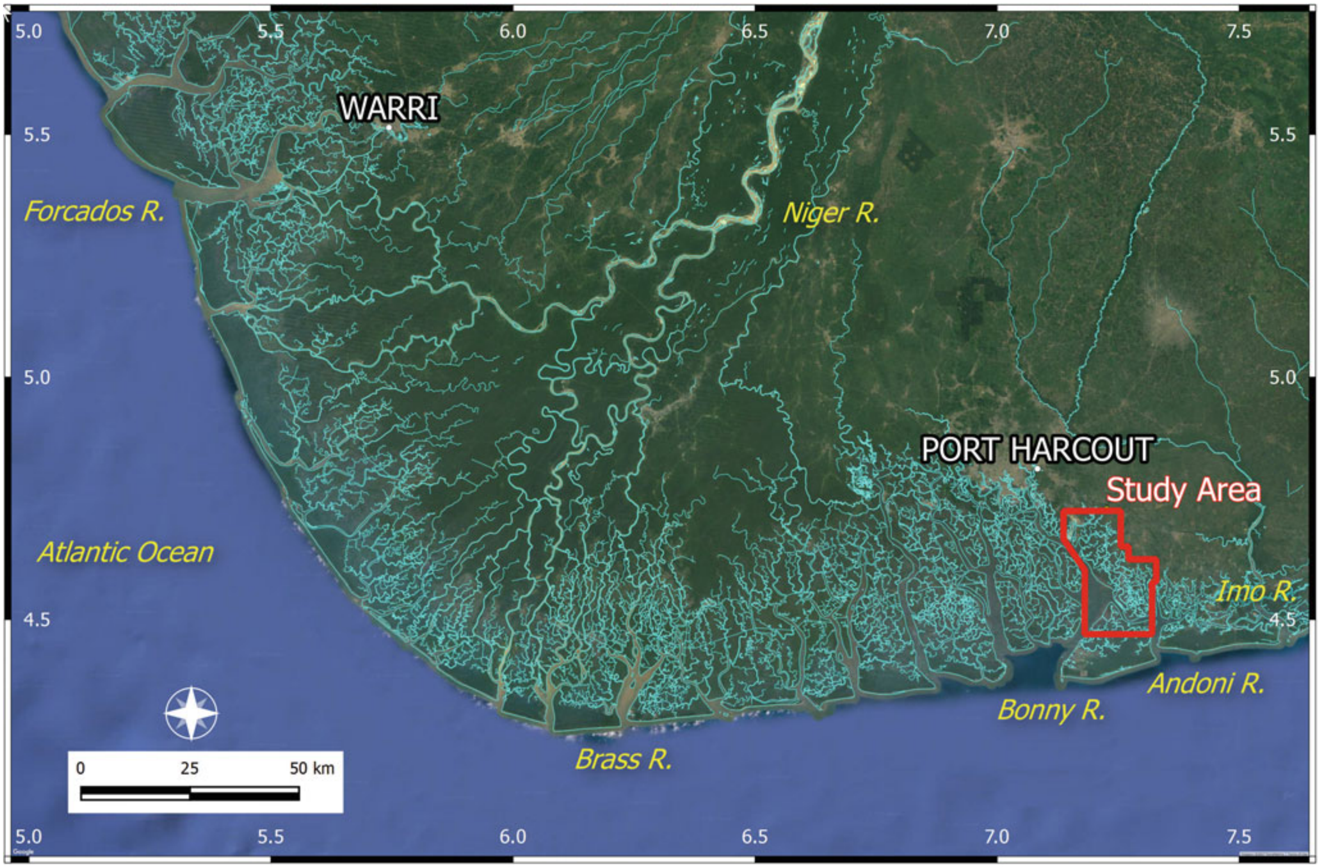

Fig. 13.1 Study area location in the eastern Niger River delta

Island in the south to the mainland in the north between Onne and Ogu (Fig. 13.2). Portions of five Local Government Areas of Rivers State are included: Andoni, Bonny, Gokana, Ogu Bolo, and Okrika. The northern part of the study area is part of Ogoniland.

Mangroves intersected by numerous intertidal channels and creeks are the dominant ecological habitat of the area. A few small villages are present on supratidal islands within mangrove areas. The mainland towns of Bodo, Ogu and Bolo are much larger. Ogu is similar in size to Bodo while Bolo is smaller. Bodo has a reported population of 69,000 (Pegg and Zabbey 2013).

Allen (1965) characterizes the eastern Niger Delta as having three geomorphological units: barrier islands formed by sand ridges, a broad tidal flat colonized by mangroves and marked by a reticulate drainage system, and an interior forested river floodplain. In the area of study, historic delta sediments dominated by silt and clay underlie most of the mangrove area, varying in stability from hard and compact to very soft and unstable where walking without sinking 40 cm or more is not possible. Within the mangrove habitat are supratidal islands composed of sand and silts and commonly forested by palm trees.

As measured at Bonny, rainfall in the area can be very heavy, sometimes over 1000 mm a month, with heaviest rains falling June to September (Worldweatheronline 2017). Average rainfall measured over several decades varies from 3500 to 4000 mm annually along the coastal belt, decreasing to 2000–2500 mm in the northern part of the study area (Adejuwon 2012). Temperatures range from 23 to 36 °C.

The tides of the study area are diurnal showing a range of 1.4–2.6 m. Upper areas are entirely drained during low tide, exposing large sand- or mud-dominated tidal flats. Tidal currents measured by the author show a range of 0.4–1.6 kn during flood conditions, and 0.6–1.2 kn during ebb, in channels between Bodo and south to Opobo channel and the Bonny River.

The inflow of freshwater to the area is relatively minor. The Bonny River extends 72 km from the Atlantic Ocean and has no further interior drainage. In contrast, the Imo River to the east extends far into the mainland and serves as a drainage basin for a large interior section, but this has no effect on the study area. Folorunsho and Awosika (2014) find that "The Bonny River system has the largest tidal volume of all river systems in the delta. There is generally a net flux of tidal

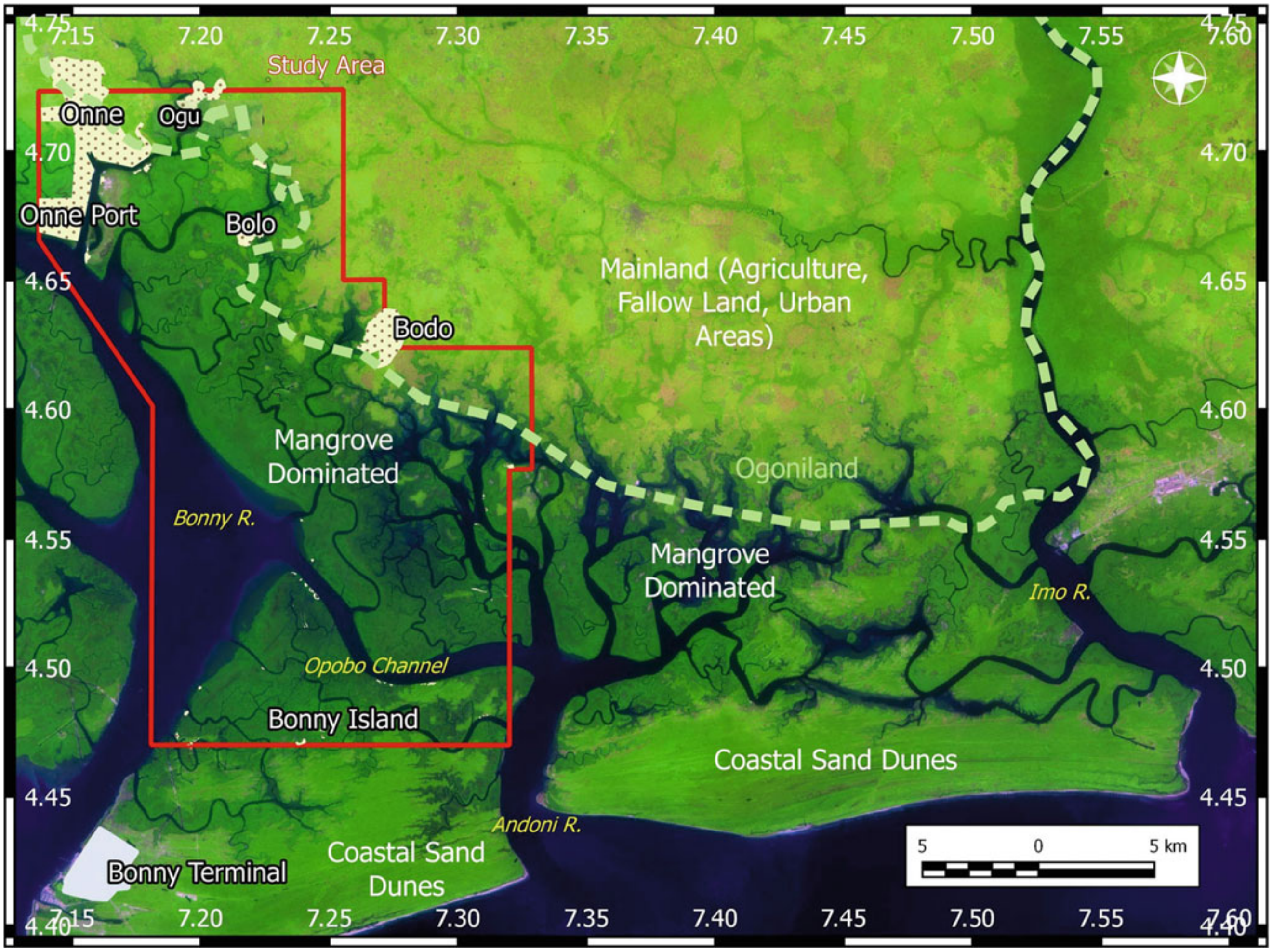

Fig. 13.2 Regional setting of the study area along the east side of the Bonny River. A SPOT image from 1999 is shown as background

water up the river, which disperses into various creeks and channels".

Salinities measured by Dublin-Green (1990) in the Bonny River of the area of study show a range of 18–20 during September (wet) and from 20 to 29 during February, May and December (dry). Field measurements by the author in the dry month of April from Bodo down to the Bonny River show only a minor difference in salinity (19.5–23.5).

The intertidal conditions, limited flushing by upland rainfall, and measured current velocities indicate that oil spilled into the creeks and lagoons potentially will cover large areas and remain within the intertidal mangrove habitats for a substantial period.

13.1.2 Mangroves and Associated Organisms

Six species of mangroves are present in the area: *Rhizophora mangle, R. harrisonii, R. racemosa, Avicennia germinas, Conocarpus erectus* and *Languncularia racemosa* (UNEP 2007, Zabbey and Tanee 2016). The red mangrove (*R. mangle*) is by far the most common.

Differences in salinity, duration of water coverage during the tidal cycle, and underlying soil conditions influence the presence and condition of resident mangroves and associated biota. High salinities and salt deposits on interior basins caused by limited water coverage during spring tides are likely to stress the plant and result in stunted mangroves and sparse surface coverage. Soil conditions are commonly dominated by mangrove root fibers forming a peaty clay called 'chikoko'.

Common aquatic/intertidal fauna include crabs, snails, polychaetes, barnacles and fish (NDES 1997; George et al. 2009; Zabbey et al. 2010). Resources used by the local population include mangroves as firewood, fish, periwinkles, cockles and crabs. Pre-impact analyses by Pegg and Zabbey (2013) at the site found 12 animal species on mangrove stems and stilt roots and 18 species on adjacent tidal flats, of which 34% were locally edible and the others occupied critical links in the food web. The loss of the mangrove forest therefore affects the local community relying on these resources (Fentiman and Zabbey 2015).

The nipa palm (*Nypa fruticans*) is an exotic species that is common in many parts of the study area and has become dominant in certain areas. It is highly opportunistic and found to out-compete mangroves in oiled and depleted soil areas (Sunderland and Morikinyo 2002). Productivity of the mangrove habitat is reduced with the introduction of nipa palm. Baker (1983) found nipa palm at only 1 of the 27 survey sites in the central west portion of the study area whereas now it is common throughout, particularly in the south and central parts of the study area.

Of all shoreline types, mangrove habitats have been rated as the most sensitive to spilled oil based on their high biodiversity, ability to trap and retain spilled oil, and the long time required for recovery (Gundlach and Hayes 1978; Gundlach et al. 1981; NOAA 2012; IPIECA 2012). Summaries of oil impact on mangroves include Duke (2016a), IPIECA (1993), Lewis et al. (2011), NOAA (2014), and USDOI (1997), among others.

13.1.3 Oil-Related Infrastructure

Development of the Bonny River area began by Shell Petroleum Development Company of Nigeria Limited (SPDC) in the 1950s. Bonny Terminal, the export hub for the region, opened in 1961. The majority share (55%) of SPDC is owned by the Nigerian government via the Nigerian National Petroleum Corporation. Shell (30%), Total (10%) and Eni (5%) have lesser shares.

SPDC eventually drilled at least 325 wells in Rivers State but suspended operations in the Ogoni area in 1993 due to civil unrest. All infrastructure was abandoned including oil and gas wells, gas plants, flow stations, manifolds and pipelines. Within the study area, there are 38 inactive oil wells and two manifolds (Fig. 13.3). The Trans Niger Pipeline (TNP) comprised of two (24-in. and 28-in.) oil pipelines remains active, crossing the area from the north to Bonny Terminal in the south. In addition to a gas line crossing the study area, there is a large-diameter pipeline operated by NNPC (Nigeria National Petroleum Corporation) which delivers crude oil for export via the Bonny Terminal. The specifics of the NNPC pipeline throughput and extent of operation are unknown.

13.1.4 Persistence of Bonny Light Crude Oil

Bonny Light crude oil is produced in the region. It is characterized as a light oil with low asphaltenes, low sulfur and relatively high concentrations of nickel and vanadium. Properties are shown in Table 13.1.

With processing, Bonny Light crude has a high yield for diesel and lighter products (Table 13.2), which makes it ideal for legal and illegal refining. Assuming that temperatures on the order of 350 °C are reached by the illegal refining process, then two thirds of the original crude oil input could be converted to saleable product by illegal refiners. As shown later, the heavier remaining oil and residuum is discarded into the surrounding environment.

When spilled, the light components of Bonny Light crude oil are exposed to a high degree of evaporation. Bonny Light is categorized as a Group 3 oil, which has a longevity of approximately a month to a few months when spilled on the water's surface (ITOPF 2011). However, once oil becomes incorporated into the surface or remains as a tarry residue, the persistence of the remaining oil is extended greatly. Gundlach (1987). estimated persistence of oil on different shoreline types using the following formula:

$$M_i = M_{io} + e^{-Kft}$$

Where:

M_i = mass of oil on beach segment i
M_{io} = mass of oil originally deposited on the beach
K_f = removal rate constant based on exponential decay
T = time in days since original deposition

As originally developed, information for oil removal in mangroves was not available, but using marshes as the closest habitat type indicates a removal rate factor of 0.001–0.1 (Etkin et al. 2007). Taking the slower value (0.001) as applicable to large expanses of oiled mangroves then the calculated oil persistence is on the order of 16 years, which is reasonable considering the extensive presence of both surface and subsurface oil in the area. This longevity is the case for oil alone. The persistence of damage to mangroves is discussed in detail later.

13.2 Methods

A detailed review of satellite imagery, photographs and video taken during low-level overflights, and ground surveys forms the basis of this study. Data were input and analyzed using an open-source geographic information system (QGIS version 2.18.4). Specific data sources and their utilization are described below.

13.2.1 Digital Imagery

Images available (Table 13.3) were reviewed in a re-iterative method, i.e. going back and forth in time using historic images to see when and where mangrove damage occurred.

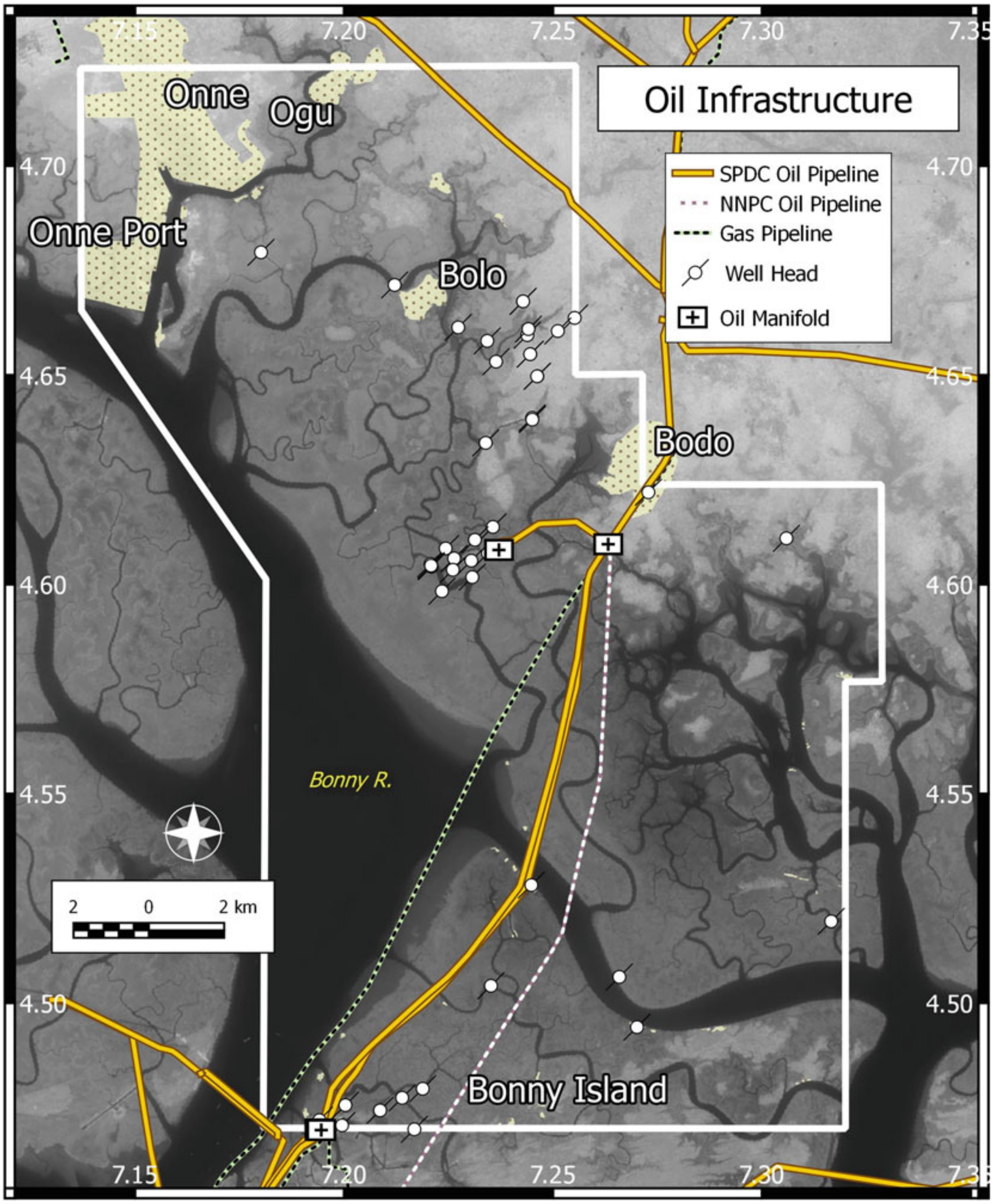

Fig. 13.3 Oil infrastructure within the study area

Table 13.1 Characteristics of Bonny Light crude oil (Brillpetco.com 2017)

Property	Measured
Gravity, API°	32.9
Gravity, SG	0.86
Total nitrogen, ppm	1170
Pour Point °C	−14.4
Viscosity at 40 °C	4.99
Vanadium, ppm	0.42
Nickel, ppm	4.16
Asphaltenes (H.C7) wt%	0.0032

Google Earth images, except for 2013, were reviewed outside of the GIS using Google Earth Pro. Each individual image listed in Table 13.3 covers a portion of the study area. Fortunately, in all cases pre- and post-impact images were available enabling assessment of mangrove loss minimally to 2013 and in most cases extended to 2015 or 2016. Imagery is available in true color and false-color infrared. As the condition of vegetation is clearer using the false-color infrared, these images are commonly selected for use in the text.

Table 13.2 Bonny Light crude true boiling point (TBP) yields (Modified from Toboc.com 2017)

TBP yields	Volume %	Total %
Butanes and lighter	0.92	0.92
Light gasoline (12.7–79.4 °C)	4.25	5.17
Light naphtha (79.4–148.9 °C)	13.73	18.90
Heavy naphtha (148.9–204.4 °C)	10.12	29.02
Kerosene (204.4–260.0 °C)	13.28	42.30
Atmospheric gas oil (260.0–343.3 °C)	22.69	64.99
Light vacuum gas oil (343.3–426.7 °C)	16.81	81.80
Heavy vacuum gas oil (426.7–565.6 °C)	13.26	95.06
Vacuum residuum (>565.6 °C)	4.94	100.00

Table 13.3 Digital imagery available for this analysis

Date	Source	Approximate resolution
30 Dec 1999	Google Earth	~20 m
Jan 2000	SPOT	20 m
12 Dec 2000	Ikonos-2	3.2 m
03 Dec 2006	Quickbird	1.0 m
03 Dec 2006	Google Earth	2.0 m
15 Jan 2007	SPOT	2.5 m
29 Jan 2008	SPOT	5.0 m
25 Jan 2009	Google Earth	2.0 m
26 Jan 2009	Quickbird	0.6 m
08 Jun 2009	Ikonos 2	0.8 m
24 Aug 2009	Ikonos 2	0.8 m
08 Nov 2009	Ikonos 2	0.8 m
19 Nov 2009	SPOT	2.5 m
27 Nov 2009	Google Earth	3.0 m
12 Dec 2009	Google Earth	2.0 m
06 Feb 2010	Google Earth	2.0 m
07 Feb 2010	Ikonos 2	0.8 m
11 Jun 2010	Google Earth	2.0 m
08 Jan 2011	Ikonos	0.8 m
23 Jan 2013	Google Earth	2.0 m
16 Dec 2013	Google Earth	2.0 m
18 Dec 2013	Google Earth	2.0 m
07 Jan 2014	Google Earth	2.5 m
12 Jan 2014	Google Earth	2.5 m
16 Jan 2014	Google Earth	2.0 m
07 Jan 2015	SPOT	1.5 m
19 Jan 2015	Google Earth	2.0 m
10 Feb 2016	Google Earth	2.5 m

13.2.2 Aerial Video and Photographic Surveys

Historic videography and photographs assisted understanding the time sequence of mangrove loss. Videotaping and still photographs from a low flying (~300 to 400 m) helicopter were taken by the author on 18 and 19 November 2000 and by Victor Imevbore of ERML (Lagos) on 11 September 2015. Aerial photographs from 29 November 2010 were provided by Thorsten Kallnischkies (contaminated land expert for UNEP's Ogoniland assessment) and from 15 April 2010 by Jonas Pålssen (World Maritime University). Figure 13.4 provides the flight tracks of the major aerial surveys.

13.2.3 Ground Surveys

Ground surveys confirmed observations made using imagery to determine mangrove and oiling conditions (Table 13.4). Surveys in 2013 and 2015 collected information on mangrove status (quantity dead, living or stressed), oiling level (surface: heavy, light or medium concentrations), subsurface oiling (silver, rainbow or black oil) as observed in a pit dug 20–30 cm, and the appearance of oil on adjacent surface waters. The 2010 UNEP survey provided oiling condition and chemical analyses (UNEP 2011; Linden and Pålssen 2013; Pålssen and Linden 2014). At 13 sites in 2015, samples were taken for chemical analysis. Results are described by Little et al. (2018) in this Coastal Research Library publication. Figure 13.5 provides field site locations showing that surveys concentrated in the center of the study area.

13.2.4 Oil Spills

Oil spill information from 1986 to June 2015 was derived from several sources, including the National Oil Spill Detection and Response Agency (NOSDRA https://oilspillmonitor.ng/), UNEP (2011) and SPDC (http://www.shell.com.ng/sustainability/environment/oil-spills.html).

Data are reported as incidents with date, location coordinates, text as to location (pipeline, wellhead, manifold, etc.) cause and amount discharged. This study uses three categories based on recorded cause: operational (corrosion, line failure, operation), illegal activities (sabotage, bunkering and theft) and unknown (unknown, not recorded and currently unavailable). Data related to the amount discharged are not considered reliable and not reported here. Among many reasons not to consider the recorded value as valid is that leak volume is difficult to estimate from a ruptured pipeline and spilled oil from a site is subject to tidal washing which can distribute spilled oil far from the source before an assessment team is able to perform a survey.

Each incident was verified as to location and duplicates in the database were eliminated. In a few cases, the location was corrected to place it on the pipeline or wellhead as confirmed by text data indicating site location.

Recent spill reports have significantly improved in quality and now contain an onsite Joint Investigation Report (prepared by government officials), response actions, photographs, and the response/cleanup closeout date. The spills reported herein show the timing, location and cause of the event, focusing on the potential impact of the event (s) on surrounding mangroves.

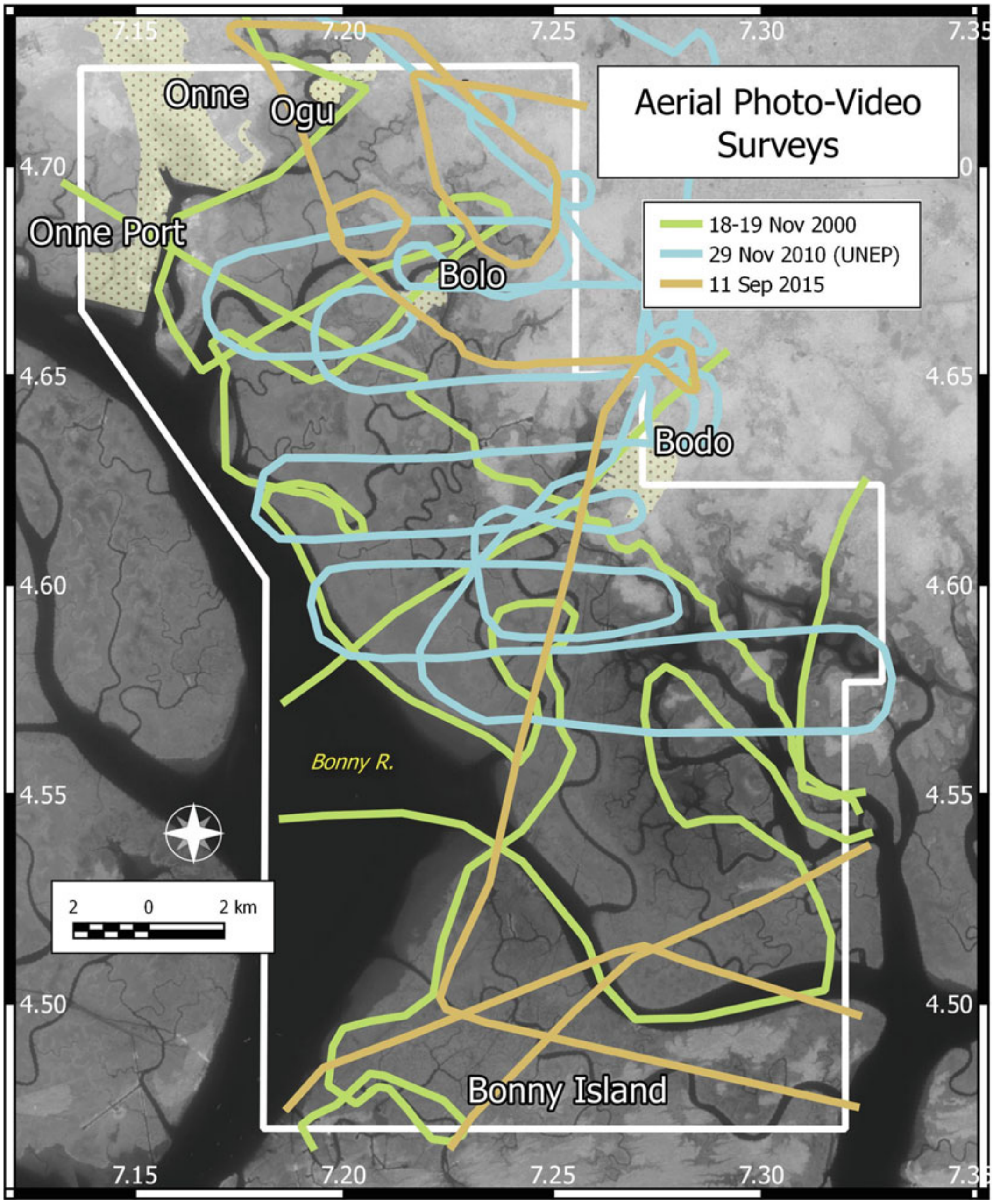

Fig. 13.4 Transit routes of primary low-altitude aerial video and photographic surveys that provided supporting information for this study

Table 13.4 Ground surveys used to assist assessment of mangrove loss. The author participated in the 2013 and 2015 surveys

Survey	Date	Stations	Data type
UNEP	20 Jun – 19 Nov 2010	16	Site oiling, chemistry
Rapid site assessment	9–13 Apr 2013	98	Surface/subsurface oiling, mangrove condition, site photographs
Pre-SCAT	1–8 May 2015	15	Surface/subsurface oiling, mangrove condition, samples taken, site photographs
SCAT	14–25 Aug 2015	35	Surface/subsurface oiling, mangrove condition, samples taken, site photographs

13.2.5 Habitat Classification

Habitats of the study area were manually digitized using QGIS software on a high-resolution monitor at an image scale of 1:500 or less. The following categories were classified.

- Mangrove Loss – dominated by dead mangrove remnants in former mangrove areas, confirmed by pre- and post-damage imagery. In some cases, the substrate has changed and no mangrove remnants remain, but former conditions were verified by imagery. Areas of infilled mangroves as

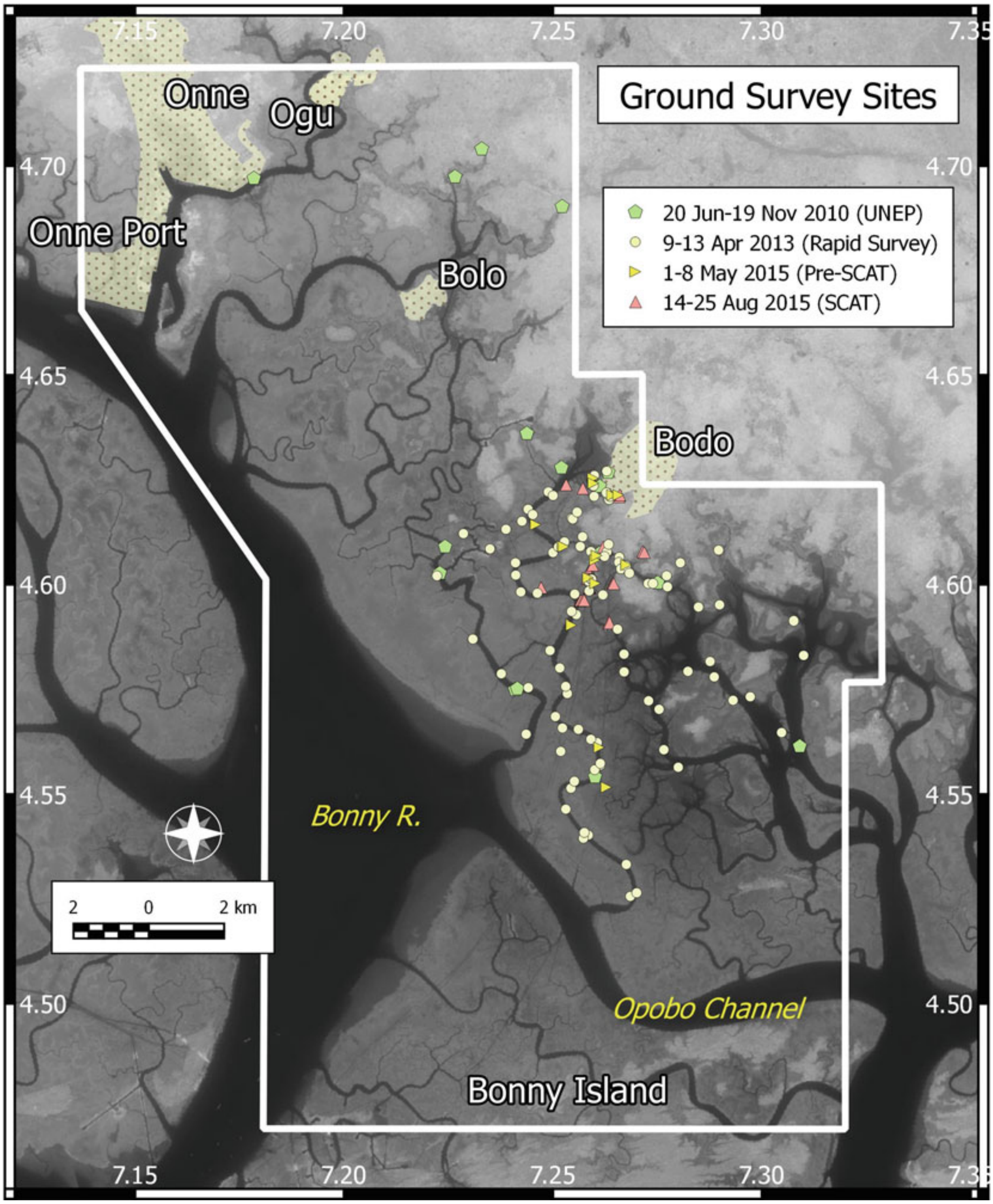

Fig. 13.5 Location of ground survey sites available to assist analysis of mangrove loss

for port or village development are purposely excluded. Within the study area, a single relatively small infilling in the easternmost part of the study area was found and excluded from the analysis.

- Mangrove No Loss – areas with little to no damage to mangrove plant coverage. Tidal flat areas within mangrove habitat having sparse, or in some cases, no plant coverage both during pre- and post-damage conditions, are considered part of this category. In other words, mangrove loss did not occur in areas where no mangroves previously existed.
- Pipeline Corridors – visibly cleared areas through mangrove habitat caused by placement of oil or gas pipelines.
- High Ground – supratidal islands within mangrove areas above the high-tide waterline, commonly dominated by palm trees.
- Villages and towns within and adjacent to mangrove habitat.
- Road – an unfinished sand road within the mangrove area,
- Illegal Refinery – area of illegal refining activity primarily on High Ground within the mangrove area.
- Water – channels and creeks in the mangrove areas. A mid-to-high tidal level is assumed such that intertidal flats

naturally devoid of mangroves are categorized as water and not counted as a former mangrove area. Images showing mid-to-high tidal levels are common and are used to confirm the high tide level,

Some small areas of mangrove loss in the study area are not measured in this study. These include pipeline corridors in former mangrove areas that are underwater during mid- to high tide, dredged slots made for bringing a drilling barge onsite and now contain a wellhead, and still visible seismic survey 'shot' lines, cut through the mangroves approximately 50 years ago for placing explosive charges and measuring subsurface geology for oil exploration. Oiled substrates without former mangroves, as along the shoreline fronting the town of Bodo, are also not included in this assessment.

The process used to define mangrove loss first starts with pre-loss conditions. Two primary pre-loss image sets were used: 3 December 2006 and 26 January 2009. Images prior to this were consulted to ensure that these were the latest before changes to mangrove condition occurred. Because each image does not cover the entire area or impacts occurred later, additional images from 2008 or later in 2009 and 2010 were used to define baseline conditions in certain areas. In the text, specific images are shown to support the analysis and indicate pre- and post-impact mangrove conditions.

From the base condition, mangrove loss was tracked using intermediary images (e.g. 2010, 2011) until 2013 at which time loss was digitized in QGIS using available high quality images. No images were available from 2012. The extent of loss after 2013 was visually determined by comparing 2013 to Google Earth images from 2015 or 2016 and oblique aerial photographs taken on 15 September 2015.

Determining mangrove loss when all mangroves are dead is straight forward to observe and digitize using the GIS. However, determining mangrove condition (alive versus dead) is complicated in cases where dead mangroves are interspersed among living mangroves and vice-versa. In most cases, areas of living mangroves were digitized such that the remaining areas (having mangrove stumps or dead mangroves) are then considered as mangrove loss. Because the dead areas are either specifically digitized, or the result of removing living mangroves, the mangrove loss category is considered to have a high degree of accuracy, estimated to be within 1% of the total area. Because of this methodology, it is more likely that areas characterized as 'Mangrove No Loss' have more dead areas than 'Mangrove Loss' areas have living mangroves. It is also recognized from ground surveys that even areas that appear totally dead from imagery may have some sparsely distributed surviving remnants.

In total, the resultant feature map of the study area was based on the digitizing of over 3800 polygons, each designated by category and having a GIS-calculated surface area. The 'Mangrove No Loss' category contains 1956 units and 1200 are defined as 'Mangrove Loss'. Figure 13.6 shows

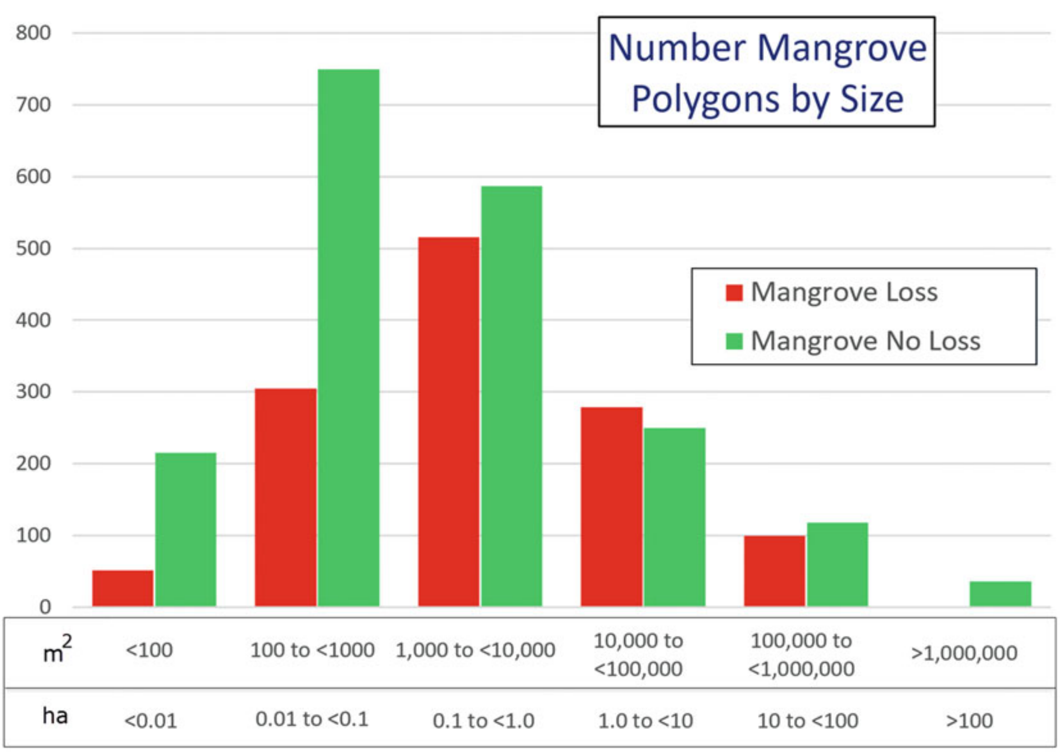

Fig. 13.6 Size of digitized polygons used to determine extent of living (mangrove no loss) and killed mangroves (mangrove loss)

the breakdown of these two categories by polygon size in hectares and square meters. Note there are several hundred areas less than 100 m^2 (e.g. 10 × 10 m) in size, an indication of the detail used during digitizing habitat features. As noted above, there are more polygons related to living mangroves ('Mangrove No Loss') because the focus was ensuring that living areas were excluded from being counted as having been killed.

13.3 Results

13.3.1 Spill Incidents

Records of 74 incidents were found for the study area extending from 1986 to June 2015. Incident locations are primarily along the SPDC pipelines but also include some wellheads (Fig. 13.7). There are likely gaps in the data as

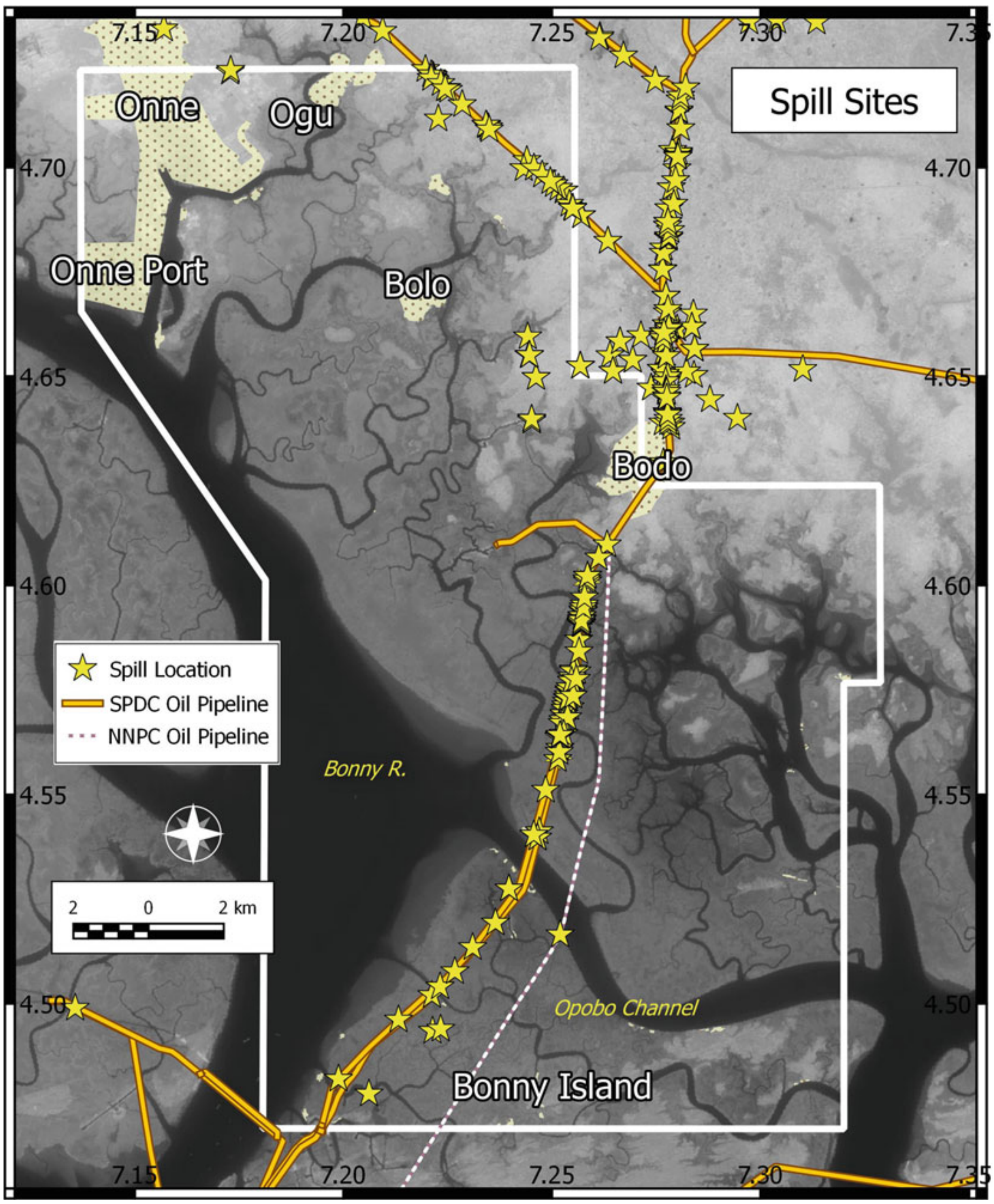

Fig. 13.7 Location of 74 spill incidents found to occur in the study area from 1986 to June 2015. Incidents primarily occur along the pipelines transporting crude oil from the north to Bonny Terminal in the south

Table 13.5 Number of spill records and cause 1986 to June 2015

Year	Incidents	Operational	Illegal	Other
1986–1997	13	1	10	2
1997–2004	0	0	0	0
2005–2007	4	4	0	0
2008	3	2	1	0
2009	2	2	0	0
2010	19	0	19	0
2011	12	0	12	0
2012	1	0	0	1
2013	9	0	9	0
2014	8	0	8	0
2015 (to June)	3	0	3	0

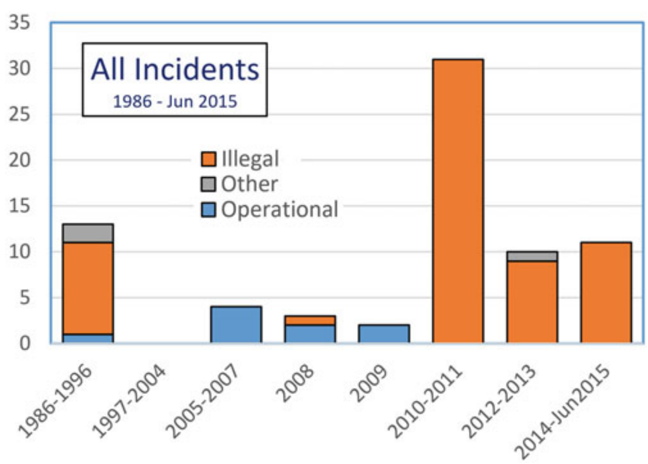

Fig. 13.8 Number of spill events and cause within the study area from 1986 to June 2015. Operational spills include those caused by pipeline or wellhead defects such as caused by corrosion. Illegal activities include those listed in the incident log as 'sabotage', 'illegal bunkering' and/or 'theft'. Other events are those listed as "other" or as 'currently unavailable'

there were no records of events from 1997 to 2004, and incidents in 2012 are abnormally low. Table 13.5 indicates that the vast majority (62) were from illegal activities.

The number of incidents within the study area jumped dramatically in 2010 reaching a high of 19 events. The years 2010–2011 showed 31 events after which the number of events dropped in half for the next 2-year periods, but remained much higher than pre-2010 conditions (Fig. 13.8).

13.3.2 Oil Theft and Illegal Refining

In the Niger Delta, there has been a systemic theft, processing and sale of stolen oil. A brief description of the process as it relates to environmental impacts follows. Images are available from The Atlantic (2013), among other sources.

Oil theft begins when crude oil is extracted from a pipeline actively transporting oil using a 'hot tap' during which the flow in the pipeline continues while a hole and valve are placed into the pipe (Fig. 13.9). The valve controls the pressure and outflow from the high-pressure/high-volume pipeline to a smaller hose for transport to an awaiting boat.

For efficiency, primary hot tapping sites are located close to a creek or channel for access by wooden fishing boats ~10 to 30m in length that will then transport the crude oil to an illegal refinery. The boats are unlined and commonly crude oil is uncontained within the vessel (i.e. open to the elements and not in storage containers). There is a high risk of oil spillage throughout the entire process.

Illegal refining sites are located almost exclusively on palm-dominated supratidal islands within mangrove areas. These sites have a channel for boat access but are above the high-tide water line so that the active refinery is not subject to intertidal flooding.

The operation at the site entails using a metal tank and high-temperature fire to boil off the oil's lighter components, which are then captured for transport and sale in the local community. Heavier oil components and residue are disposed in open pits and onto the surrounding land. Heavy smoke is visible during the distillation process due to the burning of crude oil as fuel to raise the temperature within the distillery tank.

On imagery, there are several identifying features of an illegal refinery site. The site's overall appearance is very black caused by asphaltic tar on the surface of the work site. Disposal pits give the site a mottled appearance. Adjacent mangroves are blackened by oil and likely to be dead, and lastly, an intertidal channel is visible leading to the site (Fig. 13.10). Other small sites In addition to the sites detected in this survey, there are likely to be others hidden under the tree canopy.

Between the time of the UNEP survey in 2010 and 2013, the Nigerian military formed a Joint Task Force (JTF) ostensibly to combat terrorism and oil theft. As observed during the 2013 and 2015 field surveys, the JTF keeps two large, multistory barges for personnel living quarters and several gunboats in the waters south of Bodo and in Opobo Channel. At the JTF barge site south of Bodo, the grounding and partial destruction of numerous fishing boats assumedly used for oil transport, and the lack of smoke from active sites at the time of imagery and surveys in 2013 and 2015, attests to their success in stopping many operations. It was reported that almost 2000 illegal refineries were destroyed in the Niger Delta in 2013, along with the capture of pumps,

Fig. 13.9 Example hot-tap valves from the 12″ Imo River 1 pipeline joint investigation report number 750226 (http://www.shell.com.ng/sustainability/environment/oil-spills.html)

drums of product and boats of various sizes (Information Nigeria 2013). In spite of this effort, there were still at least 11 illegal actions along SPDC pipelines between 2014 and June 2015, including one observed by the author during the August 2015 survey. As an example, the JTF broke up a very large processing center close to Port Harcourt (north of the study area) in September 2015 confiscating 5000 drums and four tanker trucks with illegally refined diesel and 21 large (>15 m) boats (Tori News 2015).

In total, this study found 217 illegal refinery sites having a total area of 115.2 ha. Locations are mostly in the center and northern sections of the study area (Fig. 13.11). Historically, illegal sites have expanded and combined. It is common for two or more small sites observed in 2010 to have merged into a single very large site in 2013.

13.3.3 Presence of Spilled Oil

Oiling of the channels and creeks of the area is widespread in spatial and temporal coverage, affecting both mangrove loss and their potential recovery. Surface water oiling in at least some portion of the study area is visible in all reviewed images and survey photographs from January 2009 to February 2016. Sheen and darker streaks are common. In most cases, surface oiling covers many kilometers of waterway. As an example, the extent of oil observed on surface waters on the 19 November 2009 image is shown in Fig. 13.12. Other examples are discussed later in the text.

13.3.4 Overview of Total Mangrove Loss

This study finds that 4414.6 ha of former mangrove areas were lost due to spilled oil and another 104.7 ha were lost due to corridors for pipeline placement. The measured value for mangrove loss is likely to be greater by a possible 1-to-2% (44–88 ha) due to digitizing limitations associated with dead areas interspersed within living mangroves. The locations of mangrove loss are shown on Fig. 13.13 and are discussed for each area (Bonny Island, Opobo Channel, Bonny River, Bodo West, Bodo East and Bolo) in the following sections.

13.3.5 Bonny Island Mangrove Loss

All of Bonny Island was reviewed for mangrove loss. Results show that losses are concentrated on the northeastern part of the island along the pipeline corridors (Fig. 13.14). The area of mangrove loss is shown in detail in Fig. 13.15, including the locations of 13 spill events that occurred in the area between 1997 and June 2015 (Table 13.6).

As seen on images, the first large-scale loss of mangroves occurred between 29 January 2008 and 19 November 2009 (Fig. 13.16). The spill event of 2 October 2008, recorded as caused by illegal activity, is located in the center of the mangrove loss area and is the most likely cause of damage. Comparing the loss from this spill to the total 2015 loss in the entire Bonny Island area indicates that approximately 80% is attributable to the October 2008 event. The remaining

Fig. 13.10 Presence of illegal refineries ('A' and 'B', 4.593 N, 7.270 W) illustrated by blackened and mottled appearance on area above intertidal waters; image from 18 December 2013 and aerial photo by J. Kallnischkies on 29 November 2010

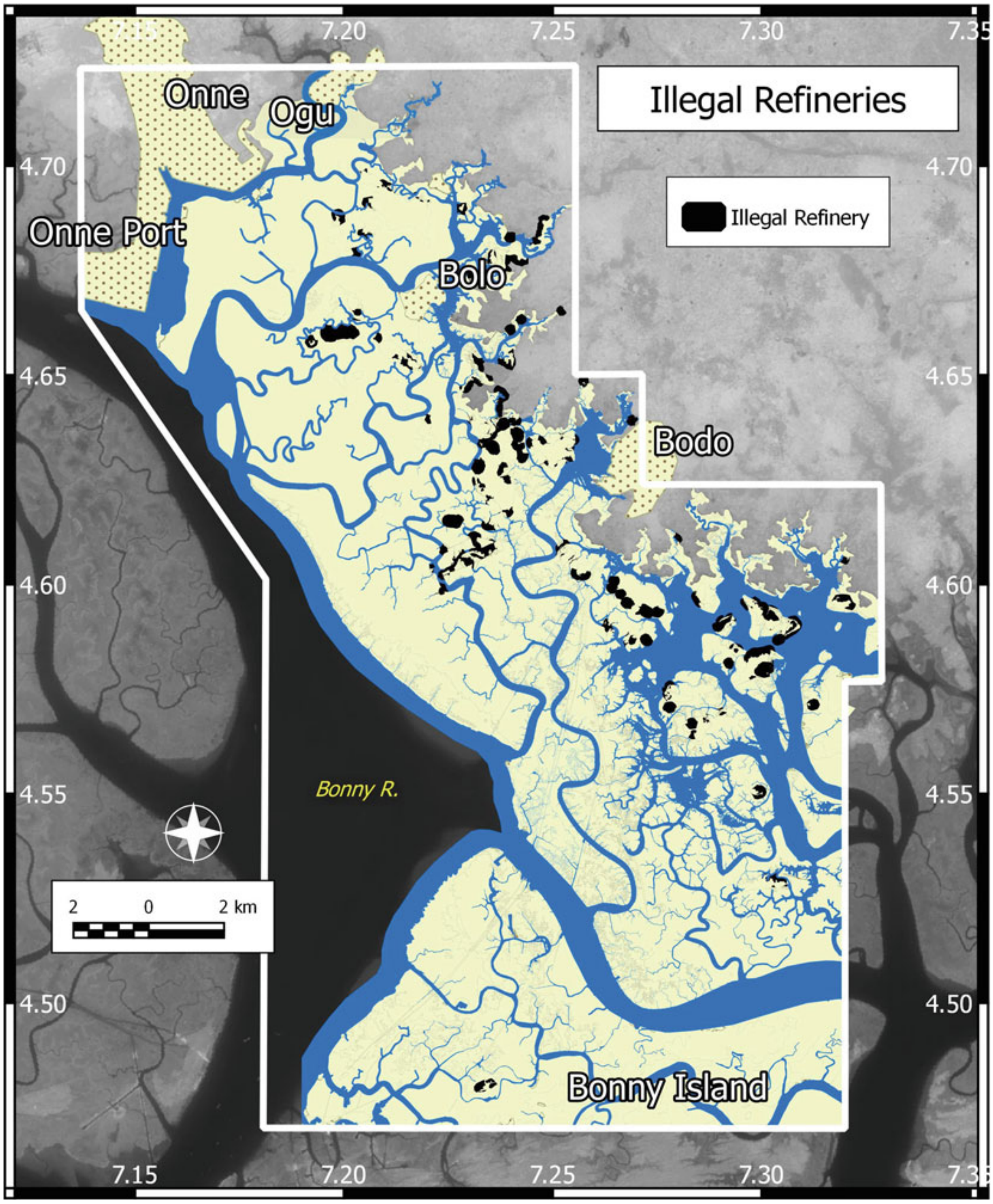

Fig. 13.11 Location of 217 refinery sites found in the study area

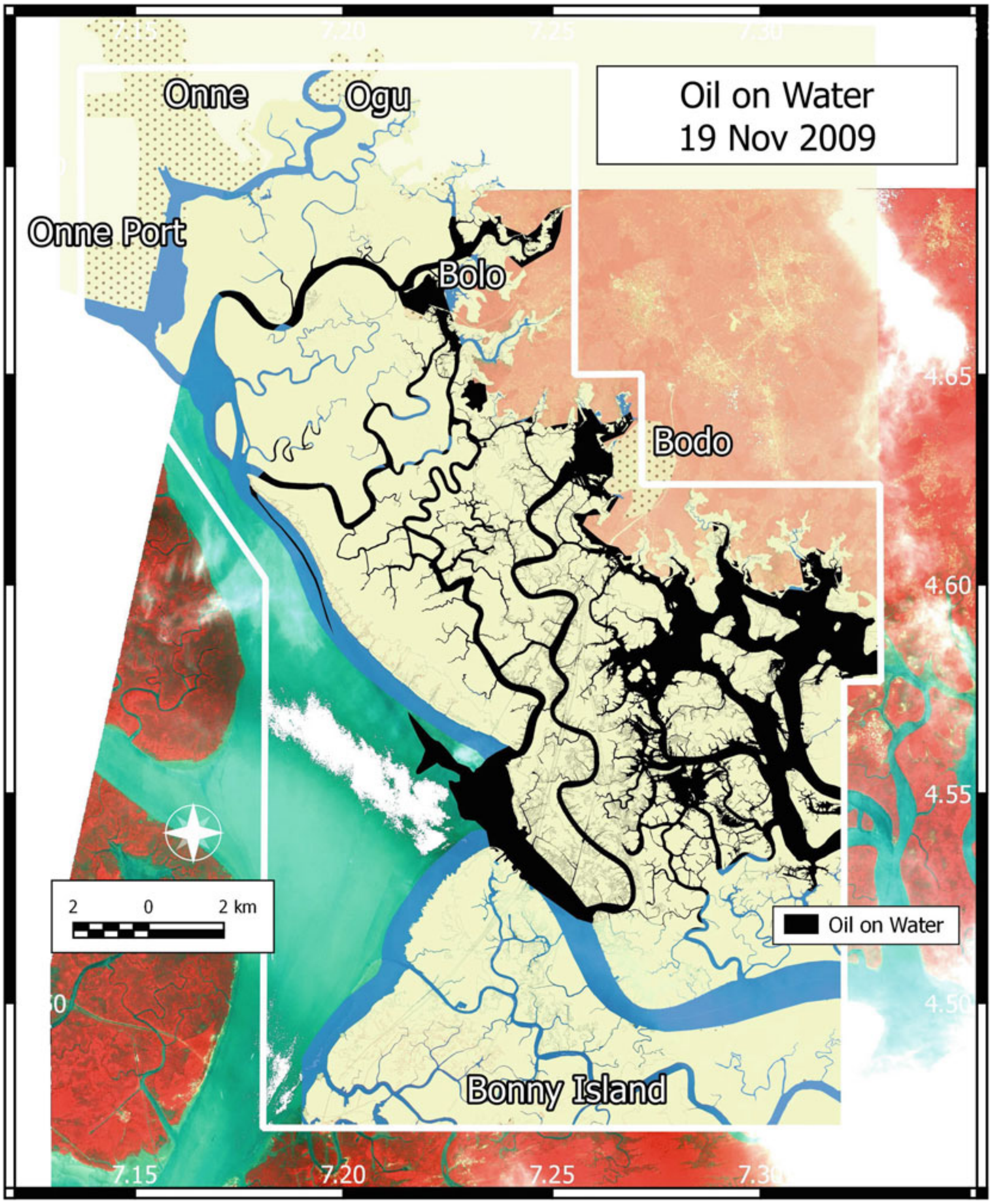

Fig. 13.12 Oiling visible on surface waters on 19 November 2009. The false color SPOT image used for the analysis is shown as background

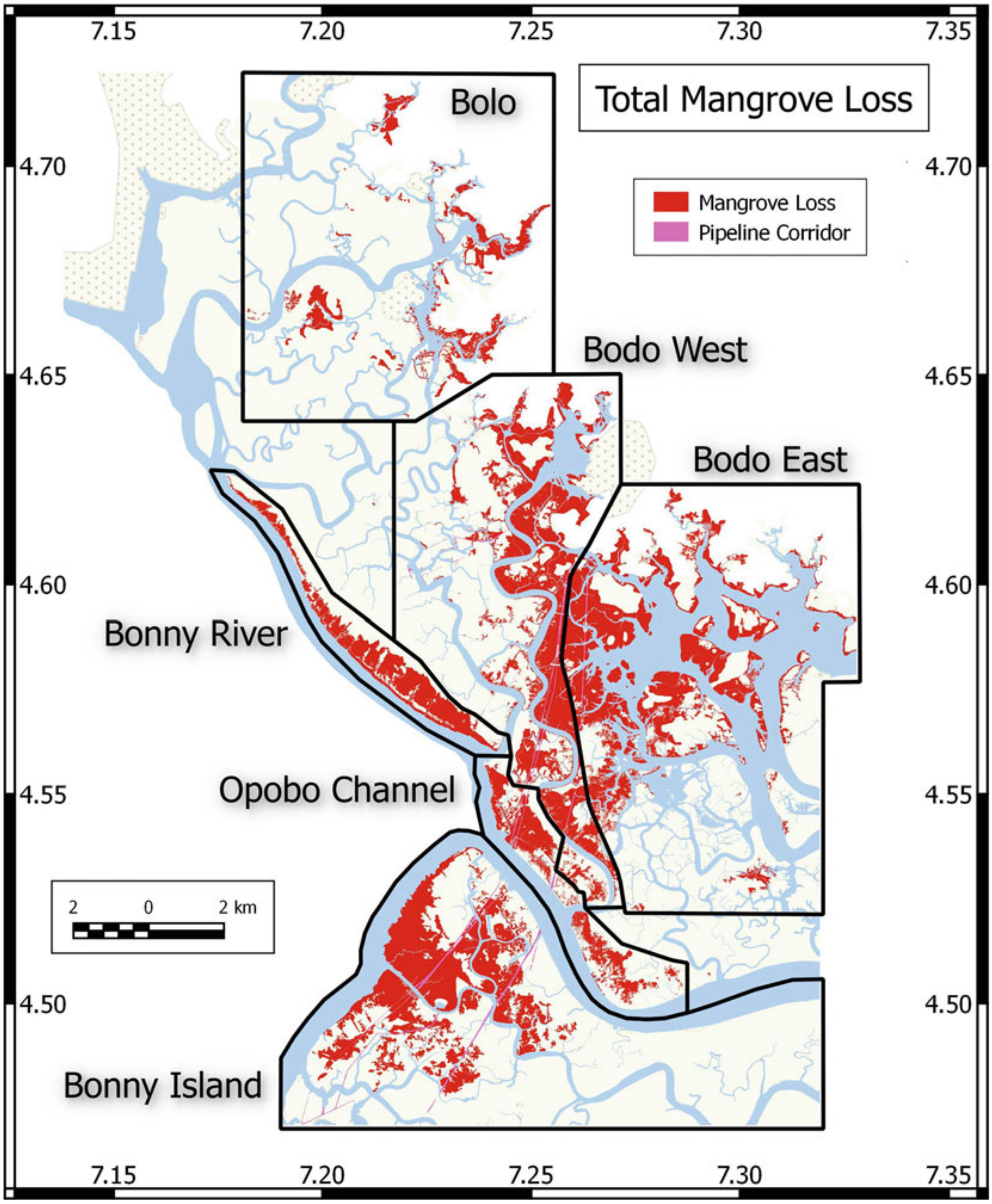

Fig. 13.13 Overview of measured categories of 'Mangrove Loss' and loss due to a 'Pipeline Corridor'. Each of the indicated six areas is shown in detail in the following text

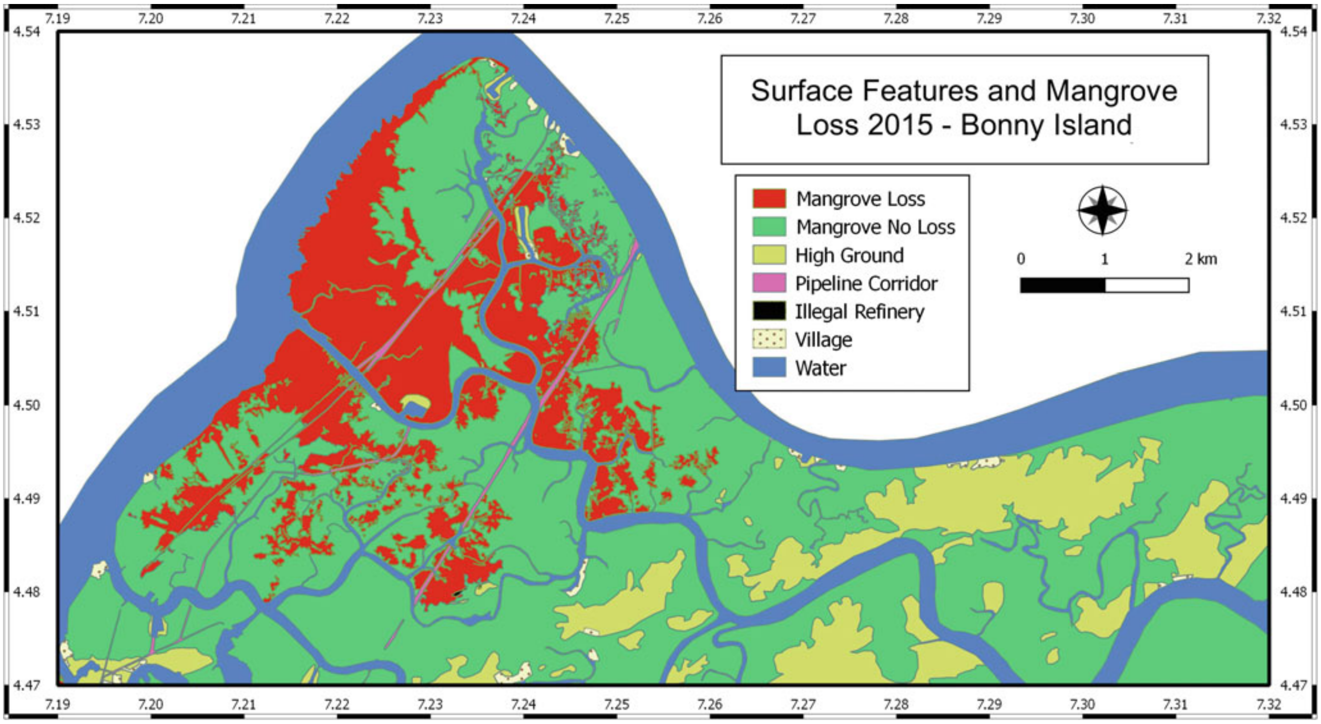

Fig. 13.14 Results of image comparisons to yield the 2015 condition of mangrove habitat and other surface features in the Bonny Island area

mangrove loss in the Bonny Island area is likely from the other spill events listed in Table 13.6.

Overview photographs of the area from 15 September 2015 provide an indication of mangrove loss (Fig. 13.17). Arrows on each photograph indicate mangroves that were alive in 2013 but are dead in 2015, showing that mangrove losses continued past 2013

Illegal refineries are not common in the Bonny Island area. Four were found in higher ground near the pipeline corridor in the south-central part of the study area (Fig. 13.18).

In summary, the majority of damage to the Bonny Island mangroves can be traced to losses following an oil spill on 2 October 2008. Mangrove losses have increased since then, including between 18 December 2013 and 15 September 2015. The total loss of mangroves, including that from pipeline corridors, is shown in Table 13.7.

13.3.6 Opobo Channel Mangrove Loss

Opobo Channel is an intertidal channel to the north of Bonny Island connecting the Bonny River to the Imo River. It contains three oil pipeline crossings and two wellheads in excavated slots along the north and south sides of the channel. The interior of several areas consists of open flats historically devoid of mangroves and are not included as measured mangrove loss. The review of imagery and aerial photos shows major mangrove losses occurred adjacent to the northern two oil pipelines and from the south bank of the Kpador Channel extending to interior mangrove areas to the south (Fig. 13.19).

In the northern area, marked as ‘A’ in Fig. 13.19, there are four recorded spills in the center of mangrove losses, two in 2009 and two in 2010 (Table 13.8).

The time sequence of mangrove loss is shown in Fig. 13.20. The December 1996 image shows no observable impact on mangroves. In August 2009, severe impacts and apparently recent tracks from vehicles are evident, likely caused by response to the spill incident in May 2009. There were no images available between 1996 and 2009, nor were there previous oil spills other than from May 2009. Images from November 2009 and February 2010 show unchanged conditions. However, additional mangrove loss occurred between February 2010 and December 2013, likely influenced by two spills recorded in May and August 2010 (Table 13.8).

The 2013 image also shows tracks from earth-moving equipment over much of the area as well as a conversion of

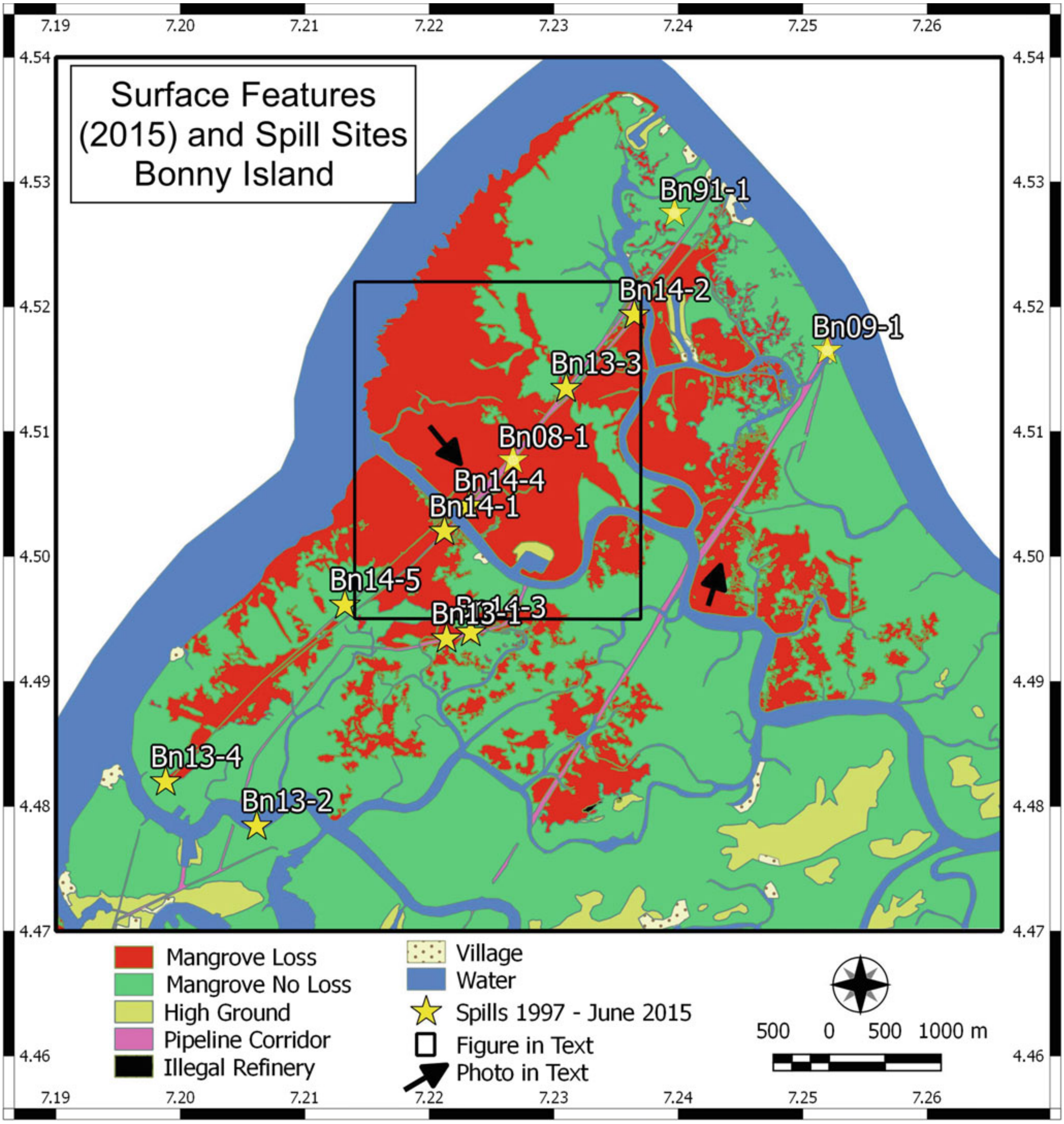

Fig. 13.15 Western portion of the Bonny Island area showing mangrove loss, oil spill sites and other surface features. The *boxed* area is further illustrated in Fig. 13.16. Spill sites (Bn13-1 etc.) are listed in Table 13.6

Table 13.6 Oil spill sites in the Bonny Island area, 1997 to June 2015. Locations are shown on Fig. 13.15

Site	Date	Cause	Latitude	Longitude
Bn97-1	10-Nov-97	Illegal activity	4.5275	7.2397
Bn05-1	23-Dec-05	Illegal activity	4.5275	7.2397
Bn08-1	2-Oct-08	Illegal activity	4.5077	7.2672
Bn09-1	16-Jul-09	Operational	4.5165	7.2520
Bn13-1	4-Apr-13	Operational	4.4934	7.2214
Bn13-2	17-Jul-13	Illegal activity	4.5275	7.2399
Bn13-3	27-Jul-13	Illegal activity	4.5134	7.2310
Bn13-4	19-Sep-13	Illegal activity	4.4820	7.1988
Bn13-5	23-Sep-13	Illegal activity	4.5020	7.2212
Bn14-1	16-Mar-14	Operational	4.5193	7.2365
Bn14-2	15-Aug-14	Operational	4.4939	7.2233
Bn14-3	22-Nov-14	Illegal activity	4.5077	7.2268
Bn14-4	24-Nov-14	Illegal activity	4.5041	7.2232

the former mangrove habitat to compact silt and clay devoid of mangrove remnants. After December 2013, four Google Earth images available to February 2016 essentially illustrate the same mangrove condition as in 2013. The influence of the 2009 and 2010 spills appears localized to the northern part of Opobo Channel, causing approximately 25% of the total damage to the area.

Opobo Channel area ‘B’ (in Fig. 13.19) is along the southern part of the channel and shows a later appearance of initial mangrove loss. Some minor impact occurred at the upper reaches of small tidal channels by February 2010, but the major change occurs between February 2010 and December 2013 (Fig. 13.21). Oiling seems likely to have originated from a combination of sources including the spill sites previously mentioned at area ‘A’, from Bonny Island, and from oil coming down the Kpador Channel from numerous spill sites in the north, discussed later as part of Bodo West. Floating oil then likely entered the small creeks of this area and impacted the interior mangroves.

The extent of mangrove loss is visually evident by comparing aerial photographs from 2000 and 2015 from the shoreline northwest of Opobo Channel area ‘A’ (Fig. 13.22).

Table 13.9 summarizes the extent of mangrove loss for the Opobo Channel area. Losses in the north are likely due to 2009 and 2010 spill incidents that resulted in large-scale losses observed in August 2009 and which increased further between 2010 and 2013. In the southern part of the area, losses cannot be tied to a specific spill event and occurred later (after February 2010). Floating oil from other areas, particularly Bodo West via the Kpador Channel seems plausible. No illegal refinery sites are found in the area due to its low-lying nature, i.e. flooded during high tides.

13.3.7 Bonny River Mangrove Losses

This area extends to the north of Bonny Island and Opobo channel along the eastern shore of the Bonny River (Fig. 13.23). The pattern of losses shows a strong decrease to the north, indicating that the origin of damages was to the south and is related to spill events discussed previously on Bonny Island and along the pipelines of Opobo Channel. The area consists of low-lying silt and clay sediments that rise gradually to a higher interior ridge.

The Bonny River area shoreline was historically covered entirely by mangroves. The sequence of mangrove loss is shown in Fig. 13.24. The first mangrove losses, varying between widths of 50 and 100 m, occurred along the outer fringe facing the Bonny River between January 2008 and June 2009. (The 8 June 2009 image is not presented but is essentially the same as November 2009). No additional losses were observed on a later image from 7 February 2010. Major additional losses then occurred by 2013 extending the zone of dead mangroves 800 m landward from the coast. Additional Google Earth images from January 2014 and February 2016 indicate no further obvious losses to mangroves after 2013.

In summary, the extent (greater in the south) and timing of the first losses is related to spills that occurred in areas to the south, including those in October 2008 and July 2009 on Bonny Island and along the north shore of Opobo Channel between May 2009 and August 2010. After 2010, losses cannot be tied to a specific event, but may have included oiling coming from nearby Opobo Channel or Bonny Island. Table 13.10 provides the summary of measured mangrove losses in the Bonny River area. Illegal refineries are not present as the area is low-lying and lacks access channels and proximity to an oil source.

13.3.8 Bodo West Mangrove Losses

The area around and to the south of Bodo is divided by an incomplete road into two areas, east and west. The road was partially constructed using dredged sand but never finished. The Bodo West area extends south to the Opobo Channel and Bonny River areas (Fig. 13.25). Transport between Bodo East and Bodo West is limited to a 26 m channel in the north and a 12 m channel in the south. The northern channel has a metal barge placed across it and preventing large watercraft from passing from one side to the other. Road construction destroyed mangroves within its path, but as there is water circulation from each side, appears not to have caused additional damage to mangrove habitat. Because

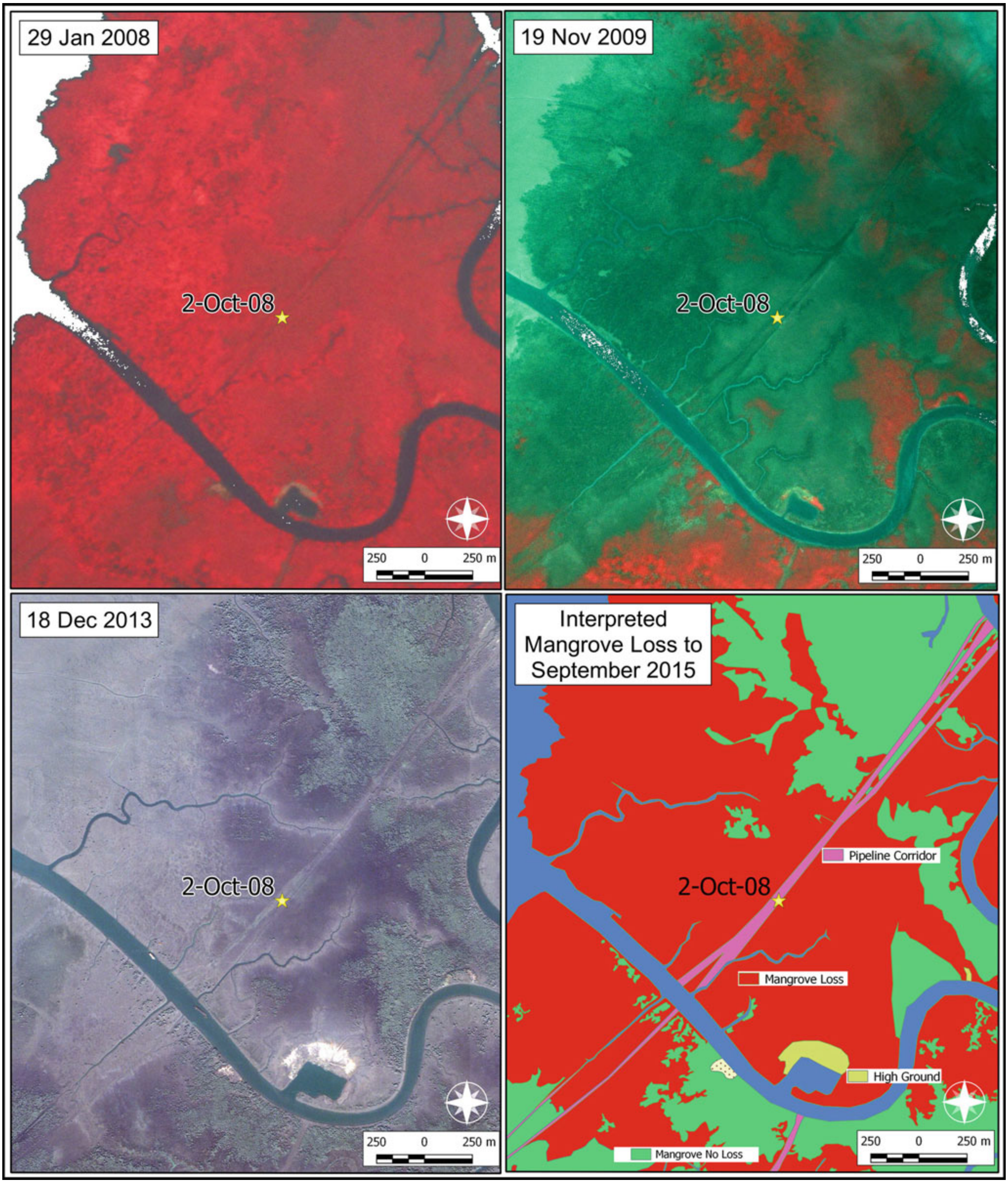

Fig. 13.16 Historic sequence at the 2 October 2008 spill site (located in the *boxed* area of Fig. 13.15) showing false color SPOT5 satellite imagery from 2008 to 2009 (before and after the spill), Google Earth imagery from 2013 and interpreted results of mangrove loss extended to September 2015 using results of the 2015 aerial survey

Fig. 13.17 Aerial photographs from 15 September 2015 of two sites in the Bonny study area showing the condition of former mangrove habitat. See Fig. 13.15 for location. *Arrows* indicate areas were alive in the image from 18 Dec 2013 but are dead in 2015

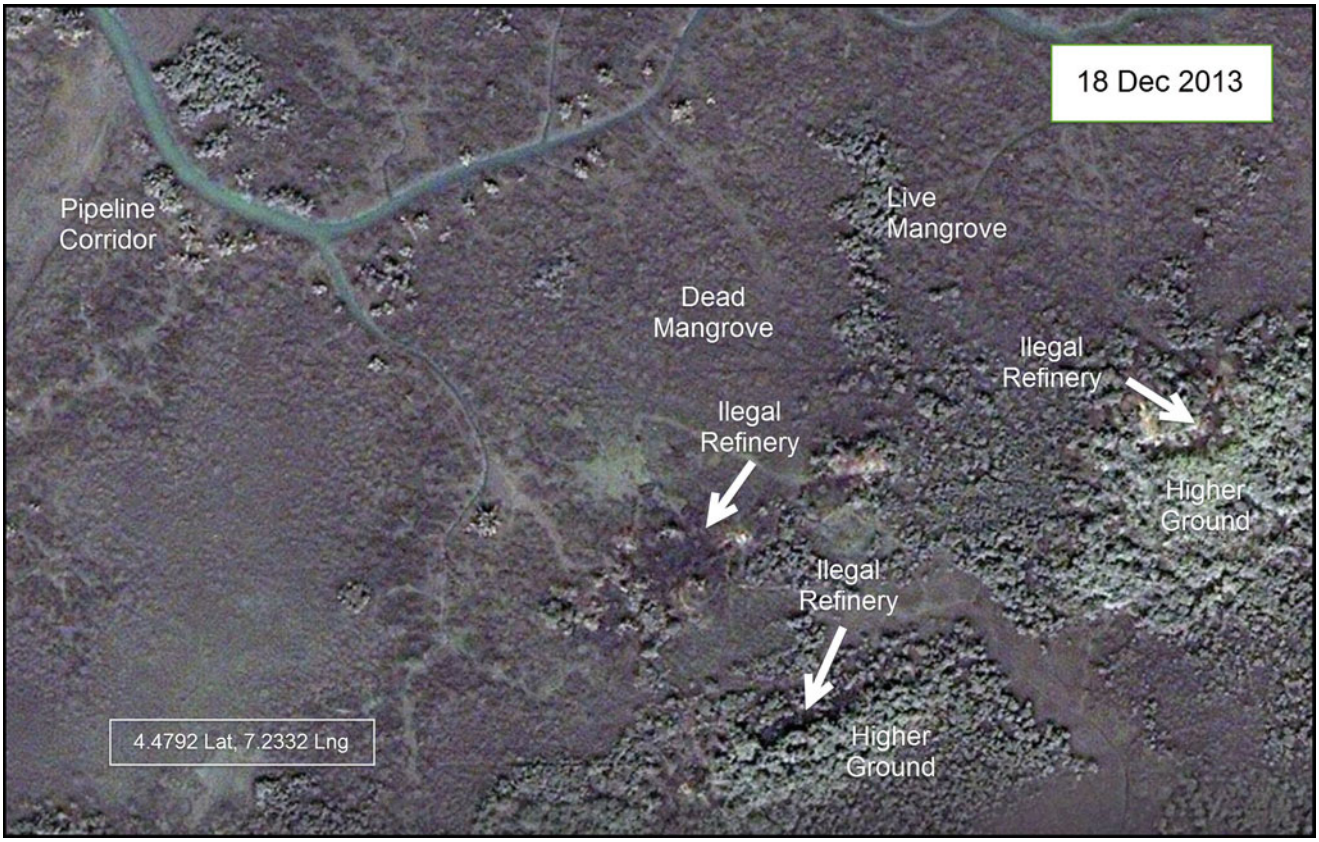

Fig. 13.18 Illegal refineries and associated habitat condition on Bonny Island, 18 Dec 2013

Table 13.7 Measured mangrove losses and illegal refineries on Bonny Island, 2008–2015

Component	Hectares	Number
Mangrove loss	1058.2	
Pipeline corridor	58.2	
Total mangrove loss	1116.4	
Illegal refineries	0.8	4

there is limited water circulation from one side to the other, there is a different oil-impact history on each side.

Bodo West has ten wellheads connected via inactive pipelines to a central gathering flow station and then to a main flow station/oil manifold in the north-central part of the area. This part of the system is out-of-service although UNEP (2011) reports that it has not been decommissioned. Two pipelines (24-in. and 28-in.) cross the area north-to-south and actively transport crude to Bonny Terminal.

The first mangrove losses occurred in 2009 and are attributable to 2008 operational leaks in areas 'A' and 'B' on Fig. 13.25. A summary of spill incidents from 1986 to June 2015 are shown for the Bodo West area in Table 13.11. Prior to 2010, recorded incidents were uncommon (ten during the period 1986–2010).

Figure 13.26 shows the historic sequence and location of spill incidents from 2008 to June 2015. From 2010 onwards, discharges from illegal activities became numerous and prevalent. Pipeline tapping to provide crude oil for the illegal refineries was common in areas of access to the Kpador Channel, the primary waterway leading to Bodo. A total of 87 illegal refinery sites were detected in the Bodo West area.

The operational spills of 2008, located within Bodo West areas 'A' and 'B', initiated mangrove losses in the area. Area 'A' is shown in Fig. 13.27. The loss is attributable to an operational leak that occurred in late 2008. There is debate on how long it took to stop the leak but it is likely that discharge from the leak continued for many weeks if not months (e.g. Guardian 2011; AI-CEHRD 2011).

The satellite image from 26 January 2009 shows visible oiling of sediments and waters in the area of the 2008 pipeline break (Fig. 13.28). Additional imagery is illustrated in AI-CEHRD (2011).

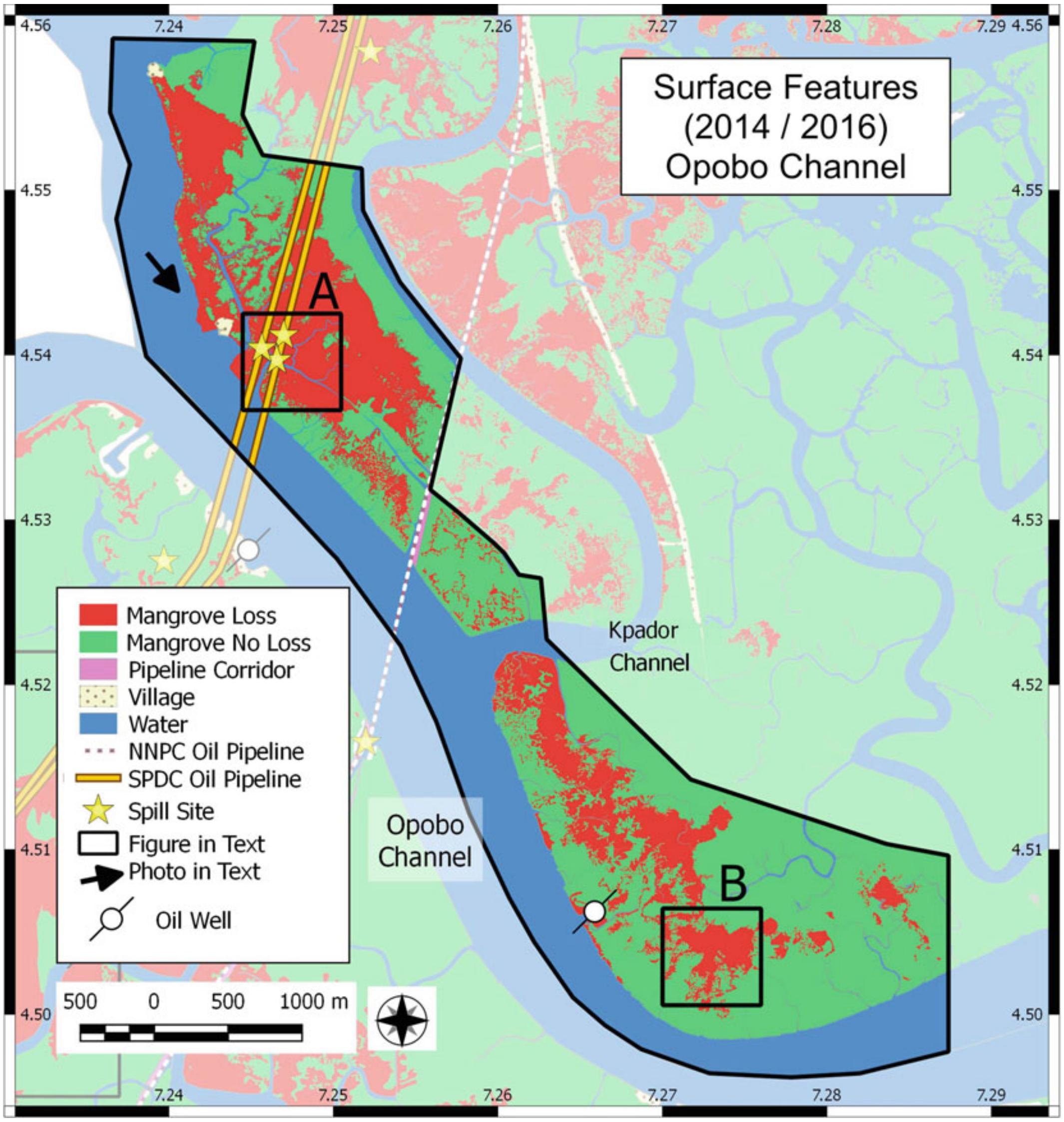

Fig. 13.19 Mangrove condition and surface features of the Opobo Channel area

Table 13.8 Oil spill sites in the Opobo Channel area, 1997 to June 2015

Date	Cause	Latitude	Longitude
8-May-09	Illegal activity	4.5412	7.2470
16-Oct-09	Operational	4.5397	7.2466
18-May-10	Illegal activity	4.5397	7.2466
5-Aug-10	Illegal activity	4.5404	7.2456

A comparison of the same area in 2000 (before spills) and 2013 (after multiple spills) illustrates the incurred extent of mangrove loss (Fig. 13.29).

Another operational pipeline discharge occurred in 2008 in Bodo West area 'B'. Like that illustrated previously for Bonny Island, the difference in mangrove coverage before and after is striking and centered at the spill site (Fig. 13.30). The spill occurred on 7 December 2008. The image from January 2008 shows no impact (before the spill) while that from August 2009 shows a large impact area centered close to the leak location. A post-impact ground photograph of the area is shown in Fig. 13.31.

In the Bodo West area, most mangrove loss is attributable to the 2008 spills. By 2009, by far the majority of mangrove loss seen in 2013 had already occurred. However, if mangroves did survive the first wave of impacts in 2008/2009, further losses occurred in response to illegal pipeline tapping and resulting oil spillage.

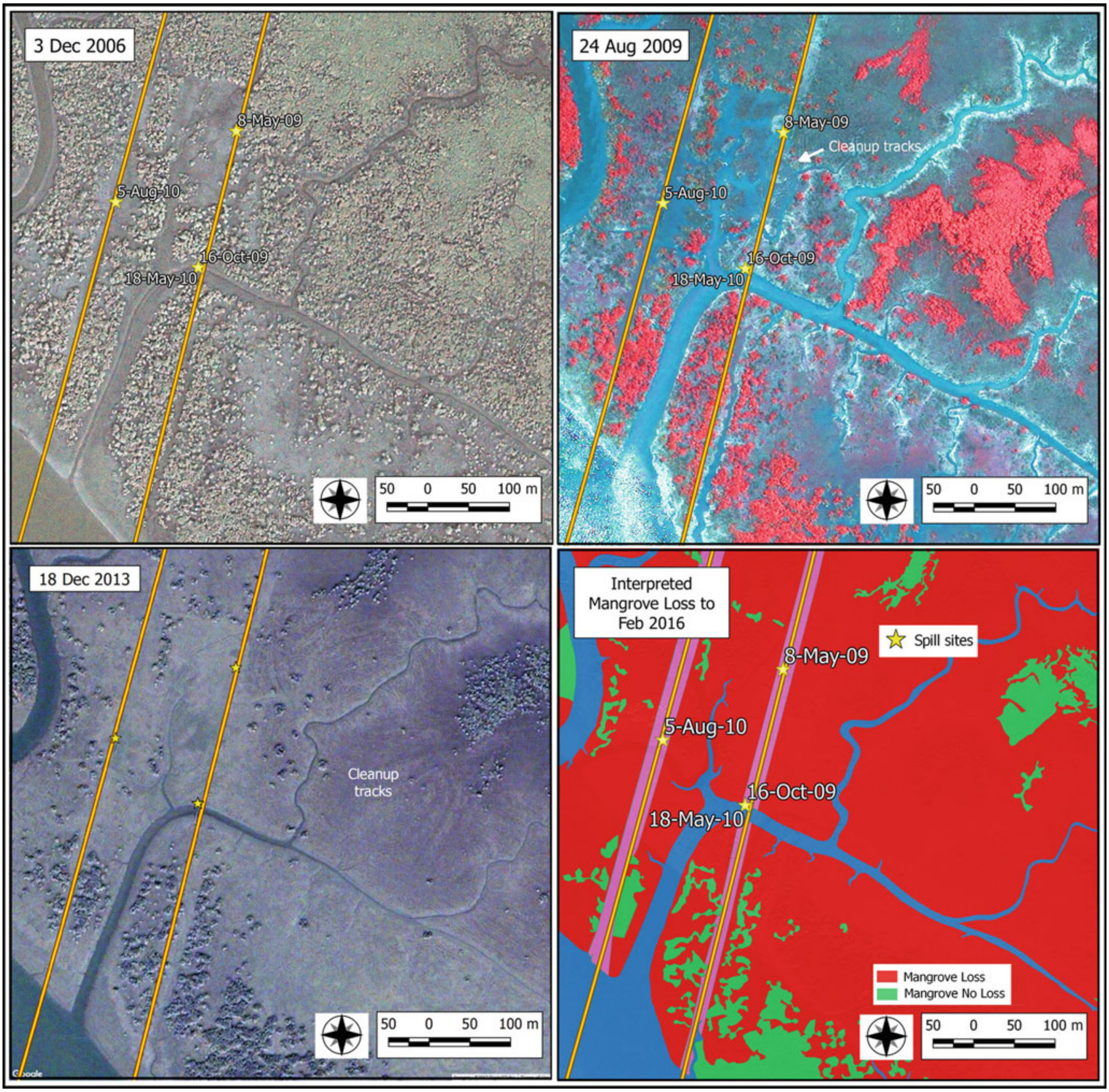

Fig. 13.20 Time sequence of imagery from Opobo Channel area 'A' (in Fig. 13.19) showing major impacts in August 2009 with additional losses noted in 2013. Google Earth imagery to February 2016 shows essentially the same conditions as in 2013, so the interpretation of mangrove loss is extended to that date

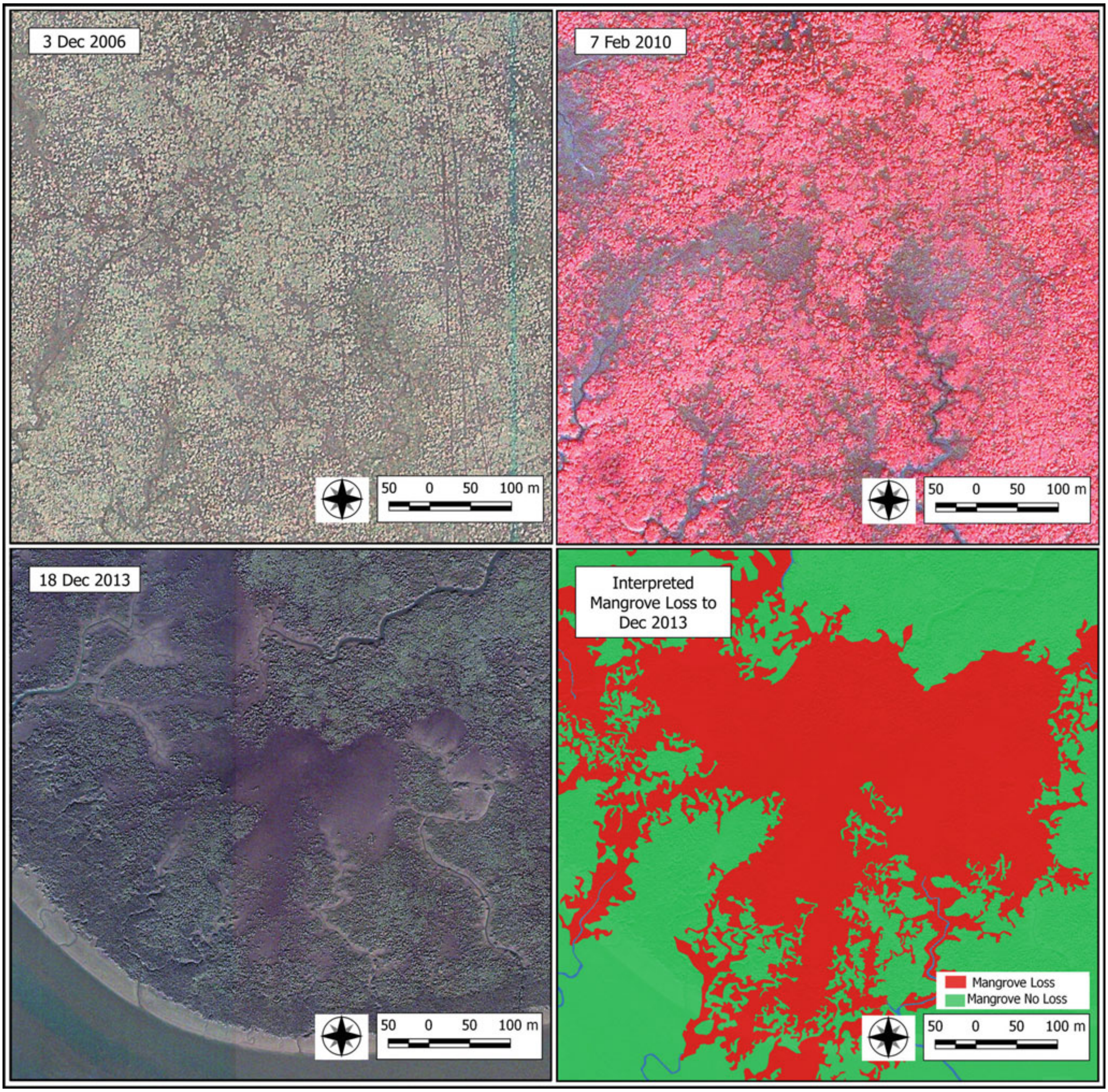

Fig. 13.21 Sequence of mangrove losses at Opobo Channel area 'B' in Fig. 13.19, showing some minor impact by February 2010 and major loss by December 2013

Fig. 13.22 Aerial photographs showing change in mangrove cover from 2000 to 2015. Site location is shown in Fig. 13.19. A coastal village and *arrows* indicate the same locations on each photograph

Table 13.9 Measured mangrove losses and illegal refineries in the Opobo Channel area, 2006 to 2013/2015 depending on image coverage

Component	Hectares	Number
Mangrove loss	280.2	
Pipeline corridor	9.3	
Total loss	289.5	
Illegal refineries	0	0

An example is provided by Bodo West area 'C' (Fig. 13.32). By 2009, most of the mangroves are killed, but some areas as along the western-most pipeline initially survived (top right image) but were subsequently lost by 2013. Imagery shows that the additional loss occurred between 7 Feb 2010 and 8 January 2011. A total of 15 spills (14 illegal, 1 unknown) are reported in this particular area between 2010 and June 2015. Two spills occurred in 2010,

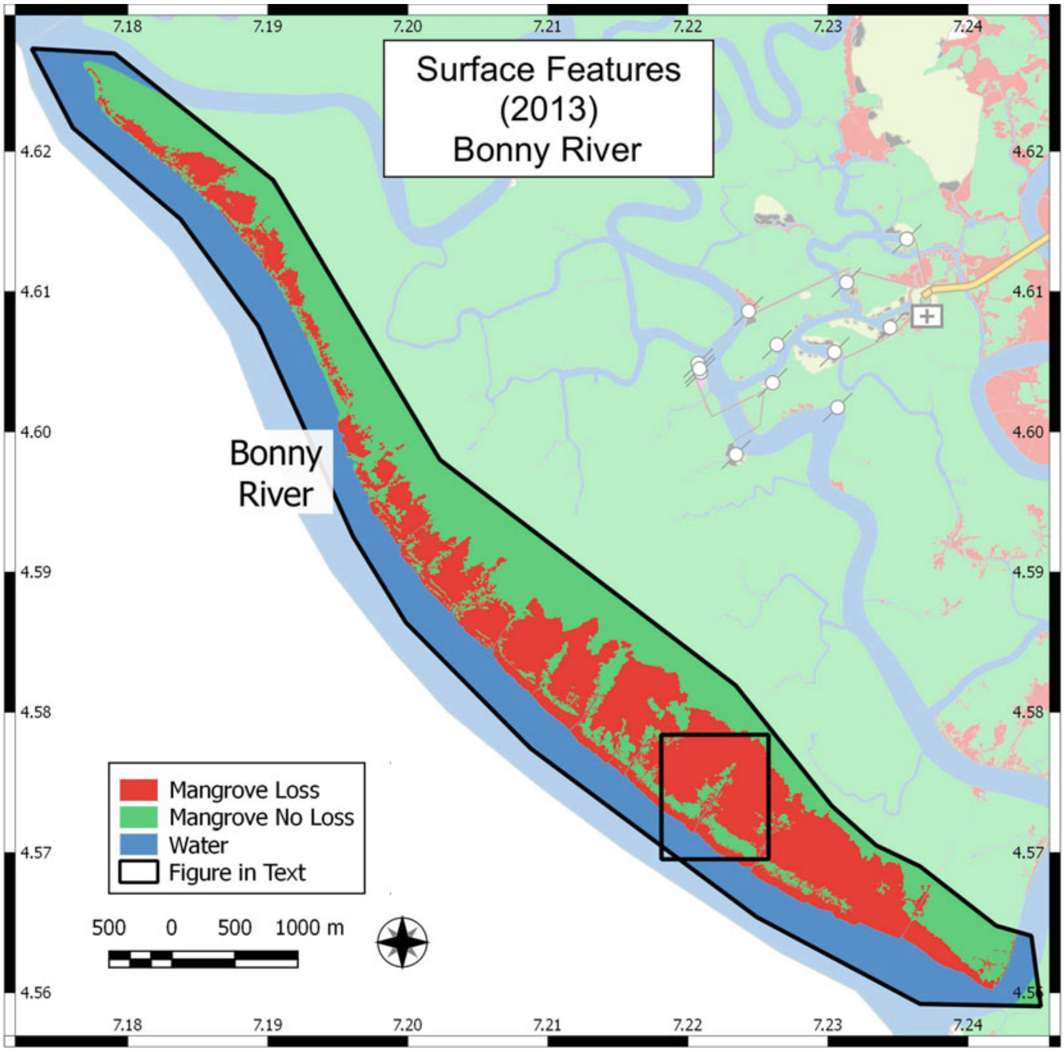

Fig. 13.23 Condition of mangroves in the Bonny River area of study in 2013

one of which is in the specific area where mangroves were lost between 2010 and 2011. No spills are reported in this area prior to 2010.

Bodo West area 'D' similarly shows major impacts originating in 2008 but worsening between 2010 and 2011, followed by additional losses by 2013 (Fig. 13.33). Oil is visible on the water in each image (2010, 2011 and 2013) indicating that the additional losses are from sources causing the chronic oiling of surface waters and not the two major spills of 2008.

In November 2010, the UNEP overflight captured extensive and heavy oil concentrations on the water in Bodo West area 'D' (Fig. 13.34).

In conclusion, major oiling and subsequent mangrove loss in the Bodo West area occurred because of two pipeline leaks caused by corrosion in late 2008. No leaks were reported for the area in 2009, after which numerous spill events almost exclusively caused by illegal activities began in 2010 and continuing at least until 2015. As noted in 2013 imagery, the events between 2010 and 2013 caused some additional mangrove losses over that observed from the 2008 spills. The oil observed in the water after 2009 was likely due to the combination of pipeline leaks at the source of illegal pipeline taps as well as from illegal refining activity and associated losses during the illegal transport of crude and refined product by

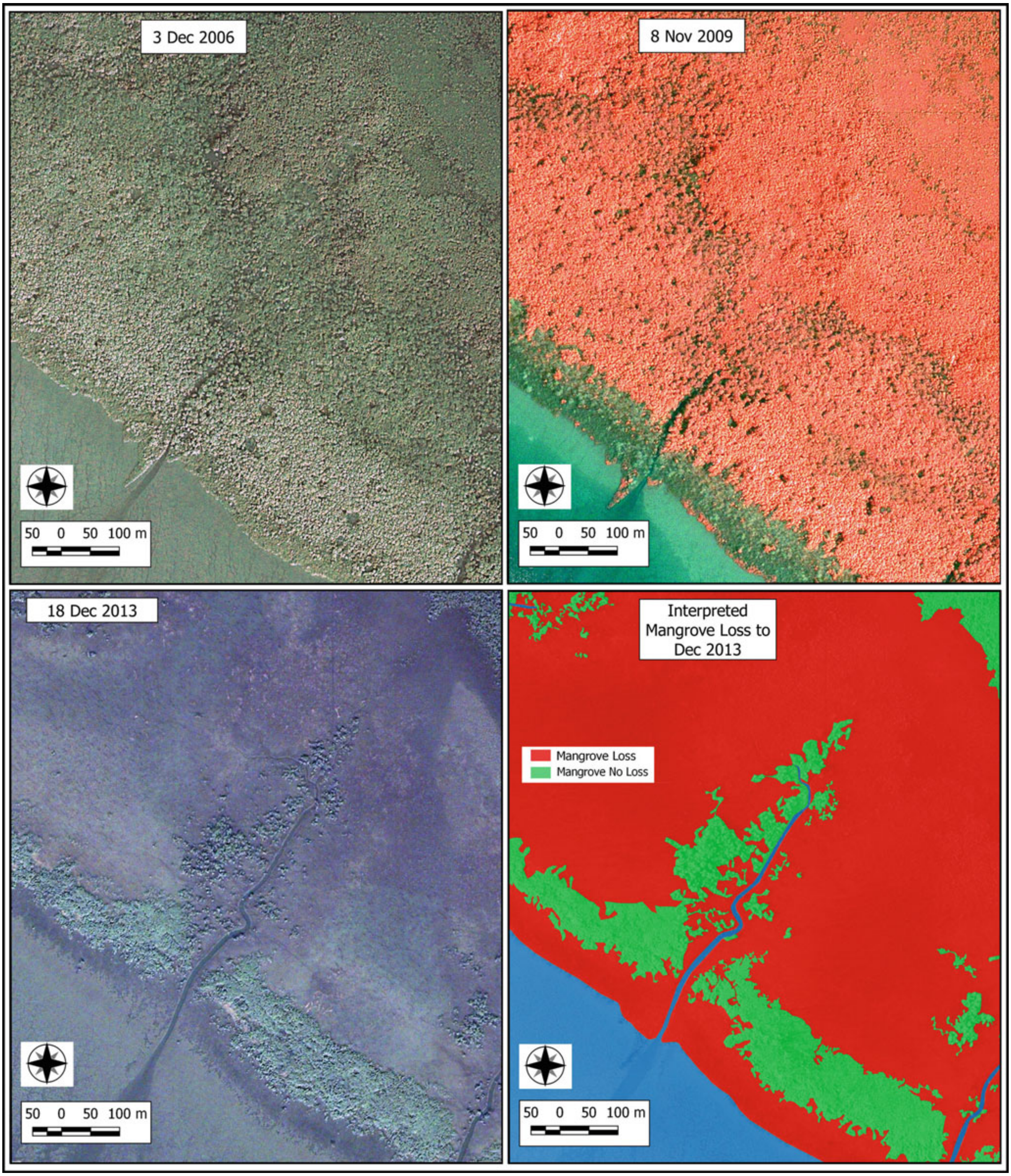

Fig. 13.24 Bonny River sequence of mangrove losses from 2006 to 2013. Other imagery shows that impacts had occurred along the outer fringe by June 2009 and was the same in February 2010. Therefore, the extensive losses shown in 2013 occurred after February 2010

Table 13.10 Measured mangrove losses and illegal refineries in the Bonny River area, 2008–2013. Losses from pipeline corridors are related to placement of a gas line

Component	Hectares	Number
Mangrove loss	464.9	
Pipeline corridor	1.7	
Total loss	466.6	
Illegal refineries	0	0

boats to and from the refining site. The summary of mangrove loss and illegal refineries is shown in Table 13.12.

13.3.9 Bodo East Area Mangrove Loss

Bodo East is separated from Bodo West by a narrow 26 m channel in the north and a smaller channel to the south. Oil

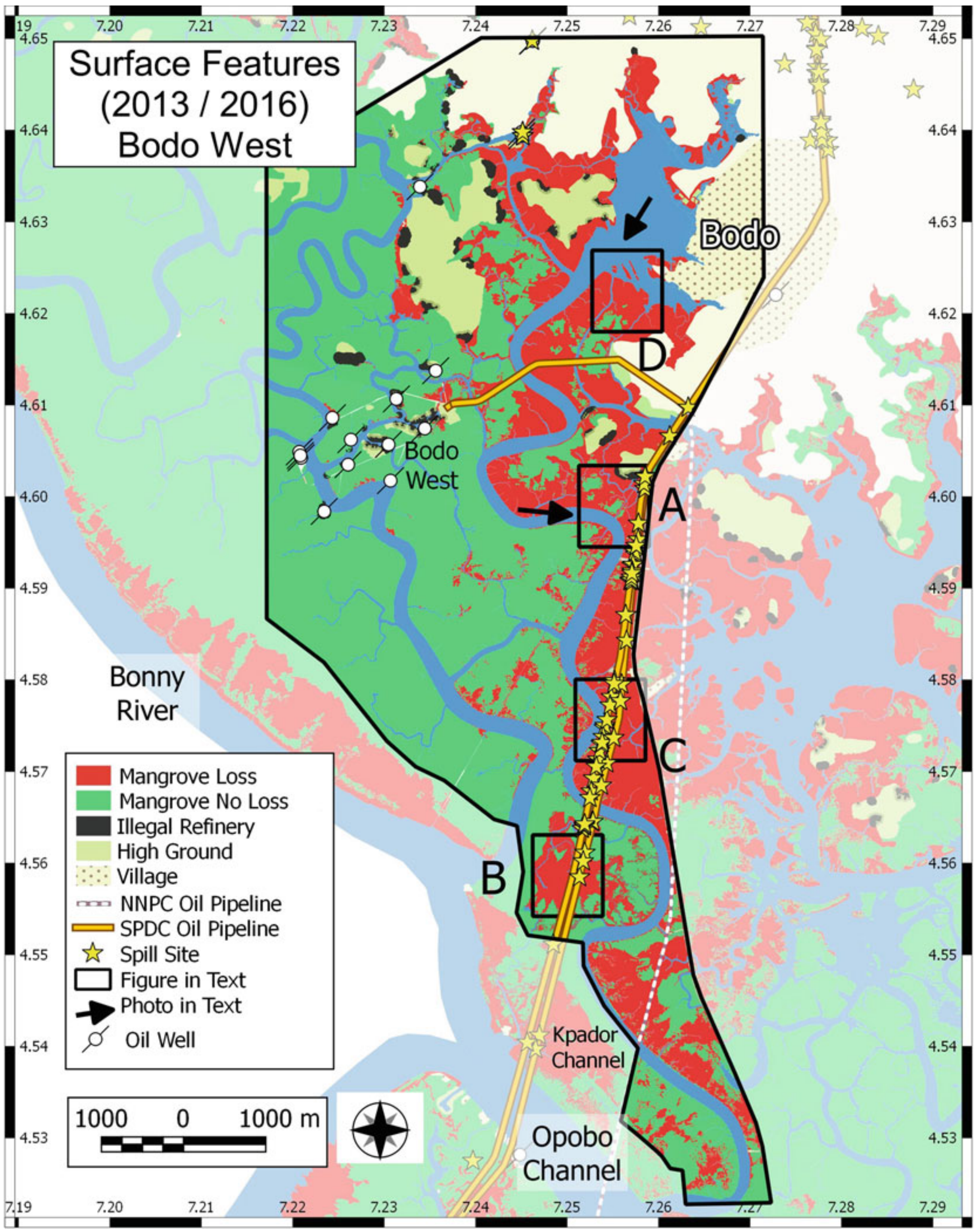

Fig. 13.25 Surface features and mangrove loss in the Bodo West area. The spill sites shown occurred between 2008 and June 2015. Illegal refineries are present in area 'A' and north, and around and to the north of oil wells in the Bodo West oil field

Table 13.11 Spill incidents and cause from 1986 to June 2015 in the Bodo West area. Two of the operational spills in 2008 continued into 2009

Year	Incidents	Operational	Illegal	Other	Location
1986–1997	6	1	3	2	Bomu oil wells
1997–2004	0	0	0	0	No incidents recorded
2005–2007	1	0	1	0	Oil pipelines to bonny
2008	3	2	1	0	Oil pipelines to bonny
2009	0	0	0	0	No incidents recorded
2010	16	0	16	0	Oil pipelines to Bonny
2011	12	0	12	0	Oil pipelines to Bonny
2012	1	0	0	1	Oil pipelines to Bonny
2013	9	0	9	0	Oil pipelines to Bonny
2014	8	0	8	0	Oil pipelines to Bonny
To June 2015	3	0	3	0	Oil pipelines to Bonny

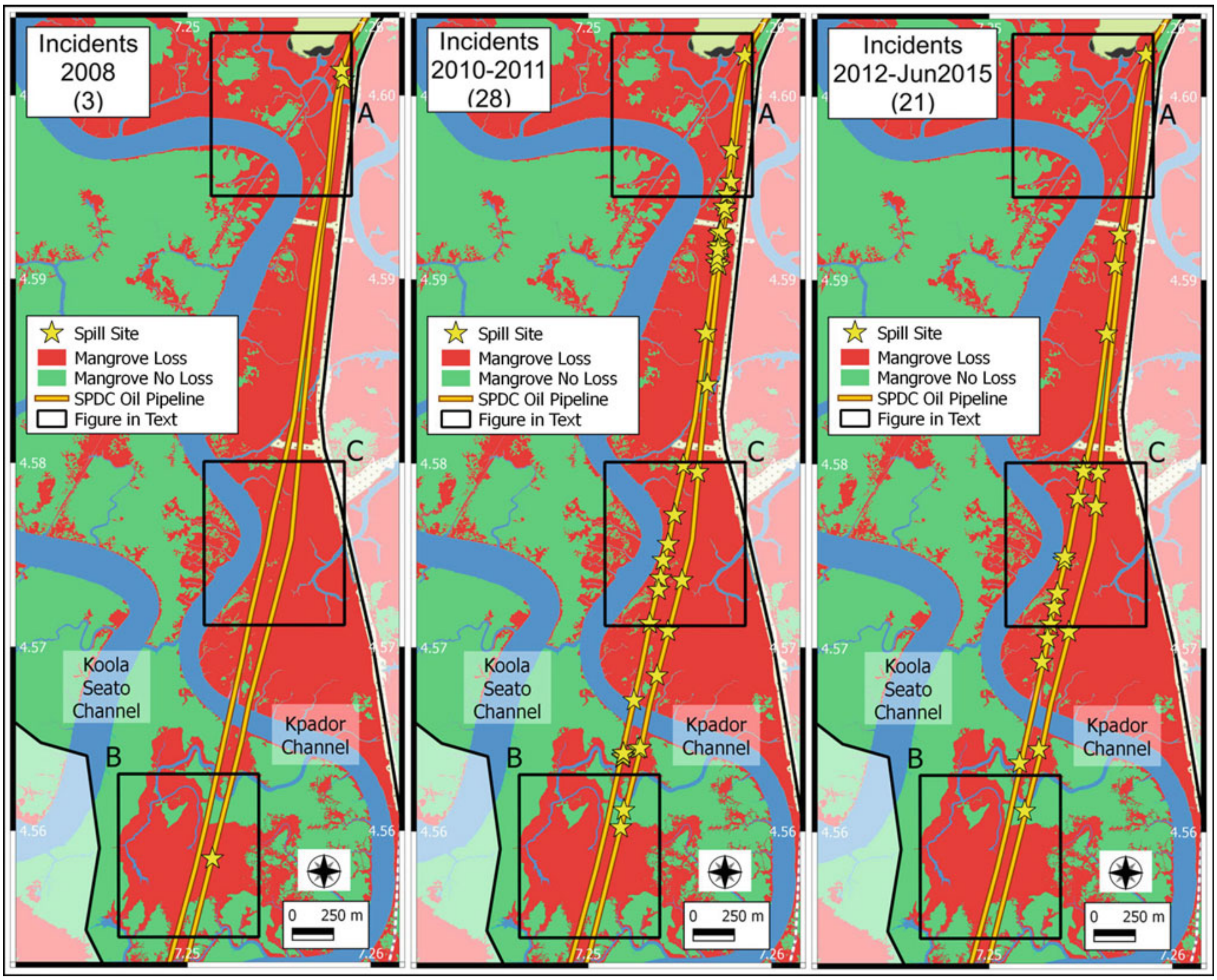

Fig. 13.26 Location of spill incidents in Bodo West 2008 to June 2015 shown for three time intervals

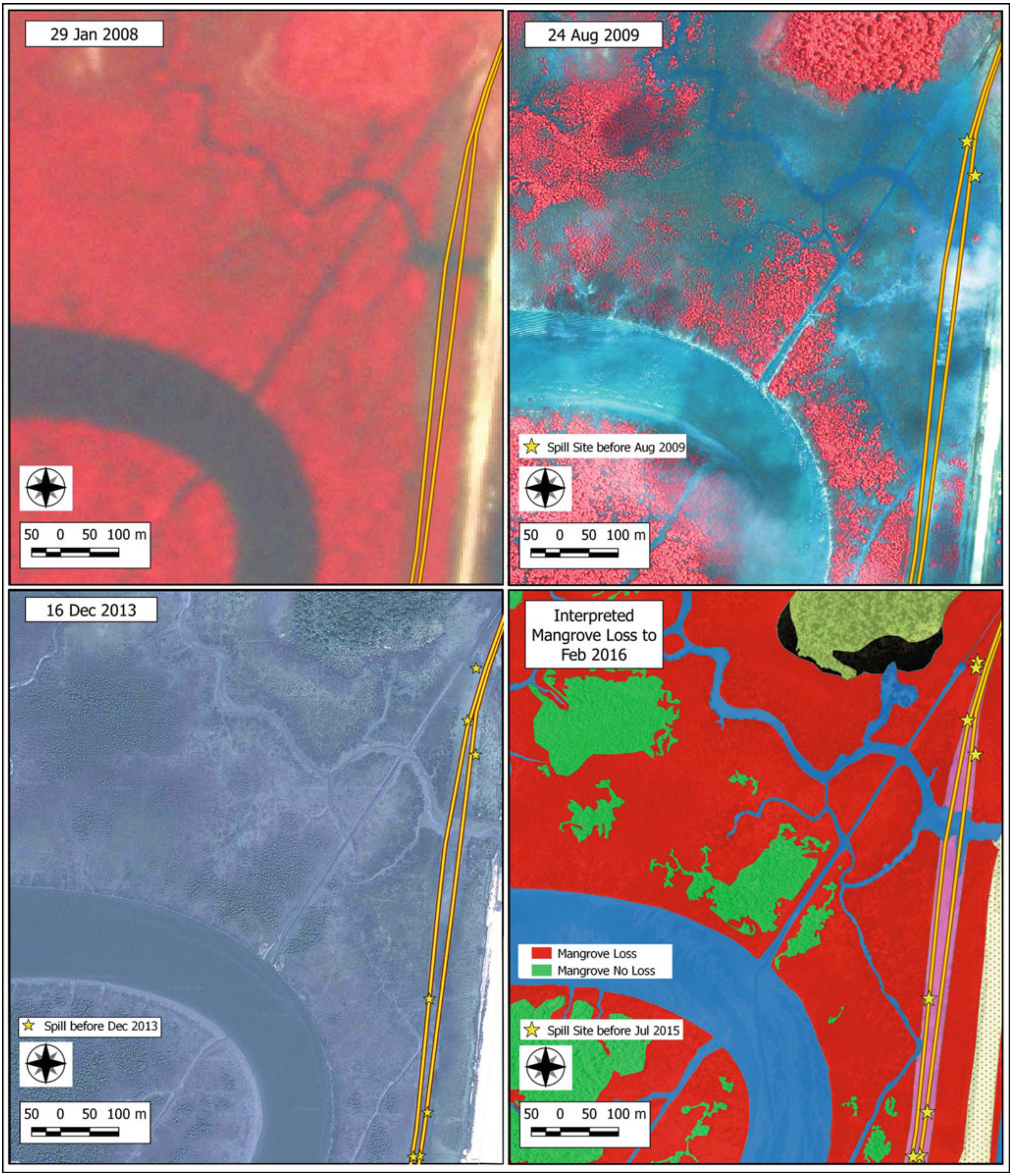

Fig. 13.27 Historic sequence of mangrove loss in Bodo West area 'A' beginning with an operational leak in the pipeline in late 2008 that resulted in large losses visible in 2009. Additional losses in 2013 are evident, after which losses stabilized to 10 February 2016. Site location is shown in Fig. 13.25

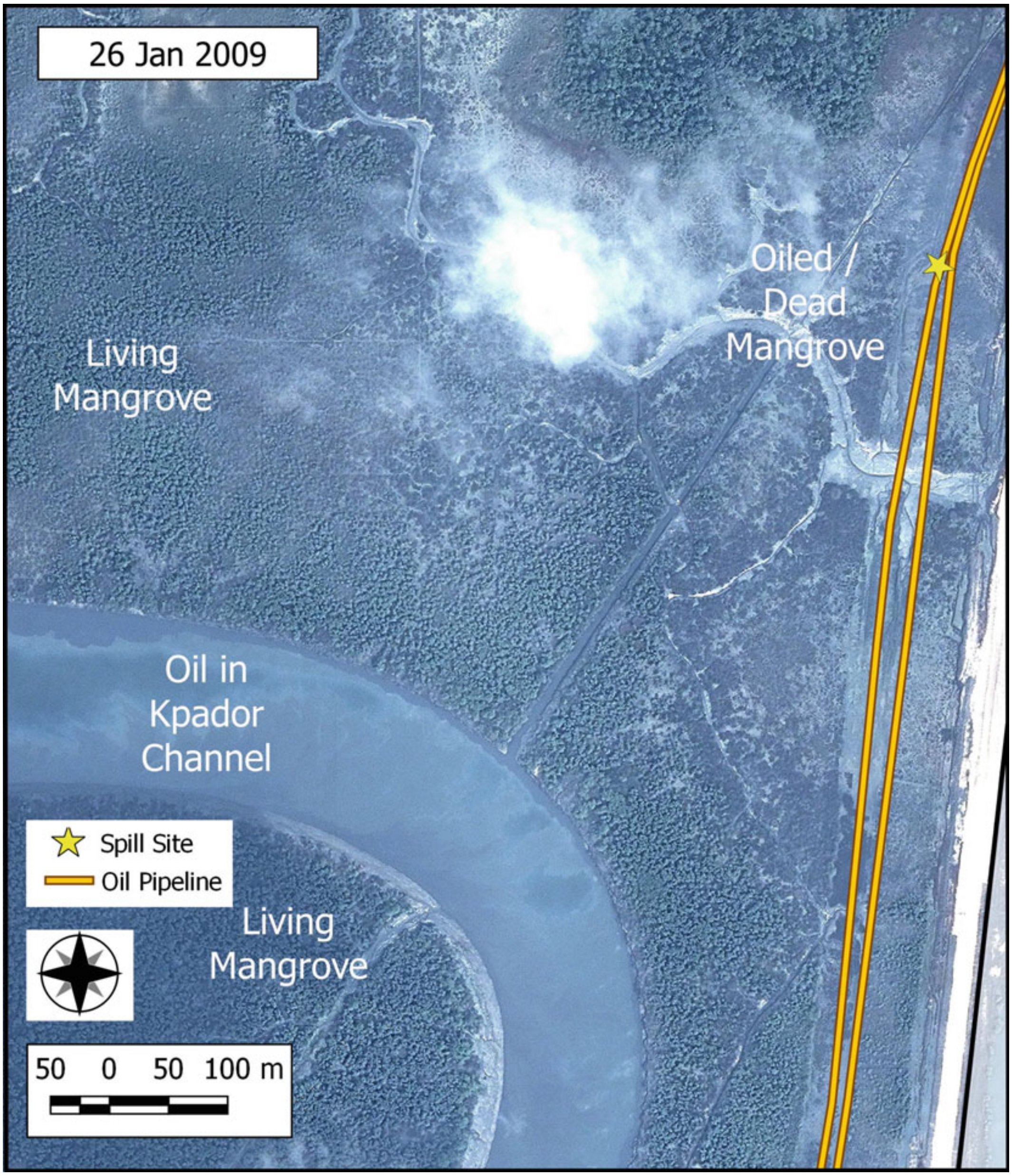

Fig. 13.28 Satellite image of area 'A' (Fig. 13.25) from 26 January 2009 showing mangrove condition and oiling after the operational spill from the indicated spill site

infrastructure is limited to an NNPC oil transport pipeline transiting from the north to the Bonny export terminal in the south. There are no wellheads or associated small pipelines in the area. The details of operation and leaks from the NNPC pipeline are unknown, although one spill (Bn09-1, Fig. 13.15) is reported at its entry point to Bonny Island far to the south. Surface features and mangrove loss in Bodo East are shown in Fig. 13.35.

Initial and major mangrove losses in Bodo East occurred between 24 August 2009 and 19 November 2009 (Fig. 13.36) and cannot be attributed to a specific event or events. Bodo West impacts occurred earlier and were already visible in January 2009. Imagery presented in the figure also shows that not all mangroves were killed by 10 February 2010, but all were lost within 11 months later on 8 January 2011. Images from 2013 to August 2015 show mangrove loss essentially the same as observed in 2013.

There are two possible sources for the damage to mangroves in Bodo East: (1) discharges from illegal refineries and (2) unreported pipeline leak(s). Review of the

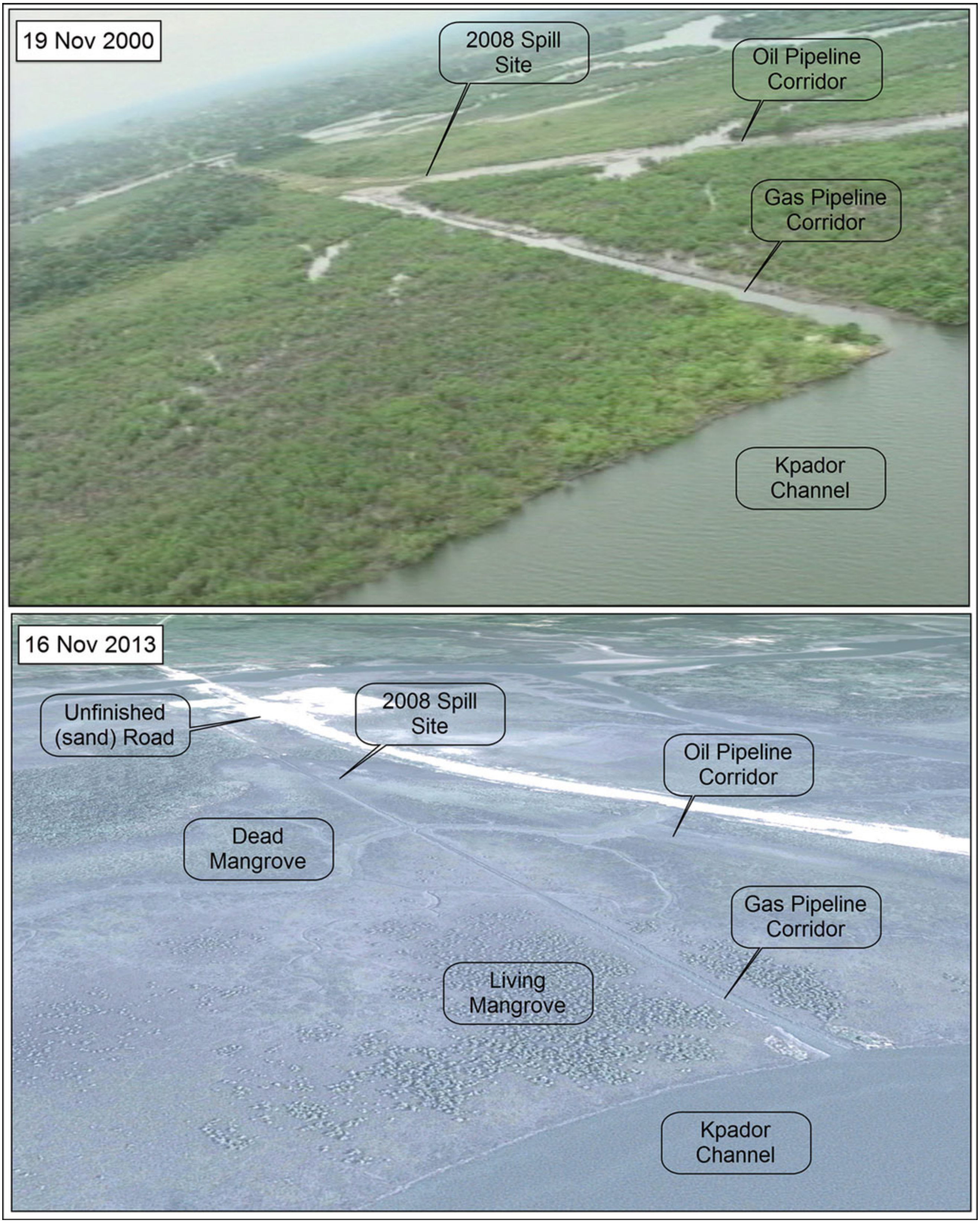

Fig. 13.29 Comparative oblique views of the 2008 spill site area in Bodo West area 'A' (Fig. 13.25) from 2000 to 2013 showing changes to mangrove coverage

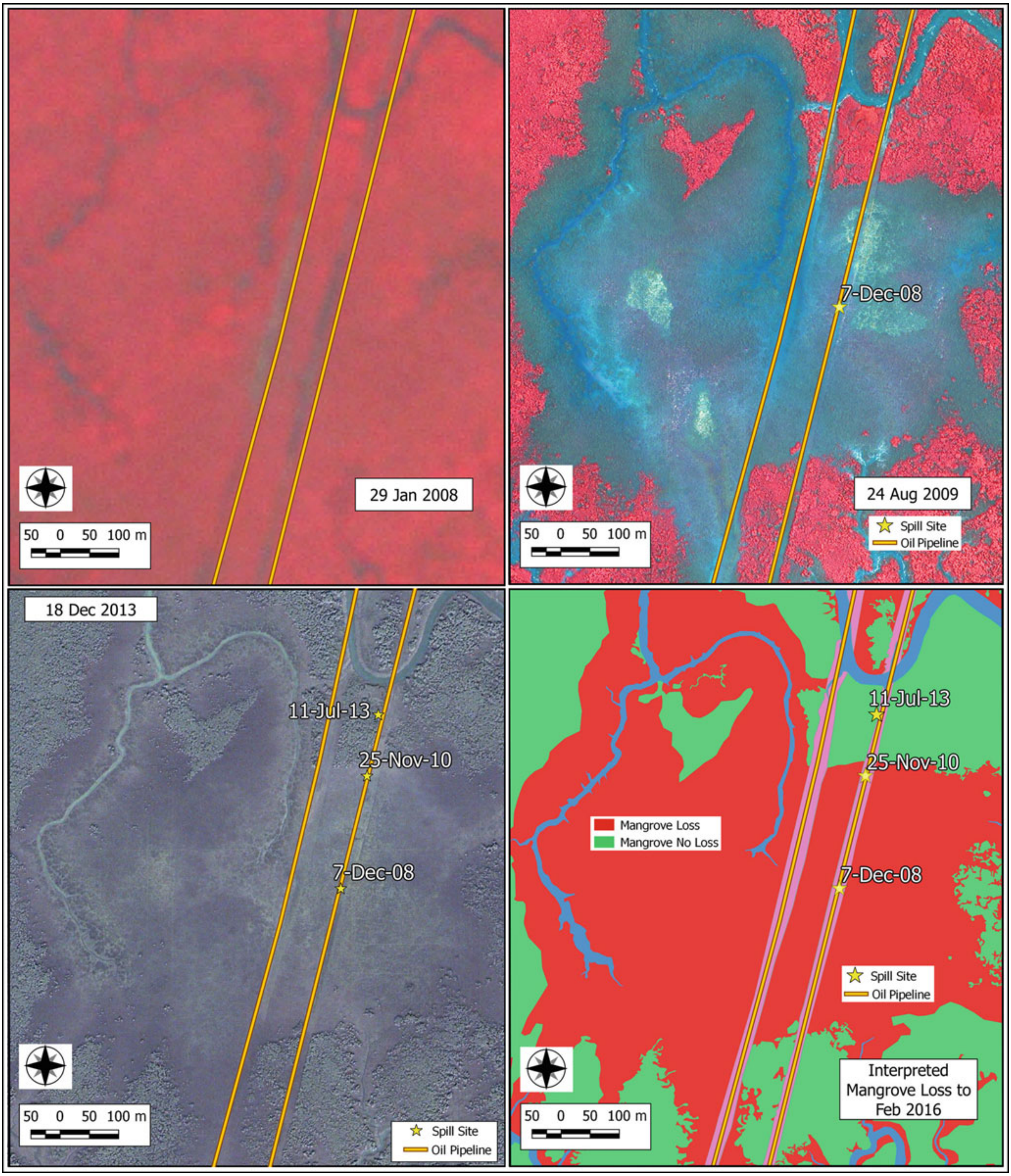

Fig. 13.30 Bodo West area 'B' sequence of mangrove loss 2008–2013, attributable to the 7 December 2008 oil spill. Additional images from Google Earth 2013 to Feb 2016 show mangrove losses remain similar to that in 2013. Figure 13.25 shows the site location

Fig. 13.31 View in 2013 across dead mangroves looking east at the site of the December 2008 operational spill site in Bodo West area 'B' from Fig. 13.25

proliferation of illegal refineries in the area show coincidence with the 2009–2011 mangrove loss. Table 13.13 shows the number of illegal operations increased from 0 to 38 by 2011, and increasing further to 60 in 2013. Because the image areal coverage varies, using the same size base (2011 image) shows that within the same area, the increase was to 52. The additional eight sites lie outside the 2011 coverage but are seen on the 2013 image.

Imagery with the location of illegal refineries from November 2009 and January 2011 area is shown in Fig. 13.37.

The UNEP survey completed an overflight of the area in November 2009 showing that oiling was very heavy in the area (Fig. 13.38). It is doubtful whether losses from illegal refineries and small boats transporting crude oil and refined products could cause such heavy oil concentrations in such a widespread area. The previous Fig. 13.34 from the same overflight in Bodo West also shows heavy concentrations.

As oil quantities are so great in the 2010 aerial photographs as well as in imagery from 2009 to 2011, it appears plausible that an unreported pipeline leak or multiple leaks were responsible for at least some of the oil observed. The most likely candidate spill site is within the slotted area made for the crossing of the NNPC pipeline, area 'B' in Fig. 13.35. Figure 13.39 compares imagery showing oil-on-water conditions in February 2010 and January 2011. Both show heavy oil concentrations and pooled oil in the dredged pipeline slot, particularly in 2011. The oil concentrations in

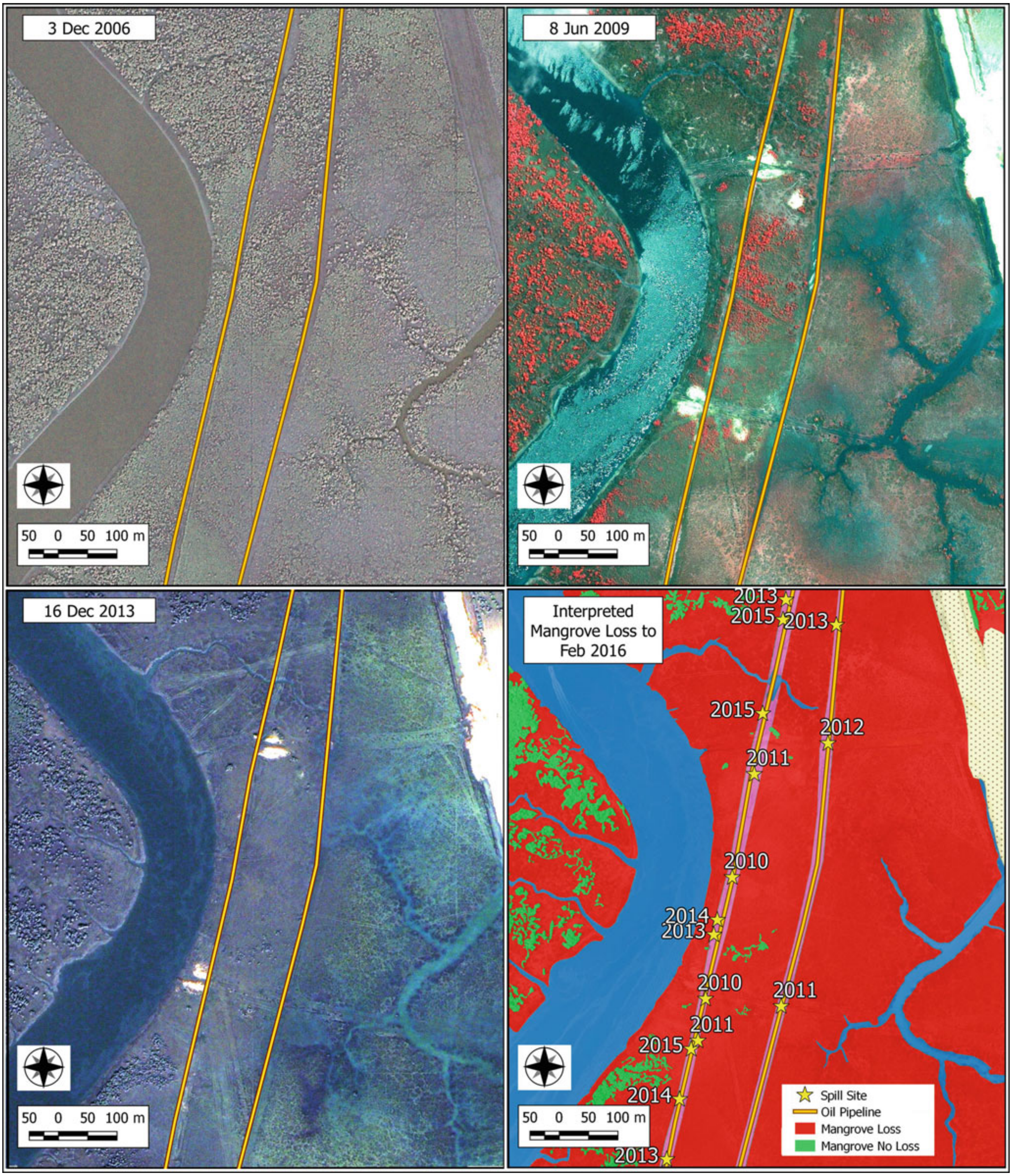

Fig. 13.32 Bodo West area 'C' sequence of mangrove loss from 2006 to 2013, updated to February 2016, with oil spill sites 2010 to June 2015. The site location is shown in Fig. 13.25. Surviving mangroves in 2009 (*bright red* coloration) were lost by 2013

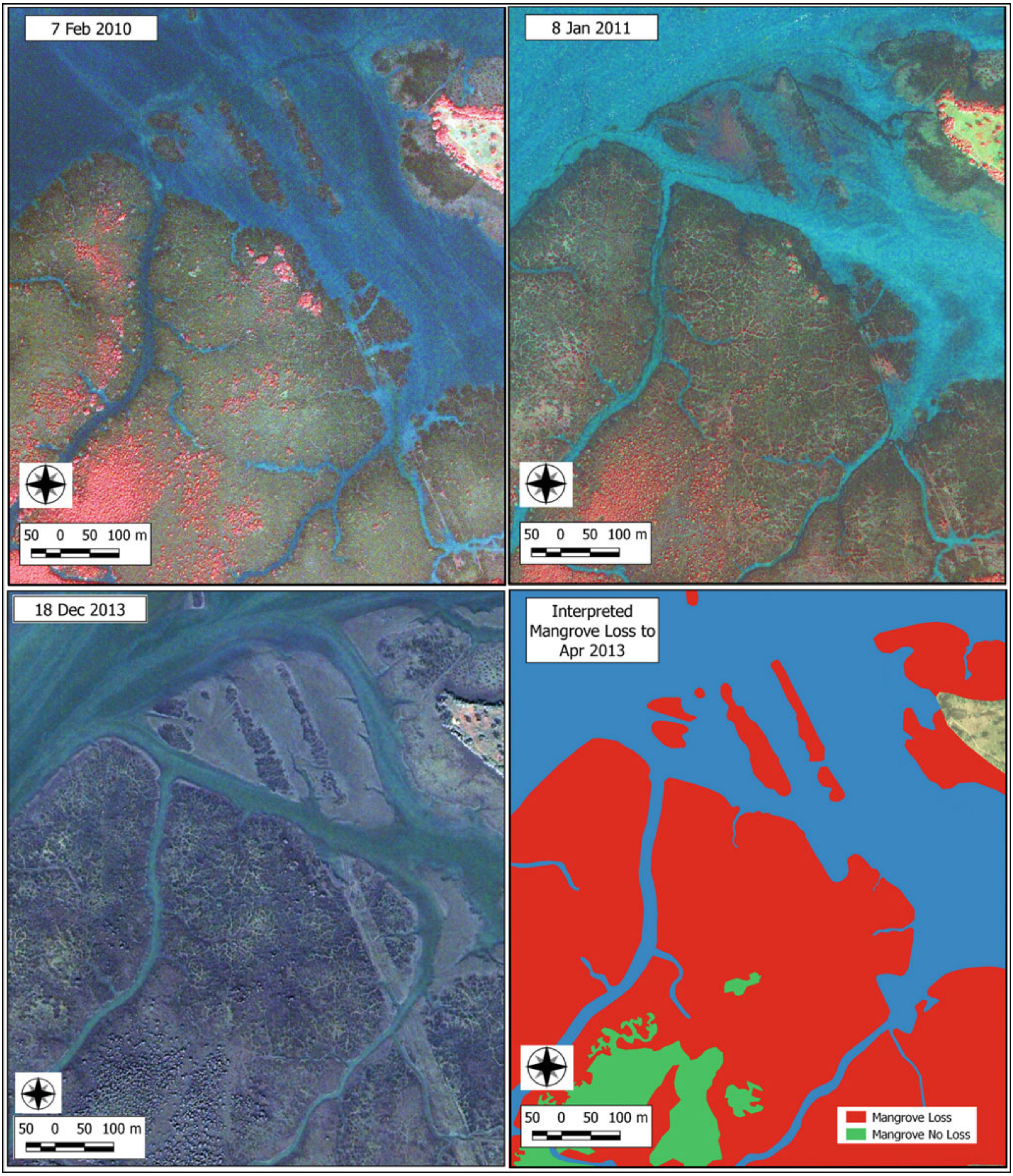

Fig. 13.33 Bodo West area 'D' sequence of mangrove loss, 2010–2013, showing an increase in loss from 2010 to 2011 and then from 2011 to 2013. The site location is shown in Fig. 13.25

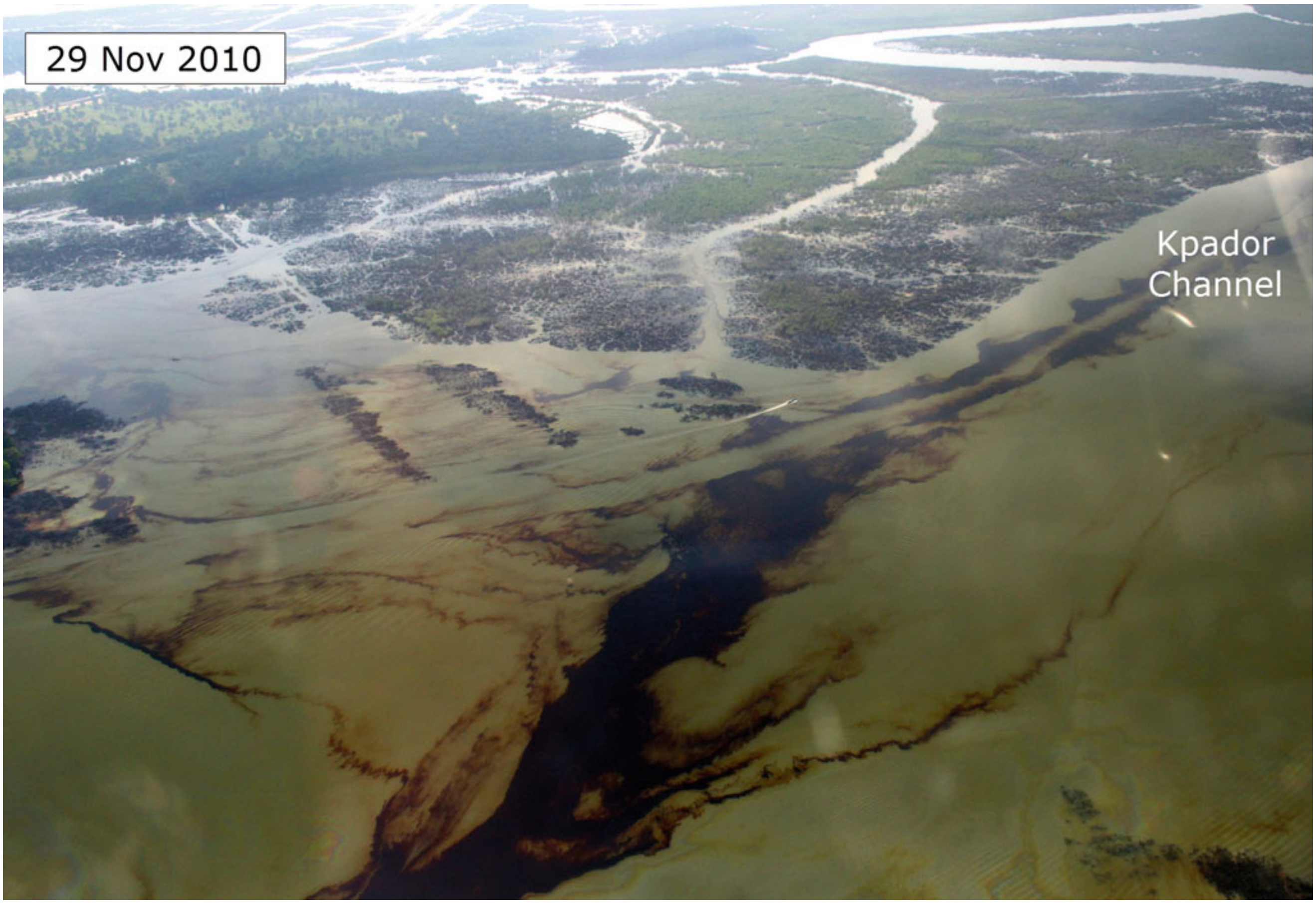

Fig. 13.34 Aerial photograph on 29 November 2010 overlooking Bodo West area 'D' looking south. Large concentrations of black oil are common on the water's surface. The site location of area 'D' is shown in Fig. 13.25. T. Kallnischkies photographer

Table 13.12 Mangrove losses and high ground contaminated by illegal oil refining in the Bodo West area, 2008–2013/2016

Component	Hectares	Number
Mangrove loss	1096.7	
Pipeline corridor	28.1	
Total loss	1,1248	
Illegal refineries	28.9	87

February 2011 seem comparable to that in the November 2010 photographs indicating the potential that a pipeline leak may have continued for several months.

Further to the south in Bodo East area 'C', mangrove losses occurred later, between February 2010 and January 2011 (Fig. 13.40). Oil is present on the surrounding waters in both images but is particularly evident in on the 2011 image. During this time, the number of illegal refineries in the local area rose from 6 to 11 and substantially increased in size. The eastern shore area of Bodo East follows the same later oiling sequence, with massive changes occurring between 7 February 2010 and 8 January 2011.

In summary, the proliferation of illegal refineries from none in June 2009 to at least 60 in 2013 undoubtedly played a role in the loss of mangroves in the Bodo East area. No pipeline spills have been reported, but the quantity of oil on the water observed in photographs from November 2010 and imagery (particularly 7 February 2010 and 8 January 2011) indicates the possibility of major oil discharge(s) from the NNPC pipeline during this period. The summary of mangrove loss and illegal refining sites for Bodo East are presented in Table 13.14. This is the largest loss of the six areas reviewed in this study.

13.3.10 Bolo Area Mangrove Loss

The Bolo area is to the north of Bodo West. It is interconnected to the south by two waterways although not widely used. The economic and political focus of the area is toward the Local Government Area administration center of Ogu and north.

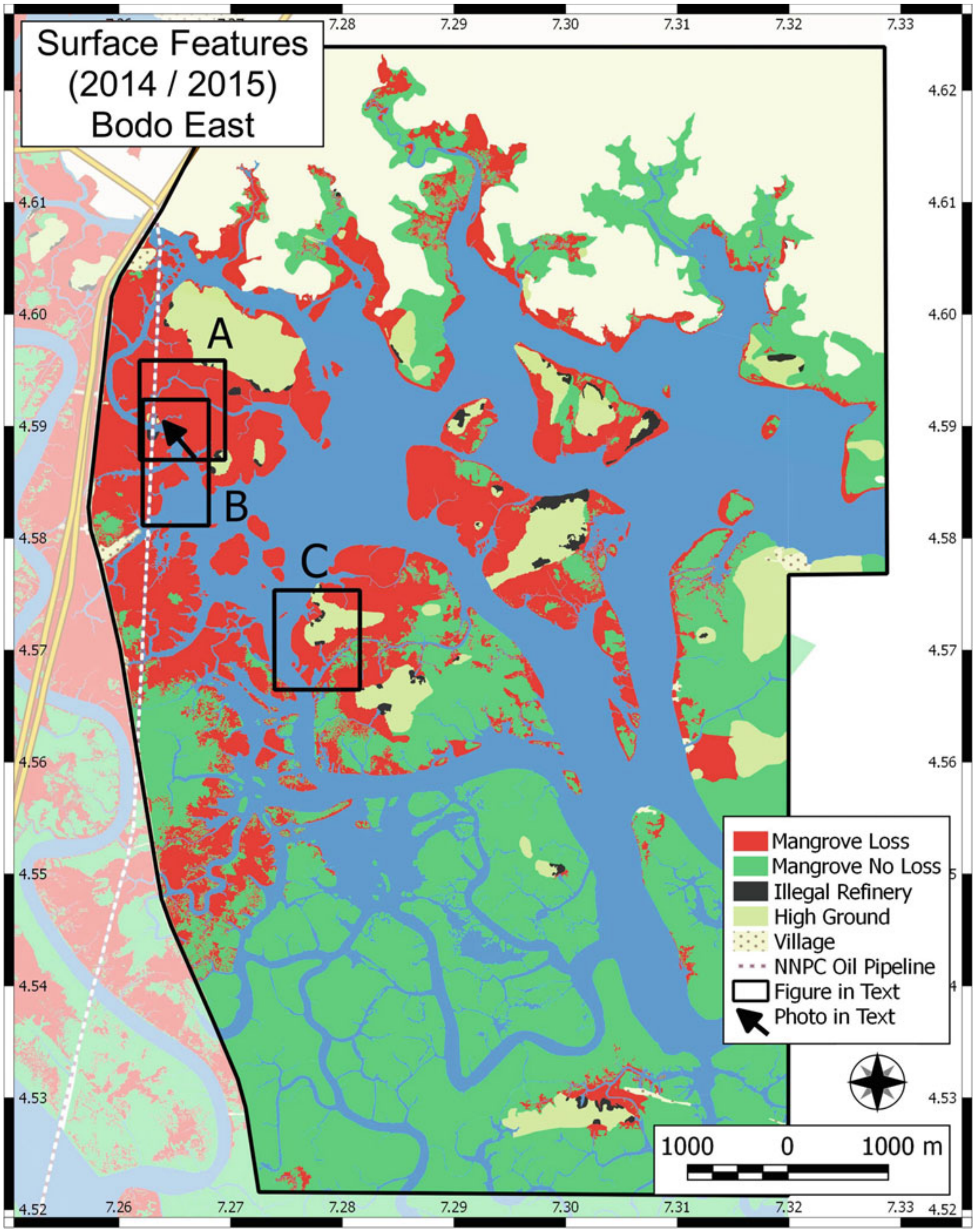

Fig. 13.35 Bodo East surface features and mangrove loss. Areas shown as 'A', 'B' and 'C' are discussed further in the text

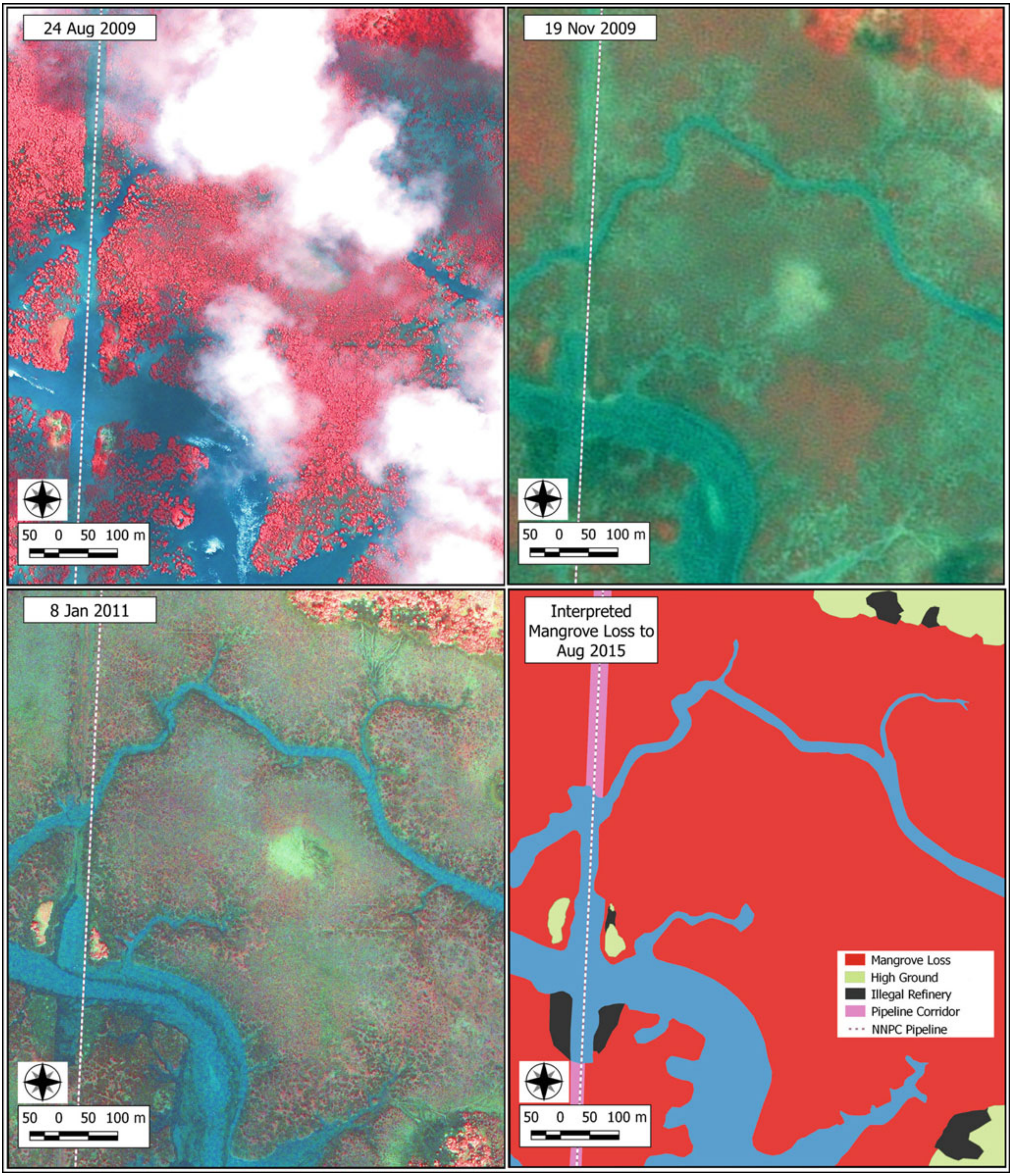

Fig. 13.36 Sequence of mangrove loss in Bodo East area 'A' (Fig. 13.35) indicating the first major loss occurred between 24 August and 19 November 2009, followed by complete loss by 8 January 2011. Other imagery not shown illustrates that complete loss occurred between the narrow window of 7 February 2010 and 8 January 2011

Table 13.13 Number of illegal refineries observed on images from 2009 to 2013 in the Bodo East area. As imagery areal extent varies among images, the 2011 image is selected to compare refinery increases within the same-sized area

Image date	Sites observed in multiple images	Sites observed in area of 2011 image
2009, 8 Jun	0	0
2009, 24 Aug	6	6
2009, 19 Nov	24	24
2010, 7 Feb	26	26
2011, 8 Jan	38	38
2013, 15 Apr	60	52

The overview of mapped surface features is provided in Fig. 13.41. There are 14 wellheads in the area, 7 of which are within or adjacent to mangrove areas. Small diameter pipelines connect to the wellheads, except for two isolated wellheads in the center-west of the area.

Comparing Bolo area ‘A’ imagery from 25 January 2009 to 29 November 2009 indicates that illegal refining activities started during this time (Fig. 13.42). The January 2009 image shows two refineries while five refineries are evident in the November image. Damage to mangroves was not evident in January 2009 and minimal in November 2009. However, major losses to mangroves are evident in 2013 as are six quite large illegal refineries. An image from January 2015 shows similar impacts as observed in 2013.

Low-altitude aerial photographs from Bolo area ‘A’ in 2010 are compared to 2015 in Fig. 13.43. In November 2010, mangroves were in good condition and refineries were small and few in number. The conditions in 2015 show a massive die off of mangroves. Oil is present in the channels in both photographs.

Area ‘B’ in Bolo shows a similar timeline, but more severe consequences (Fig. 13.44). In January 2009, mangroves are healthy and illegal refineries are not evident. Later in November 2009, two small illegal refineries have started. In 2013, most of the mangroves are dead and nine illegal refinery sites are evident along the north shore. A comparison of the 2013 and February 2016 images shows the same conditions, with few remaining remnants of the former mangrove habitat.

A 2015 aerial photograph of the northeast section of Bolo area ‘B’ is shown in Fig. 13.45. Oil is present on the surface of sediments as are scrape marks likely caused by cleanup operations. Heavy tar conditions indicative of an illegal refinery are shown by a white oval in the following figure. The damage to mangroves was likely caused by discharges from illegal refineries and possibly influenced from a pipeline leak upstream of the site where the Bomu-to-Bonny Terminal pipelines (24- and 28-in.) pipelines cross the estuary (upstream above area ‘B’ on Fig. 13.41). On 17 April 2010, there was reported an illegal activity that caused an oil discharge and fire at this location. Further to the north also on Fig. 13.41, mangroves to the east of Ogu are similarly damaged and likely to have been affected by reported spills along these pipelines.

In summary, mangroves were damaged in the Bolo area between late 2009 and 2013. Losses appear to have stabilized after 2013, as illustrated by 2015/2016 images that show similar losses to 2013. Most likely causes for all areas are illegal refining with the addition of potential discharges from illegal tapping of the SPDC pipelines in areas upstream of, or adjacent to, mangrove habitat. The summary of mangrove loss and identified illegal refineries is presented in Table 13.15.

13.3.11 Mangrove Loss Summary for All Areas

More than 4400 ha of former mangrove habitat were lost from spilled oil between 2008 and 2016 in the study area (Table 13.16). Another 104 ha was lost due to pipeline corridors cut through mangrove areas several decades ago. Additionally, 217 distinct illegal refineries sites were found, destroying 116 ha of supratidal (palm dominated) habitat adjacent to mangroves.

Four sites of pipeline leaks were responsible for causing initial, rapid and large-scale losses of mangroves in 2009. These include the 2008–2009 spills on Bonny Island (~940 ha), Opobo Channel (~170 ha) and the two spills in Bodo West (~1000 ha). The Bonny Island incident was attributed to illegal activity while the three others were operational (pipeline leaks) in nature.

The sequence of mangrove losses for the entire study area is shown in Fig. 13.46. Major losses occurred in 2009 from the spills described above, causing mangrove losses on Bonny Island, along the Opobo Channel and Bodo West. In 2010, there was an increase in the number of spills caused by illegal activities which, because the majority of mangroves were already killed in 2009, caused only a minor increase in mangroves lost, as along the Bonny River and into Bodo West. In 2011, due to illegal activities and a possible spill

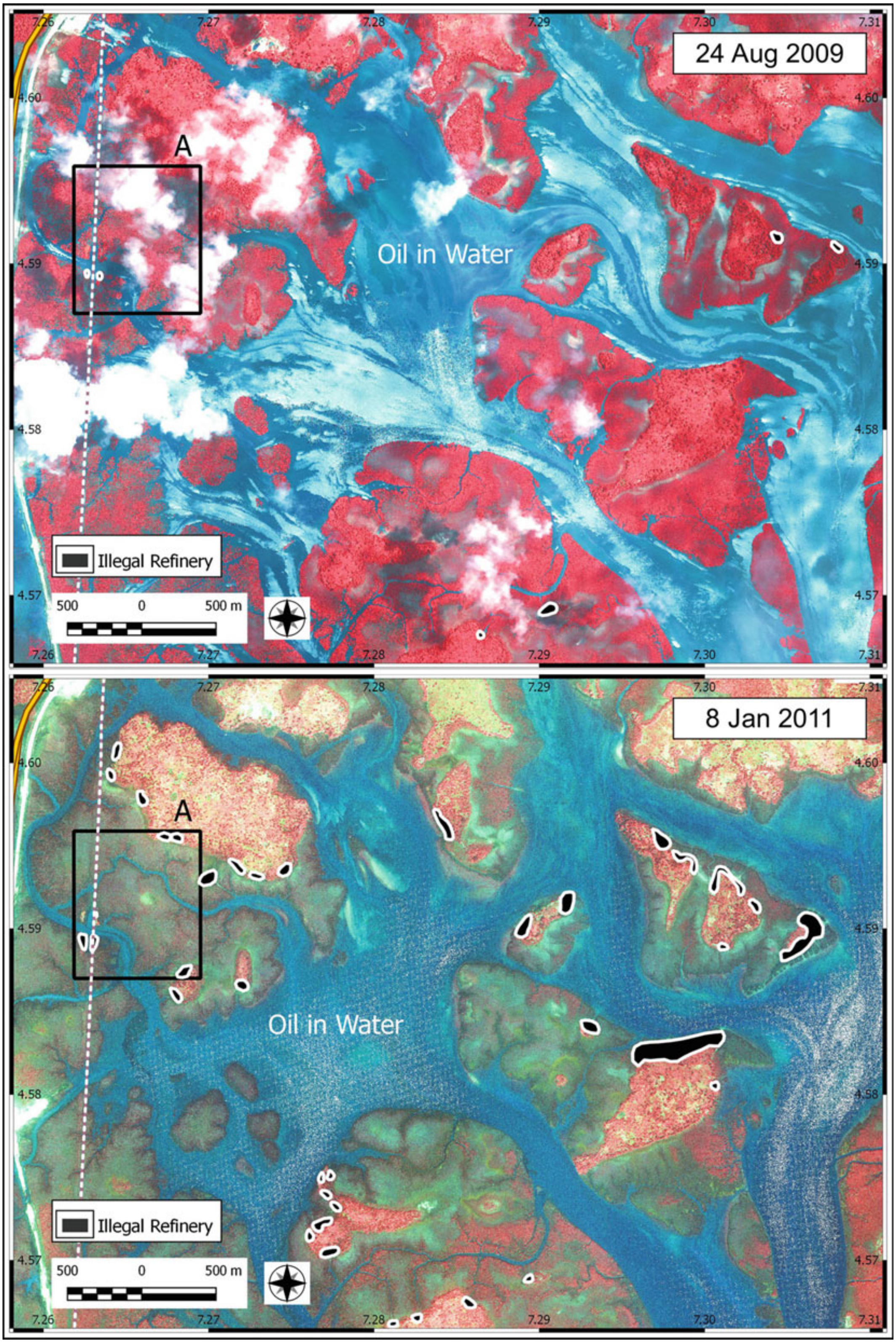

Fig. 13.37 False color infrared imagery of northern Bodo East illustrating mangrove condition and location of illegal refineries. In August 2009, mangroves were healthy and six refineries present. In February 2011, mangrove losses were extensive (*dark* coloration) and 38 refineries present. Area 'A' is shown in Figs. 13.36 and 13.38

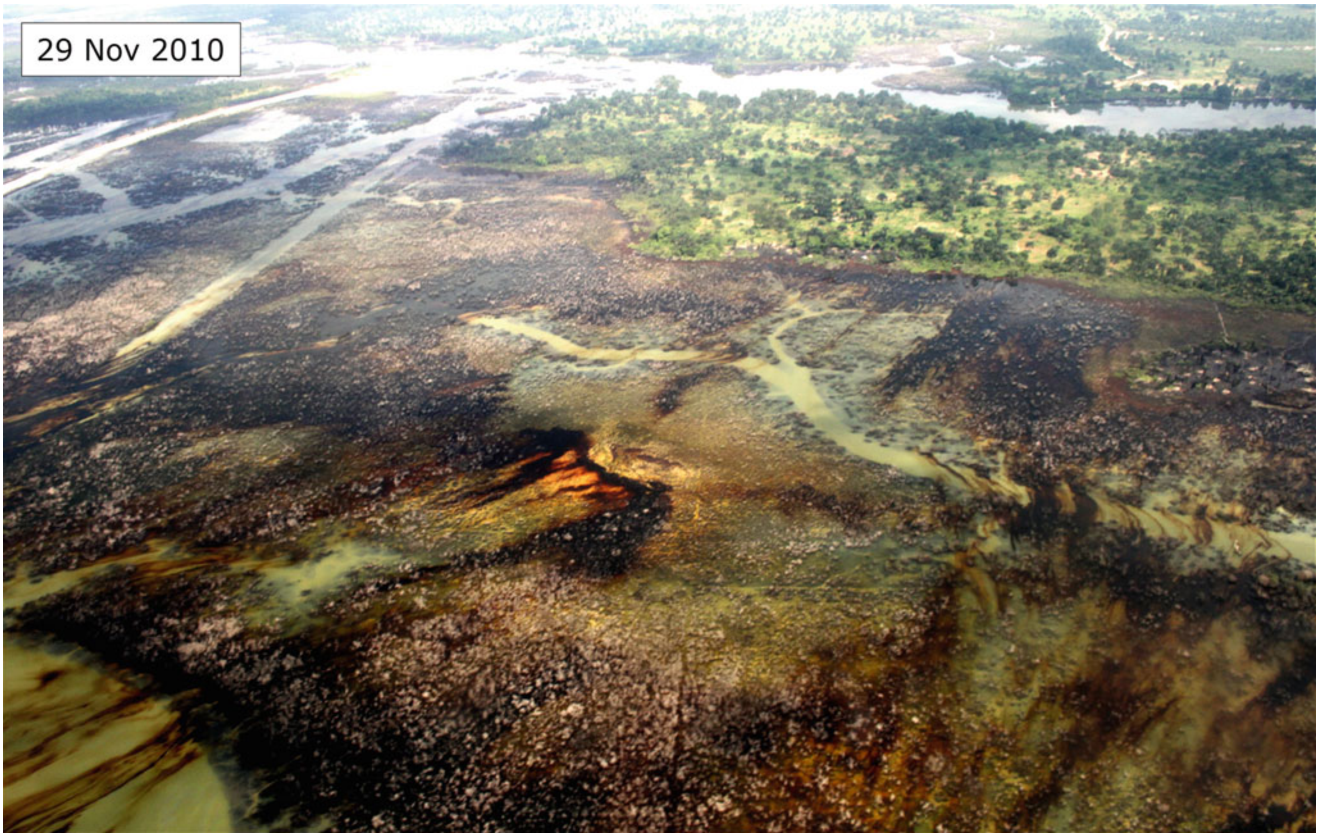

Fig. 13.38 Aerial photograph from 20 November 2010 of the Bodo East area 'A' (Fig. 13.35) looking NNE showing heavy oil concentrations. T. Kallnischkies photographer

leak on the NNPC pipeline, oil-related damages spread into Bodo East, causing over 1000 ha of mangrove loss.

Additional damages observed in 2013 occurred in the Bolo area due to illegal refining and likely from pipeline leaks from the oil-transport pipelines passing at the head of mangrove embayments in the northeast of the Bolo area. Losses also increased along the Bonny River from <100 m in 2010 to over 800 m landward in 2013. Other smaller increases in Bodo East and West are associated with illegal refining activities. Losses observed after 2013 are small and primarily on Bonny Island.

13.4 Discussion

13.4.1 Mangrove Losses and Recovery at Other Sites

Worldwide, the historic losses of mangroves due to oil-related activities are commonly tied to a specific event, e.g. pipeline rupture, tank rupture or well blowout. In most cases, the extent of mangrove loss from these single events is relatively small. Sites having confirmed losses of greater than 5 ha are shown in Table 13.17. A few other sites are offered by Duke (2016a, b) including those in the area of this study. Only the Funiwa 5 well blowout off the coast of Nigeria in 1980 is even close to the scale of the losses reported herein.

The full recovery of large areas of mangrove loss has not been documented. In those areas where recovery is being monitored, studies indicate ranges of 20–30 years and continuing (Table 13.18).

A minimum estimate of 30 years for mangrove recovery is therefore expected, assuming that recovery is not affected by other factors such as additional oiling or toxic concentrations remaining in sediments. Duke (1999) projected a required recovery to 50 years based on the regrowth of trees, and "assumes recovery proceeds unimpeded, which it often does not." Applying the predictions of oil longevity and mangrove recovery supports the likelihood that mangroves in the study area will require several decades to recover, with a minimum of 30 extending to possibly 50 years. Confounding recovery potential is that oil concentrations within sediments in many areas are very high and at levels toxic to mangrove regrowth (Little et al. 2018, Chap. 14, this volume).

Additionally, many locations show that the substrate is substantially altered from previous conditions of high organic matter and prop roots to hard clay without plant debris or

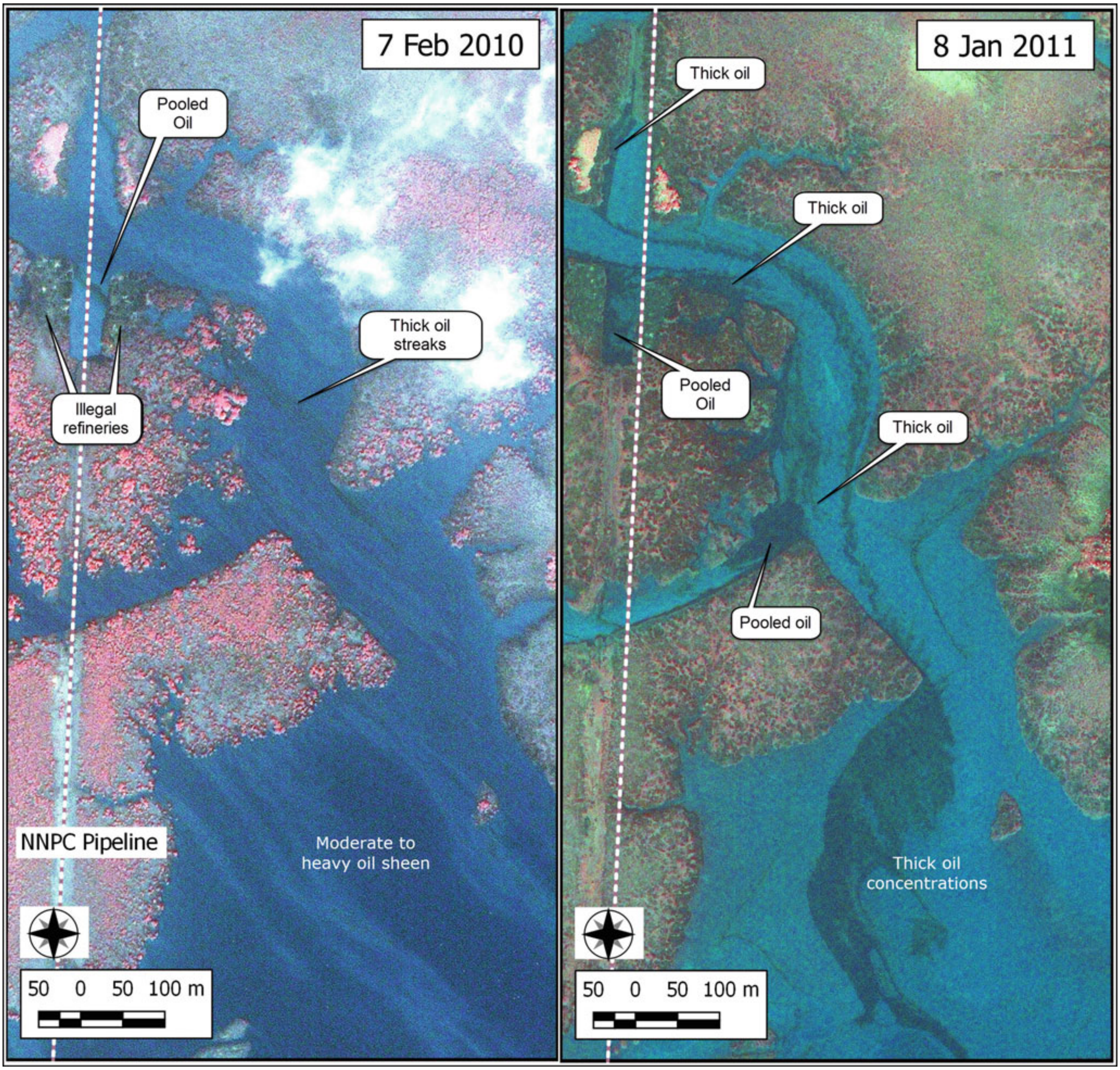

Fig. 13.39 Bodo East area 'B' images from February 2010 to January 2011 showing substantial oiling of the water's surface possibly originating from a pipeline leak in the slotted area where the NNPC pipeline crosses the channel (*upper left* of each image). Illegal refineries are located on the banks of the slots. Site location of Bodo East area 'B' is shown in Fig. 13.35

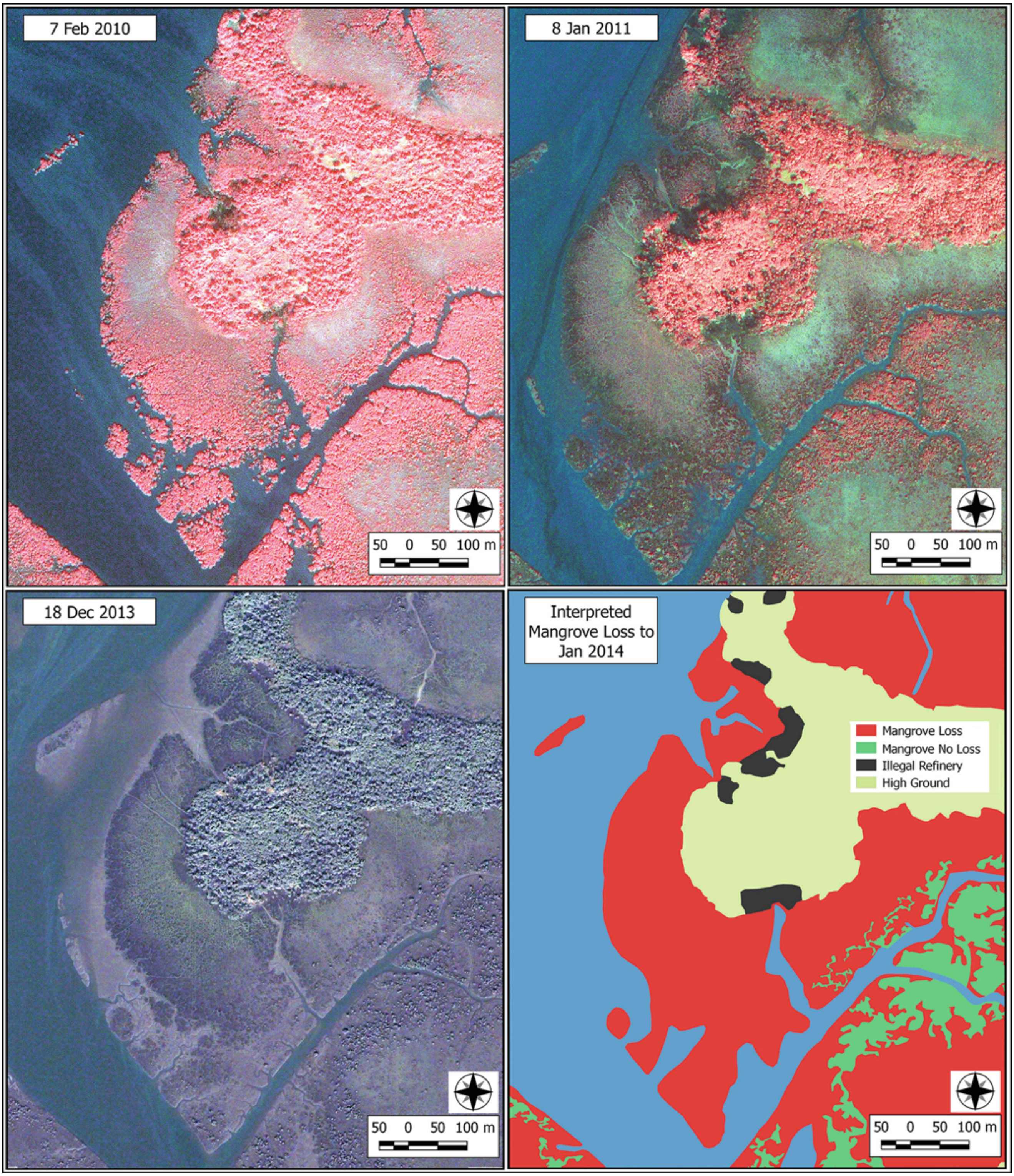

Fig. 13.40 Sequence of mangrove loss in Bodo East area 'C' from 2010 to January 2014. The location of area 'C' is shown in Fig. 13.35. A Google Earth image from 12 January 2014 shows similar conditions as observed from the 2013 image

Table 13.14 Mangrove losses and high ground contaminated by illegal oil refining in the Bodo East area, 2008–2015

Component	Hectares	Number
Mangrove loss	1175.9	
Pipeline corridor	7.4	
Total loss	1183.3	
Illegal refineries	35.4	60

organic matter. Mangrove resettlement will be inhibited and these areas may never return to their pre-oiling condition without additional effort.

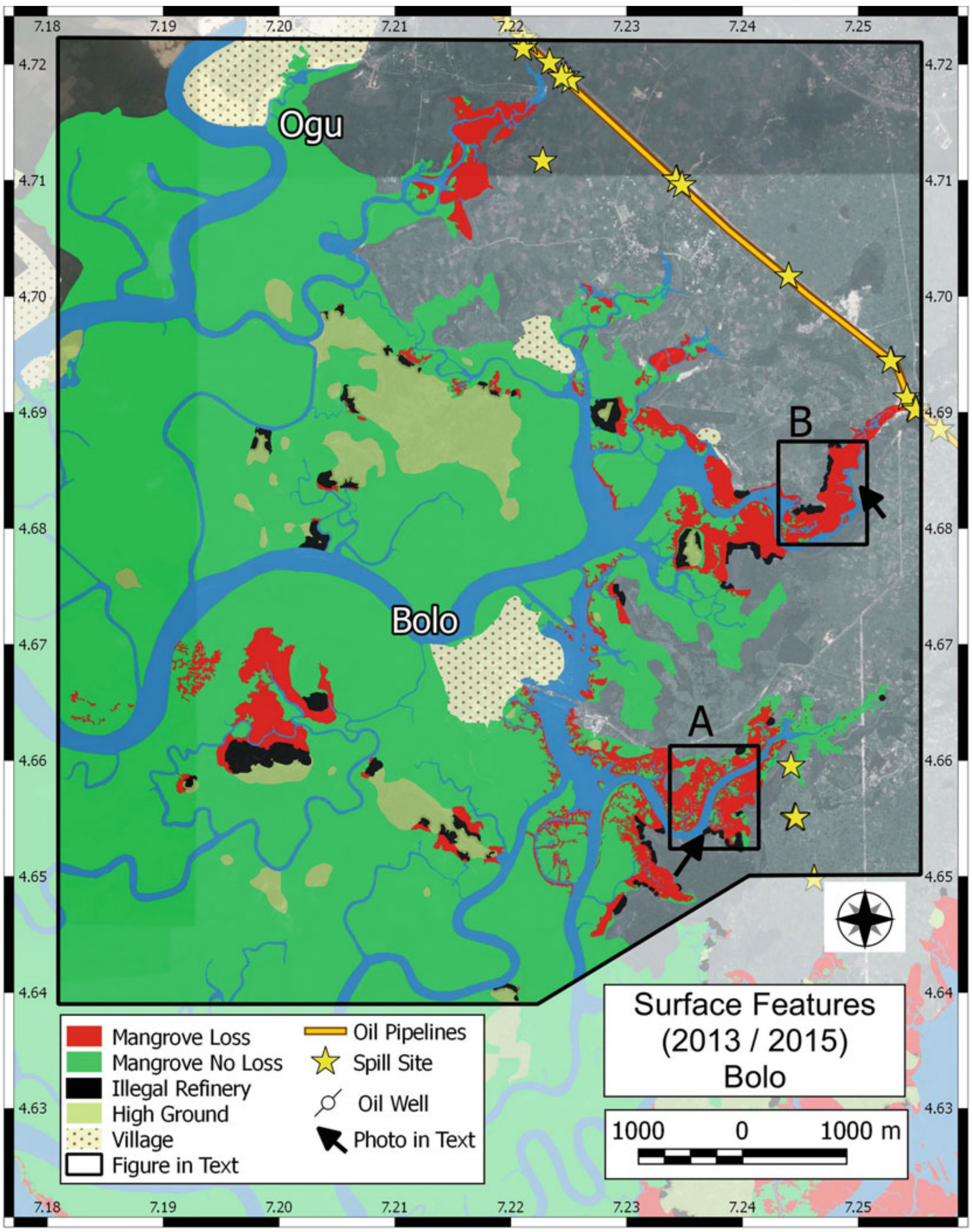

Fig. 13.41 Overview of surface features of the Bolo area based on imagery and photographs continuing to 2013 or 2015, depending on image coverage. Bolo areas ‘A’ and ‘B’ are discussed further in the text

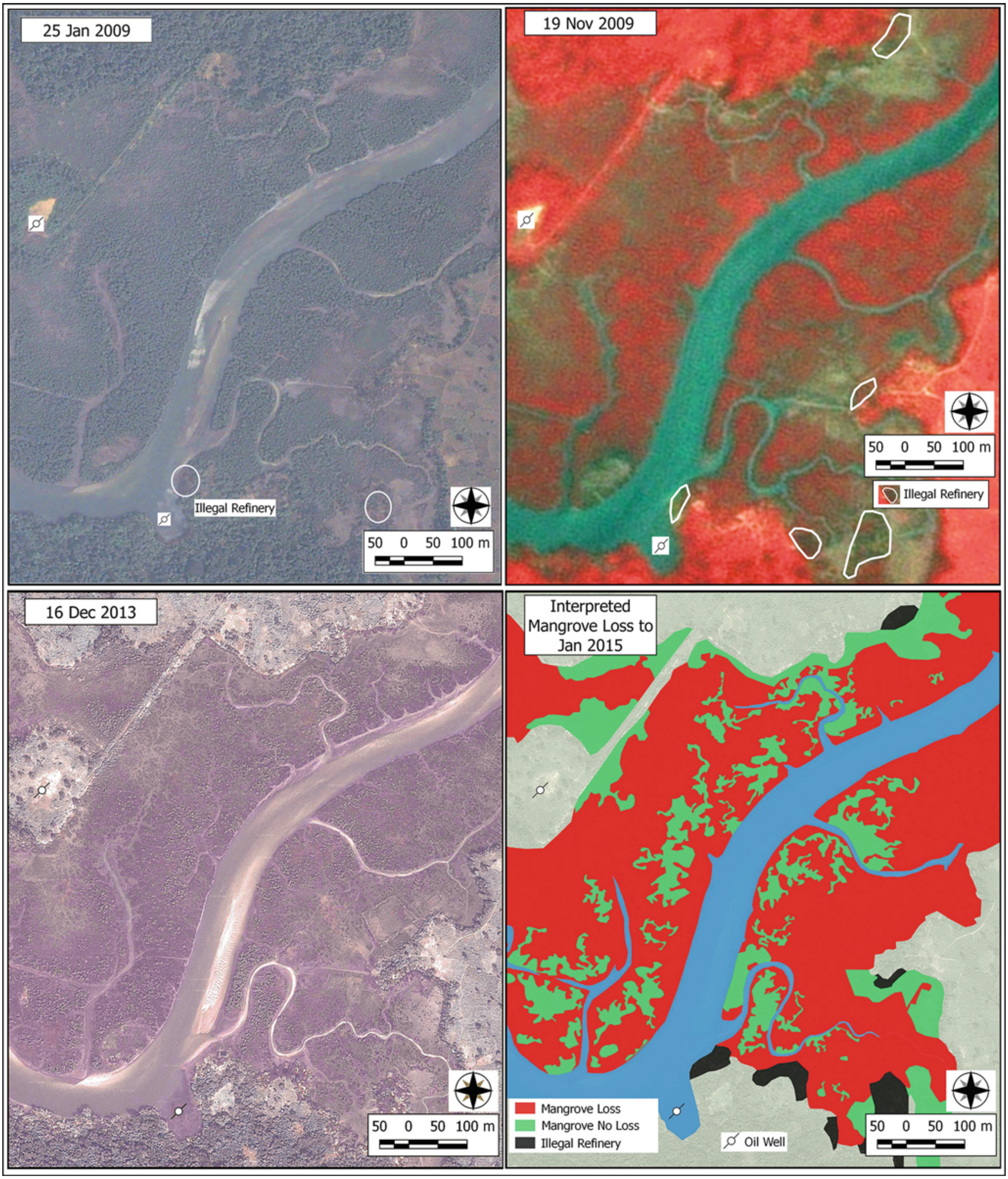

Fig. 13.42 Sequence of impacts in the Bolo area 'A' showing no mangrove loss in January 2009, to five illegal refineries and some mangrove loss in November 2009, and ending with extensive loss in 2013 and six large illegal refinery sites. Imagery from 19 January 2015 shows similar mangrove loss and refineries to 2013. The location of Bolo area 'A' is shown in Fig. 13.41

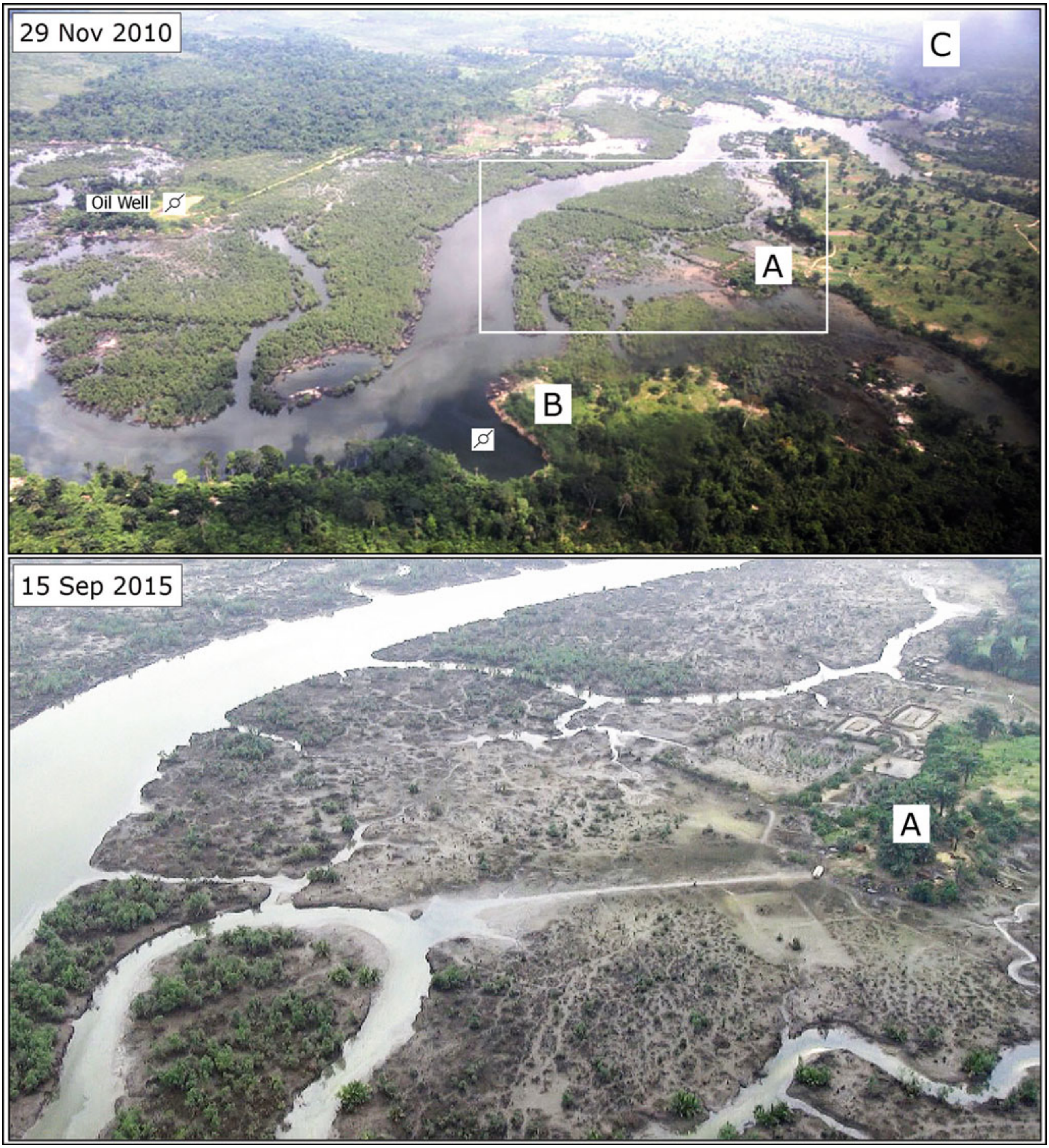

Fig. 13.43 Aerial photographs of Bolo area 'A' (Fig. 13.41) from 29 November 2010 to 15 September 2015 (Photos by T. Kallnischkies (*upper*) and V. Imevbore (*lower*)) Letters *A*–*C* show illegal refineries. The *white box* in the *upper photo* is the location of the *lower photo*. Smoke is seen at location *C* likely indicating active refining

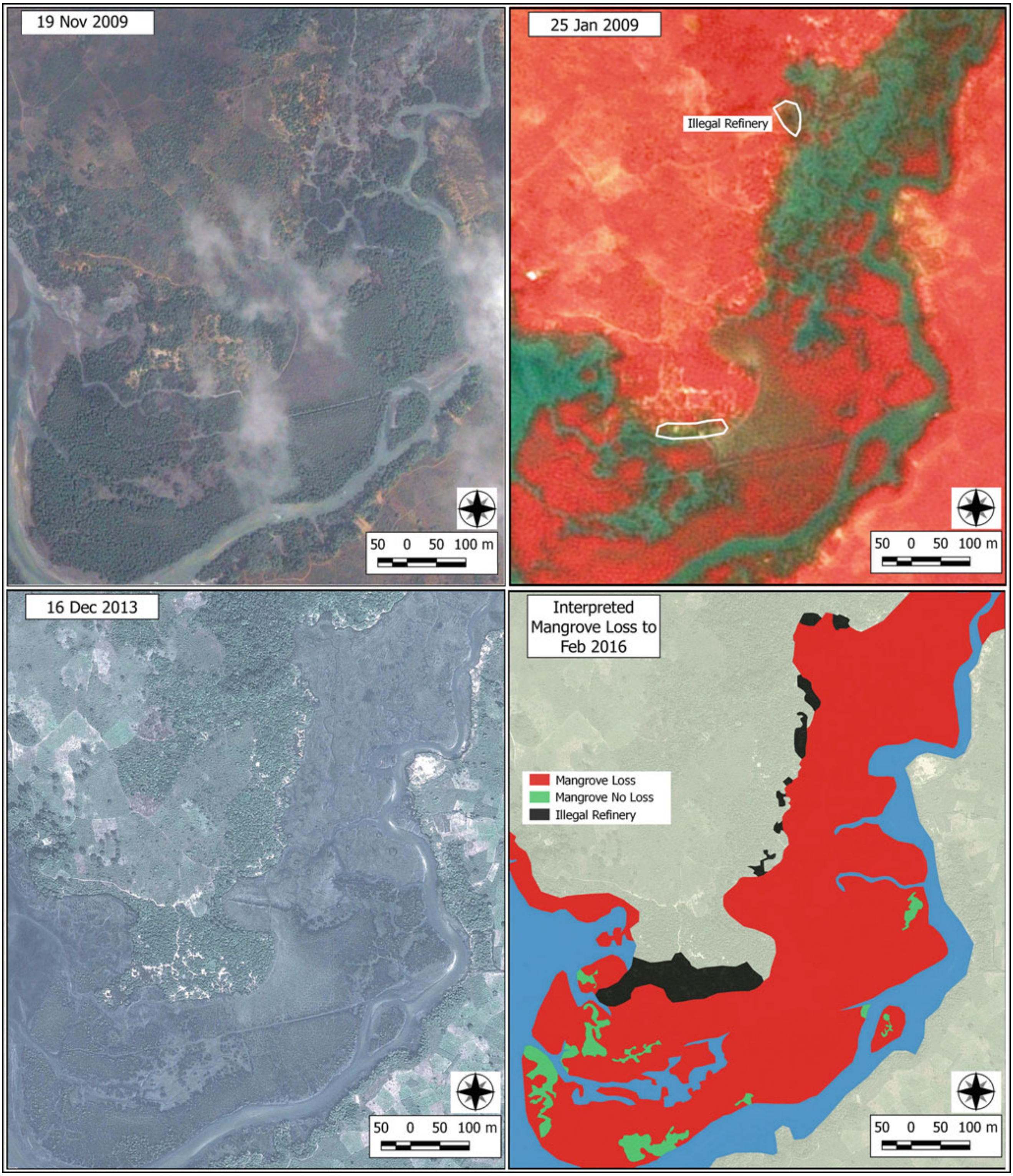

Fig. 13.44 Sequence of mangrove loss in Bolo area 'B' from 2009 (little to no loss with few refinery sites) to 2013 (major losses and nine refinery sites), extended to 10 February 2016 imagery which shows similar conditions to that of 2013. The site location of Bolo area 'B' is shown in Fig. 13.41

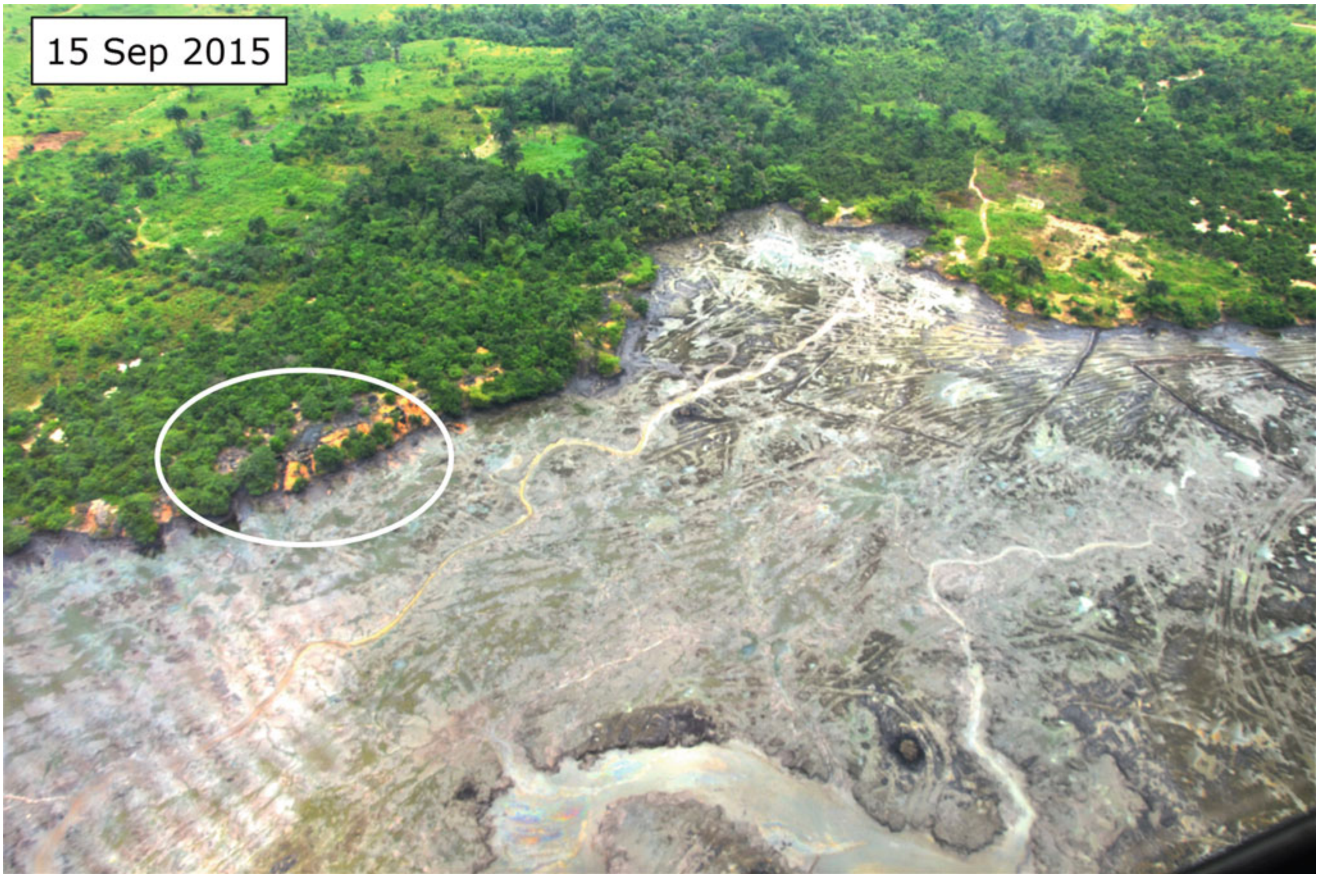

Fig. 13.45 Aerial photograph from 15 September 2015 of the northeastern section of Bolo area 'B' from Fig. 13.41. Scrape marks potentially from a cleanup operation are evident. Oil is in the water and along the shoreline. The *oval* indicates a likely illegal refinery. A pipeline discharge occurred upstream (to the *right*) in April 2010 (Photograph by V. Imevbore)

Table 13.15 Mangrove losses and high ground contaminated by illegal oil refining in the Bolo area, 2008–2015

Component	Hectares	Number
Mangrove loss	338.7	
Pipeline corridor	0	
Total loss	338.7	
Illegal refineries	51.2	66

13.4.2 Enhancing Recovery

The Shoreline Cleanup Assessment Technique (SCAT) teams fielded in May and August 2015 reviewed 32 sites in the study area and developed a series of recommendations designed to enhance recovery of the area. For reference, SCAT is a well-known and internationally accepted program to scientifically advise on the cleanup and recovery of oiled shorelines (Owens and Sergy 2003; IPIECA 2014; NOAA 2013).

Recommendations of the SCAT teams are focused on successfully restoring mangroves to enable full habitat functionality by successful application of a net environmental benefit analysis (IPIECA 2015). By bringing back the mangrove plants, the associated biota will follow. Recommendations include the following:

- *Do More Good than Harm:* Cleanup operations must be controlled so that damages are not increased, particularly where oil has deeply penetrated into soft muds. Operations must be altered or stopped until additional damage can be prevented. Natural recovery may be a preferred option in many areas.
- *Establishment of a Cleanup Endpoint:* The stopping point for active cleanup will be the reduction of oil in sediments to a level where mangrove seedlings will be able to survive and thrive, and for the removal of surface tar and asphalt. Even after extensive cleanup options, some level of oiling is likely to remain,
- *Initiation of Mangrove Planting:* Mangroves appear likely to survive in areas having some silver and rainbow sheen, and possibly even in areas where substantial brown or black oil is visible when sediments are agitated. In areas

Table 13.16 Summary of mangrove loss and illegal refineries for the study area east of the Bonny River

	Loss of mangroves habitat			Illegal refineries	
Area	Oil-related loss (ha)	Pipeline corridor (ha)	Total (ha)	Number	High ground (ha)
Bonny Island	1058.2	58.2	1116.4	4	0.8
Opobo Channel	280.2	9.3	289.5	0	0
Bonny River	464.9	1.7	466.6	0	0
Bodo West	1096.3	28.1	1124.8	0.87	28.9
Bodo East	1175.9	7.4	1183.3	60	35.4
Bolo	338.7	0	338.7	66	51.2
Total	4414.6	104.7	45,219.3	217	116.2

showing little-to-no oiling, mangrove planting can be initiated without physical cleanup.

- *Cleanup Prioritization:* Priority areas for treatment are contaminated sites within 5 km of human habitation and sites actively releasing moderate to heavy sheen or black oil to waterways.
- *Cleanup methods – Hard Substrates:* Rakes and shovels are preferred to remove oil and avoid sediment removal. Where liquid oil is found under surface oil, low-pressure flushing is advised.
- *Cleanup methods – Soft Substrates:* Includes soft muds where oil or heavy sheen becomes exposed upon agitation. Low-pressure flushing is likely to be effective at releasing oil.
- *Prevention of re-oiling:* Oleophilic snare, sorbents and boom can be used to prevent the spread of released oil.
- *Need for SCAT advice:* SCAT teams should be fielded to determine the level of oiling at each location, recommend and verify cleanup methods specific to each type of habitat, monitor cleanup effectiveness and recommend changes as needed, and to document cleanup activities and completion. SCAT can test and advise on alternative methods such as bioremediation or other environmentally friendly technology.

13.5 Conclusions

This report documents the analysis of multiple satellite images, aerial photographs and ground surveys to determine the probable cause and timing of over 4400 ha of mangrove loss along areas east of the Bonny River between Bonny Island in the south and the mainland areas of Ogu/Onne in the north. In addition, 217 illegal refinery sites damaging 115 ha of palm-dominated supratidal areas adjacent to mangroves are identified.

Outside of the operationally caused spills along Opobo Channel and in Bodo West in 2008, recorded spill incidents are reported as mostly due to illegal hot tapping of the SPDC pipelines transporting oil from the north to Bonny Terminal in the south. After 2009 and into 2010, most mangrove losses are related to spills resulting from hot tapping of pipelines and from the illegal refining and related transport of crude and refined product in open fishing boats.

Smaller areas of mangrove loss as from flooded pipeline corridors, wellhead slots and seismic shot lines (cleared during early exploration of the area) are not included in this analysis, nor are extensively oiled shorelines not having previous mangroves. While this report has located the extent of mangrove loss east of the Bonny River, areas to the west of Bonny River also show large areas of mangrove loss due to oil-related activities and will be a subject of a future study.

Imagery reveals that surface oiling of creeks and channels throughout the area was common from 2009 to 2016. Illegal activities apparently decreased in 2013, and less oil was evident on the water's surface in 2015 during aerial and ground surveys.

The sediments in many areas, particularly in Bodo West and East, show high levels of surface and/or subsurface oiling that will inhibit or prevent mangroves restoration (see Little et al. 2018, Chap. 14, this volume).

Restoration planning for the area is underway. The Bodo Mediation Initiative (BMI) sponsored Shoreline Cleanup Assessment Technique (SCAT) teams in 2015 (and continued in 2017/2018) that identified sites for potential cleanup and established a set of guidelines to ensure that cleanup activities will not cause more harm than good. Mangrove planting is an important part of these guidelines, and can be undertaken immediately in areas that have low or no remaining oil concentrations.

Other studies following the duration of time required for natural regeneration of oil-damaged mangrove areas indicate a time of 30 years and longer. Within the oil damaged study area, some regeneration is seen but is relatively sparse. Affecting factors include remaining oil on surface and subsurface sediments, new oiling spread by intertidal currents from land sites or heavily oiled areas, lack of adjacent seed stock, loss of original base sediments (conversion from organic rich to hard clay), and presence of algal mats. In many areas, the return to a healthy mangrove habitat will never occur without intervention.

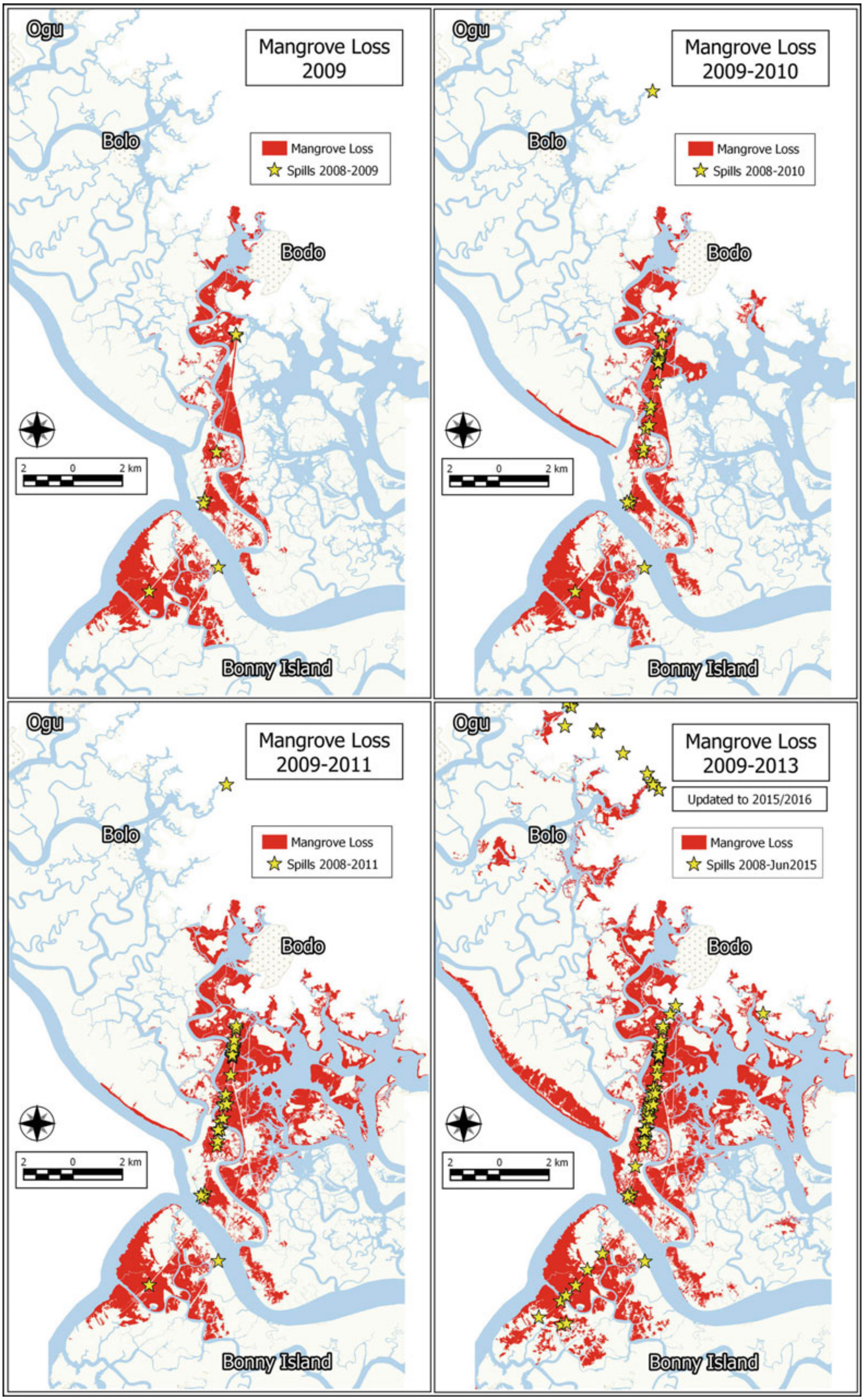

Fig. 13.46 Cumulative mangrove losses for the study area, 2009–2013, with updates in certain areas to 2015 or 2016. The sequence of spill events is from 2008 to June 2015

Table 13.17 Documented mangrove loss >5 ha from oil-related events

Mangrove loss	Event	Location	Citation
338 ha	Funiwa 5 well blowout, 57,150 t crude oil, 1980	Offshore Nigeria	Gundlach et al. (1993)
64 ha	Fuel tank rupture, 200–475 t, medium crude oil, 1986	Bahia Las Minas, Panama	Keller and Jackson (1993)
46 ha	*Witwater*, 2150–2850 t diesel and Bunker C, 1968	Bahia Las Minas, Panama	Duke and Pinzon (1991)
12 ha	Tank leak, JP-5 fuel 380 t, 1999	Roosevelt Roads, Puerto Rico	NOAA (2014)
10.5 ha	Pipeline break, 31,500 t crude oil, 1983	Southeast Brazil	Santos et al. (2012)
5.5 ha	Tank leak, JP-5 fuel 170 t, 1986	Roosevelt Roads, Puerto Rico	Ballou and Lewis (1989)
5 ha	Tanker spill at refinery, 11,250 crude oil, 1971	St. Croix, US Virgin Islands	Lewis (1983)

Table 13.18 Field studies indicating time to full recovery of oil-damaged mangroves

Duration	Characteristics	Location/loss	Citation
20 years and continuing	October 1983, 31,500 t crude oil within 300 ha. Mangroves show reduced structural development and different species composition	Southeast Brazil 10.5 ha	Santos et al. (2012)
23 years and continuing	*Witwater*, 1968. 2150–2850 t diesel and Bunker C	Panama, 46 ha	Keller and Jackson (1993)
31 years and continuing	TROPICS experimental sites treated with dispersed and undispersed Prudhoe Bay crude	Panama, two 900 m^2 sites	Renegar et al. (2017)
29 years and continuing	*Zoe Colocotronis*, 1973, basin mangroves still recovering in 2002, but possible damage from reoiling	Puerto Rico, 2.7 ha	Getter and Lewis (2003)
30 years	Regression curve based on several spills	Various	Duke (2016a)

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