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# Analysis of the Impacts of armed conflict on the Eastern Afromontane forest region on the South Sudan — Uganda border using multitemporal Landsat imagery

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ABSTRACT

The impacts of armed conflict on ecosystems are complex and difficult to assess due to restricted access to affected areas during wartime making satellite remote sensing a useful tool for studying direct and indirect effects of conflict on the landscape. The Imatong Central Forest Reserve (ICFR) in South Sudan together with the nearby Dongotana Hills and the Agoro-Agu Forest Reserve (AFR) in Northern Uganda share a boundary and encompass a biologically diverse montane ecosystem. This study used satellite data combined with general human population trends to examine the impact of armed conflict and its outcome on similar forest ecosystems both during and after hostilities have occurred. A Disturbance Index (DI) was used to investigate the location and extent of forest cover loss and gain in three areas for two key time periods from mid-1980s to 2001 and 2003 to 2010. Results indicate that the rate of forest recovery was significantly higher than the rate of disturbance both during and after wartime in and around the ICFR and the net rate of forest cover change remained largely unchanged for the two time periods. In contrast, the nearby Dongotana Hills experienced relatively high rates of disturbance during both periods; however, post war period losses were largely offset by some gains in forest cover. For the AFR in Uganda, the rate of forest recovery was much higher during the second period, coinciding with the time people began leaving overcrowded camps. The diversity and merging of floristic regions in a very narrow band around the Imatong Mountains makes this area biologically distinct and of outstanding conservation importance; therefore, any future loss in forest cover is important to monitor — particularly in South Sudan where large numbers of people continue to return following the 2005 peace agreement and the 2011 Referendum on Independence.



## 1. Introduction

The direct effects of war on civilians are generally well-understood and have been extensively documented (Clodfelter, 2002; Ismael, 2007; Keegan, 1994; Sidel & Levy, 2008; Tardanico, 2008). The indirect effects of war due to the use of munitions on a nation's land, air and water can also have adverse, long-term and far-reaching effects on human populations and the surrounding environment (Joksimovich, 2000). Often overlooked is the effect of war on land cover, which in turn impacts biodiversity (Dudley & Woodford, 2002), despite the fact that 90% of the major armed conflicts between 1950 and 2000 occurred within countries containing biodiversity hotspots and more than 80% took place directly within the hotspots (Hanson et al., 2009). Several studies have concluded that armed conflict is generally deleterious to plants and animals due to habitat destruction and fragmentation, direct loss of animals from poaching or land mines, over-exploitation and degradation of natural resources, and increases in land and water pollution (Baral & Heinen, 2005; Eniang et al., 2007; Gleditsch, 1998; Jacobs & Schloeder, 2001; Kalpers, 2001; Kanyamibwa, 1998; Messina & Delamater, 2006; Nils Petter Gleditsch, 1998; Pearce, 1995; Shambaugh et al., 2001; Van Houven & Nimir, 2004; Vanasselt, 2003). In some cases, however, wars have been found to have a positive impact on biodiversity, through the formation of “no go zones” due to reduced security, resulting in a decrease in human pressure on the environment and wildlife (Kaimowitz & Faune, 2003; Martin & Szuter, 1999; McNeely, 2003; Nietschmann, 1990; Vogel, 2000).

Difficulty of access to an area during war combined with no clear spatial or temporal definition for the extent of conflict makes an accurate and timely assessment of the impacts extremely challenging (Glew & Hudson, 2007). Because of these limitations, information derived from satellite remote sensing data can provide insight into how conflict *directly* affects the physical landscape during wartime, and *indirectly* leads to changes in human populations and land use activity that drive the observed land cover modifications. For example, data from satellite remote sensing have been used to identify the effects and quantify environmental damages in Kuwait from military activity

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that occurred during the 1990–1991 Gulf War (El-Gamily, 2007; Koch & El-Baz, 1998). Satellite imagery was also used to show how the spraying of defoliants on coca crops in Columbia negatively affected native plant and food crop parcels (Messina & Delamater, 2006) and to monitor the burning of fields, forests and villages by the Turkish army in Kurdistan (De Vos et al., 2008).

Because the impacts of war on the environment are often felt both prior to and following conflict (Machlis & Hanson, 2008), time-series of satellite imagery can be used to monitor the landscape over a longer period to record changes resulting from the effects of war (Pearce, 1995), including the abandonment of agricultural lands (Suthakar & Bui, 2008; Witmer, 2008). One of the more visible effects of war is the imprint left on the landscape due to mass migration and subsequent settlement of people in internally displaced person (IDP) or refugee camps. Much has been written and debated about the impact of IDPs and refugees on the environment, but it is generally agreed that emigration tends to reduce pressure at the origin and increase pressure at the destination (Hugo, 1996), leading to desertification, deforestation, and general land degradation at the latter (Allan, 1987; Biswas & Tortajada-Quiroz, 1996; Ghimire, 1994; Hugo, 1996; Sato et al., 2000). This has significant implications for the environment since the number of forcibly displaced people has risen in recent years, despite a reduction in the actual number of civil conflicts (Cohen & Deng, 2008). Peace can be equally damaging to the environment if mass migration is reversed back to the point of origin, accompanied by resource exploitation necessary to rebuild communities and revive the local economy (Robinson & Sutherland, 2002).

The objective of this study was to use information derived from remotely sensed satellite imagery to compare and contrast changes in forest cover in a cross-border conservation hotspot located on the border of South Sudan and Northern Uganda. We hypothesize that forest cover will remain constant or increase during the war periods on the South Sudan side of the study area as people leave the region and abandon farming and other activities that affect land cover, and that forest cover will decline with migration of people back to the area. In contrast, forest cover is expected to decrease during the war years in the Northern Uganda study area as a result of the heavy concentration of IDP camps located in the study area and then rebound in recent years due to abandonment of the camps.

## 2. Sudan and Uganda conflicts

In January 2005, the historic Comprehensive Peace Agreement (CPA) put an end to nearly fifty years of civil war in Sudan (excluding a period of peace from 1972 to 1983) that resulted in an estimated two million dead and over four million IDPs (Haynes, 2007). The war largely pitted the Arab-dominated North against the Christian/animist South in a multifarious conflict that had wide-reaching impacts on neighboring countries, due in large part to the outpouring of some 600,000 Sudanese refugees, mainly into Uganda, Kenya, Ethiopia and the Democratic Republic of Congo (Burr & Collins, 1995; UNHCR, 2007a; USAID, 2006). Nearly all Southern Sudanese who stayed in the country migrated north to IDP camps in and around Khartoum and the 'transition zone' border area between Northern and Southern Sudan (Duffield, 2002). One of the few exceptions was the Laboni IDP camp located in Southern Sudan's Eastern Equatoria State, where in 1992 thousands of people from the Bor Dinka ethnic group were relocated due to inter-ethnic fighting (Dowden, 1994), and who have since migrated north to Jonglei State following the 2005 Peace Agreement.

Since 2005, an estimated two million refugees and IDPs have returned to Southern Sudan (Hovil, 2010). According to the official 2008 census for Southern Sudan, the total population was 8.26 million, compared with an estimated 6 million in 2005 (OCHA, 2006) and 5.3 million in 1983 (House, 1989). And while no official population estimates are available since 2008, widespread returns in advance of the January 2011 Referendum on Independence – including more than 180,000 returnees over a period of just three months – have caused the population to surge to an estimated 9.5 million according to OCHA (IRIN February, 2011).

In neighboring Uganda, around 90% of the population in the north had similarly been uprooted as a result of conflict — in this case between the Lord's Resistance Army (LRA) and government forces (Miller, 2006). The seeds of the war were planted in 1986 after Ugandan President Yoweri Museveni took power through an armed uprising, that resulted in the fleeing of soldiers loyal to the old regime, many of whom were of the Acholi and Lango tribes whose villages and towns were located on the northern border with Sudan (Ochan, 2009). Opposition to the new regime gave rise to various resistance movements, most notably the LRA, led by the notorious Joseph Kony, whose terrorist tactics have resulted in decades of brutality against civilians in Uganda, Sudan and the Democratic Republic of Congo (Eichstaedt, 2009). As with Southern Sudan, the civil war in Uganda led to mass upheaval of the local population. While some fled to neighboring countries, the majority of civilians were forced to relocate into overcrowded IDP camps in the north of Uganda as part of a 'protected villages' policy that began in 1996 in an effort to isolate LRA combatants (http://www.c-r.org/accord). This policy was reversed in 2006 due to improvements in the security situation, such that only 73,239 IDPs (of the original 1.8 million) remain in Northern Uganda as of March 2011. According to the Internal Displacement Monitoring Centre (IDMC), this figure is down from 166,000 IDPs in November 2010, 295,000 IDPs in June 2010, 437,000 IDPs in December 2009, 710,000 IDPs in February 2009, 869,000 IDPs in November 2008 and 915,000 IDPs in October 2008.(IDMC fact sheet — http://www.internal-displacement.org/idmc/website/countries.nsf/(httpEnvelopes)/2439C2AC21E16365C125719C004177C7?OpenDocument).

## 3. Methods

### 3.1. Study area

The Imatong Mountains are located on the South Sudan — Uganda border between 3°40′ and 4°20′ North latitude and 32°30′ and 33°10′ East longitude (Fig. 1). The mountains form a northern continuation of the upthrusts as part of the great East African mountain systems (Chipp, 1929). The entire study area covers 8375 km$^2$. The boundaries of the study region were selected to include the Imatong Central Forest Reserve (ICFR) and the Agoro-Agu Forest Reserve (AFR), as well as another region with significant forest cover, the Dongotana Hills located to the northeast of the Reserve (Figs. 1 and 3). The ICFR spans 1032 km$^2$ (Sommerlatte & Sommerlatte, 1990) and the Agoro-Agu Forest Reserve is 236 km$^2$ (Davenport & Howard, 1996). The forested area of the Dongotana Hills is approximately 21 km$^2$. The ICFR was named a forest reserve in 1952 (Sommerlatte & Sommerlatte, 1990); however, actual management and law enforcement have been lacking as a consequence of the civil war. Altitudes in the study region vary from 568 m to 3172 m above sea level (A.S.L.). The mountains consist of granitic crystalline rocks, most of which are folded and foliated and soils largely fall within the following four categories: (1) dark cracking clays, (2) non-cracking clays, (3) red loam and ironstone soils, and (4) hill or mountains soils (Friis & Vollesen, 2005).

Precipitation over the Imatong Mountains follows a gradient with a general decline from west to east, where a rain shadow has the effect of creating much drier environments along the escarpment and ridges. Precipitation increases with altitude, resulting in a transition of the montane forest zone to the alpine zone. Rainfall across the study region is seasonal with the rainy season beginning in late March and lasting until the end of October (Sommerlatte & Sommerlatte, 1990) (Fig. 2a). The climate is temperate and fairly

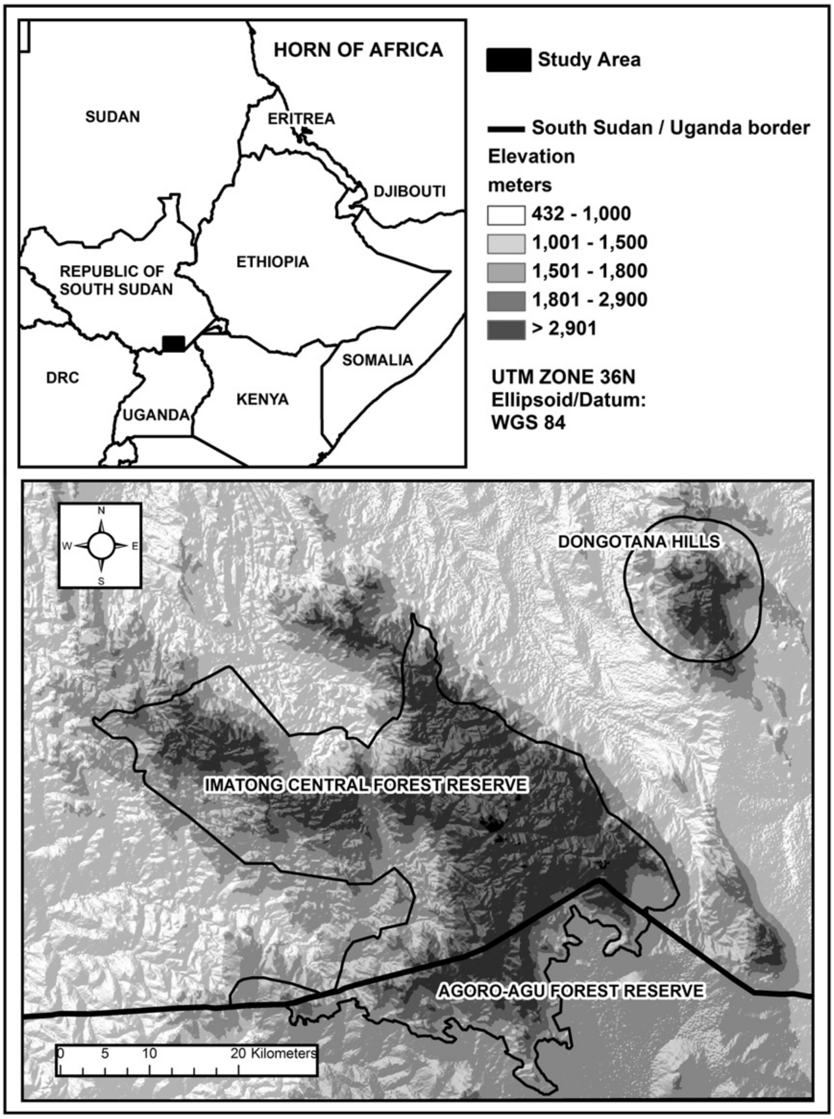


**Fig. 1.** Study area located in South Sudan and Northern Uganda.

constant throughout the season with warm day time temperatures up to 35 °C and cooling to 15 °C at night (at Katire, 800 m A.S.L.) (Fig. 2b). Major vegetation types range from *Albizia-Terminalia* woodland and savanna in the lowland zone to *Erica* thicket in the Ericaceous zone. The associated floristic affinities and location are summarized in Table 1. There are three major areas of lowland rain forest at Lotti, Talanga and Laboni and these are not or only partially included in the ICFR (Jackson, 1953) (Fig. 3). Aerial observations in 2009 indicate that of these forests, only the Lotti remains largely intact.

Precise population data for the ICFR and surrounding area are not available; however, discussions with local residents in early 2009 indicated that improvements in the security situation since 2005/2006 have led to a significant rise in the number of people returning to resettle in the area. In Eastern Equatoria, the State where the Imatong study area is located, total population increased from between 537,822 to 632,760[1] in 1998 and 906,126 in 2008 alone (Southern Sudan Centre for Census, 2010).

[1] The lower estimate is provided by the Sudan Relief and Rehabilitation Association (SRRA) — the humanitarian agency of the Sudan People's Liberation Movement (SPLM). The higher estimate is derived from the World Health Organization (WHO) Sudan National Immunization Days (SNID) campaign to eradicate Polio.

The adjacent Agoro-Agu Forest Reserve is located within Lamwo county in the extreme north of Kitgum district of Uganda between 3°40–3°53′ N and 32°42′–33°04 E. It has an altitudinal range of 1100 to 2700 m A.S.L. (Davenport & Howard, 1996) (Fig. 1). A 1996 study commissioned by the Ugandan Forest Department – limited in its scope due to the security situation – recorded moderate to high levels of biodiversity and noted that the Reserve was extensively encroached throughout the lower and medium altitude areas, particularly in the southern and eastern sections (Davenport & Howard, 1996). Results from this study (described below) confirm that the majority of observed forest loss during this time occurred at lower altitude areas, when the forest was being used by locals for harvesting trees for building poles, honey collection, bushmeat and medicinal plants. Though not specifically documented, it is likely that similar to the IDP camps in Pader district, the presence of these camps in and around the AFR had a negative impact on the surrounding land and forests (Owona, 2008). Since 2006, the number of people living in the IDP camps in Northern Uganda has dwindled, as discussed in Section 2 of this paper.

Although the forests of the Dongotana Hills are similar in structure and composition to those of the ICFR and the AFR, the area has never formally been declared as a conservation reserve. The closest large town, Ikotos, is located due south of the Dongotana Hills (Fig. 3),

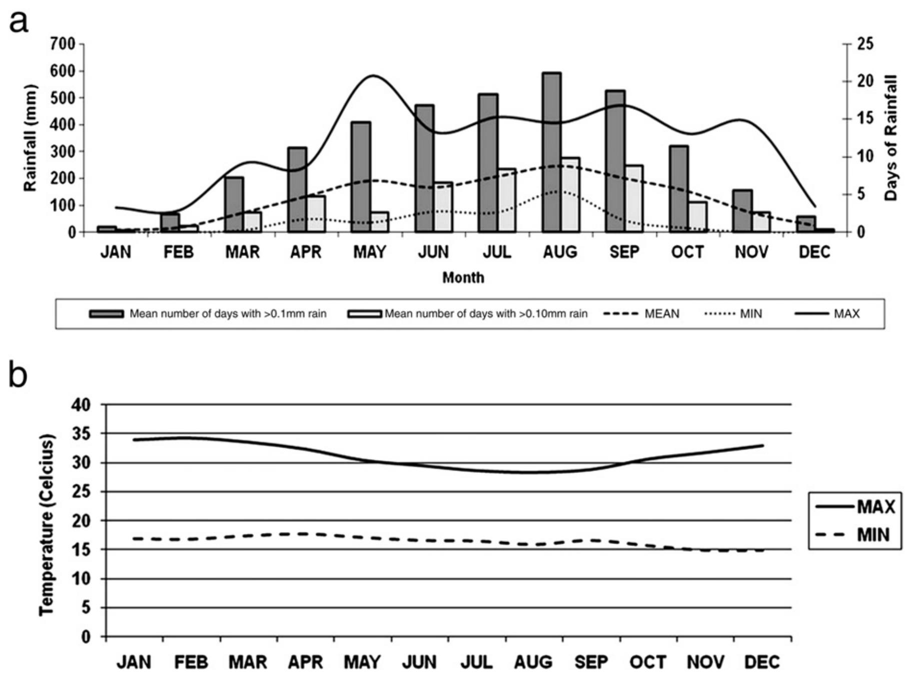


**Fig. 2.** a. Average rainfall for Katire, South Sudan. b. Average temperature for Katire, South Sudan.

with an estimated population of 20,242 in 2007 including small villages surrounding the town (UNHCR, 2007b).

### 3.2. Technical approach

This study used data layers created from analysis of multi-scale remote sensing data in a geographic information system (GIS) to detect changes in forest cover occurring in the study area. Within the study area, three separate areas – all with similar vegetation – were compared in terms of change in forest cover over time. These areas include 1) the ICFR and a 5 km buffer on the South Sudan side only; 2) the AFR and a 5 km buffer on the Ugandan side only (with the exception of a small area not covered by the Landsat scenes representing approximately 6% of the entire area); and 3) the Dongotana Hills and a 5 km buffer (Fig. 3). The outlines of the forest reserves were supplied by the Wildlife Conservation Society (WCS) and are currently used by the various non-governmental organizations (NGOs) working in the area and the Government of South Sudan (GOSS) and have been documented by prior studies of the area (Sommerlatte & Sommerlatte, 1990); the extent of the Dongotana Hills was created by digitizing the forest outlines of a pre-existing Africover data product (Di Gregorio & Jansen, 2005). A buffer area around each of the reserves was created for the ICFR and the AFR since previous research has shown that areas adjacent to established protected areas are often subject to extensive forest loss due to human pressures (DeFries et al., 2005; Hansen & DeFries, 2007). A distance of 5 km was specifically selected to be consistent with other similar studies related to African protected areas (Bergl et al., 2007) and best practice guidelines (Morgan & Sanz, 2007). And for Southern Sudan specifically, a USAID-commissioned report determined that IDP camp residents generally traveled from between 2 and 6 km in search of firewood, which is relevant to this study since we are examining the impact of people on the forest (USAID, 2003).

Spatially explicit data were derived over the study area using moderate (30 m) spatial resolution satellite data (described in the Data section below) acquired for two primary study periods roughly representing years of ‘war’ and ‘peace’. The first period is from mid-1980s to 2001 during which time both Sudan and Uganda were heavily embroiled in their respective conflicts. The second period covers 2003 to 2010, when peace and stability slowly began to return to both countries — peace was formally declared in Sudan in 2005 with the signing of the Peace Agreement, and shortly thereafter the LRA moved its base further west creating a respite from attacks in the study area and allowing civilians in northern Uganda to leave the IDP camps.

**Table 1**
Floristic affinities of the main vegetation types found in the Imatong Mountains.

| Floristic affinities | Altitude zone | Elevation (m) | Vegetation type |
|---|---|---|---|
| Sudanian | Lowland zone | 1000–1500 | *Albizia–Terminalia* woodland and savanna woodland (on the wet western side) |
| Somalia-Masai | Lowland zone | 1000–1500 | *Acacia–Combretum* wooded grassland and savanna woodland (on the dry eastern side) |
| Guineo-Congolian | Lowland to intermediate zone | 1000–1800<br>1200–1500 | *Khaya-Cola* forest<br>*Khaya-Syzgium* forest<br>*Entandrophragma-Manilkara* forest |
| Afromontane | Lower montane zone | 1200–2400 | *Loudetia* grassland<br>*Acacia abyssinica* woodland<br>*Croton-Macaranga-Albizia* forest<br>*Oxytenanthera* bamboo thicket<br>*Podocarpus-Olea-Syzygium* forest |
| | Upper montane zone | 2400–2900 | *Hagenia-Maesa* woodland<br>*Hagenia-Hypericum* woodland<br>*Podocarpus-Olea* forest<br>*Podocarpus-Dombeya* forest<br>*Exotheca* grassland<br>*Carex* sedge swamp |
| Afroalpine | Alpine or Ericaceous zone | >2900 | Erica thicket |

### 3.3. Data

We acquired four pairs of Landsat TM and ETM+ images (Worldwide Reference System (WRS) path/rows: 171/57 and 172/57), representing both the ‘war’ and ‘post-war’ periods described above.

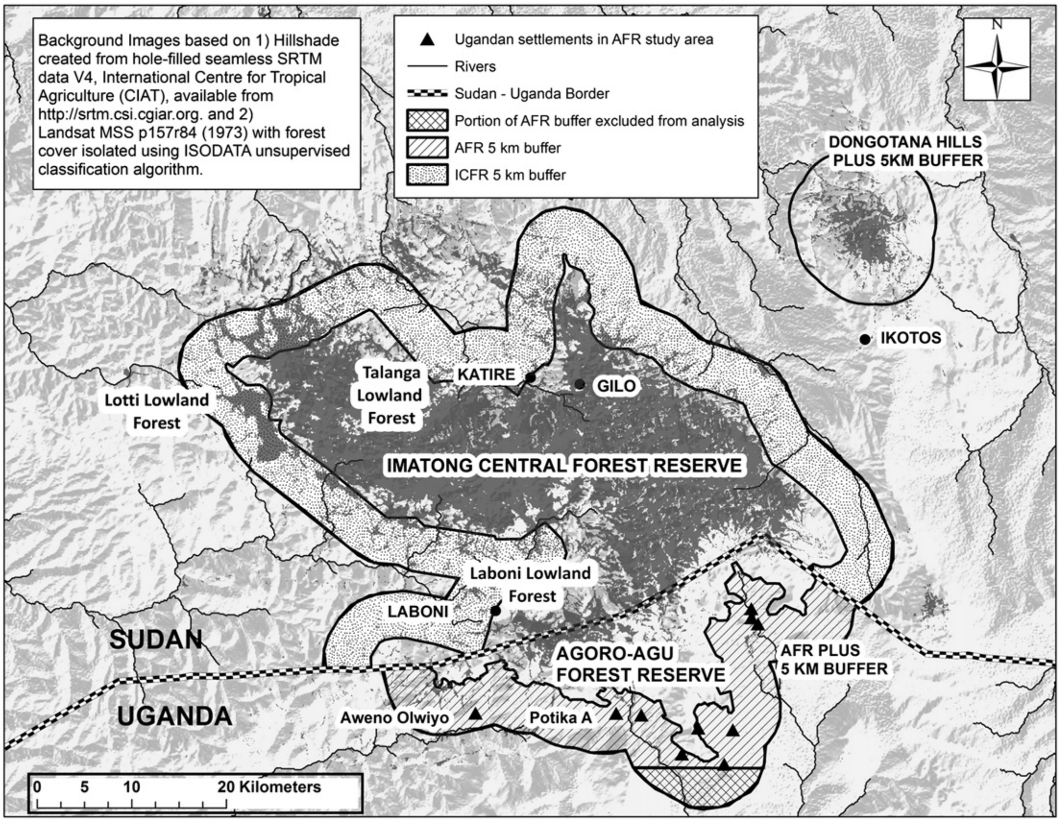


**Fig. 3.** Select areas of analysis in South Sudan and Northern Uganda.

For Landsat p171r57, the acquisition dates were 01-13-1987, 01-27-2001, 01-17-2003, and 12-14-2010. For Landsat p172r57, the acquisition dates were 01-17-1986, 01-02-2001, 02-09-2003, and 12-21-2010 (Table 2). Eight scenes were necessary because the study area is situated at the edges of path/row 172/57 and 171/57. All of the Landsat scenes were acquired during the dry season and on near-anniversary dates, to reduce scene-to-scene variation and to minimize the introduction of spurious changes due to changes in topographic shadowing, sun angle and vegetation phenology (Hayes & Sader, 2001; Singh, 1989). To assess whether changes in seasonal plant phenology influenced the spectral signatures from the Landsat TM and ETM + imagery used for this study, we analyzed data from the 16-day normalized difference vegetation index (NDVI) product (MOD13Q1) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra (EOS AM) satellite for years 2000 to 2010. Other studies have shown that despite differences in spectral and spatial resolution, comparisons of NDVI values across satellite sensors – including MODIS and Landsat – show general agreement (Brown et al., 2006). Results confirmed that the NDVI values for the days when Landsat images were acquired were congruent with the long-term average NDVI for that month implying that the Landsat scenes were representative of the mean phenological condition occurring in this area during the middle of these dry season months.

Administrative boundaries, settlements including villages and IDP camps, and the reserve boundaries were obtained from a variety of organizations with in-depth knowledge of the area. High resolution imagery for 2010 over a significant portion of the study area was not available. Therefore, validation of the results was performed using the existing 2003 and 2010 Landsat imagery over the entire region combined with aerial photos for two select regions during the second time period (Table 2).

### 3.4. Methods

To classify forest cover and forest cover change, we initially explored the efficacy of both post-classification comparison and direct change detection methods (Foody, 2004; Johnson & Kasischke, 1998). Ultimately, the selected change detection procedure was based on the Disturbance Index (DI) methodology, which uses different combinations of indices generated by the Tasseled Cap transformation to quantify changes in the forest canopy (Healey et al., 2005). The Tasseled Cap transformation reduces the Landsat reflectance bands to three orthogonal indices or features by creating weighted sums from all Landsat reflectance bands (Crist & Cicone, 1984; Kauth & Thomas, 1976) and has been widely used by researchers to monitor changes in land and forest cover (Franklin et al., 2001; Parmenter et al., 2003; Skakun et al., 2003). The first feature – 'brightness' – is defined in the direction of the principal variation in soil reflectance; the second feature – 'greenness' – represents a contrast between the near-infrared and visible bands and correlates closely with the amount of green vegetation in the image (Lillesand et al., 2003). The third feature – 'wetness' – was intended to be used to examine variations in soil and canopy moisture (Parmenter et al., 2003), but has also been shown to be sensitive to variations in forest stand structure (Cohen et al. 1995). The DI transformation was developed to isolate un-vegetated spectral signatures associated with stand-replacing disturbance and is based on the assumption that areas where forest cover has been reduced will have a higher Tasseled Cap brightness value and lower Tasseled Cap greenness and wetness values than undisturbed forest areas (Healey et al., 2005). The DI has been used in other studies to show the differentiated effects of socio-economic changes on forest disturbance (Kuemmerle et al., 2007).

Precise geometric correction of images is critical when performing change detection analyses (Coppin et al., 2004; Kuemmerle et al.,

**Table 2**
Datasets and characteristics from data used for this study.

| Dataset | WRS: (P/R) | Spatial res. | Acquisition date | Producer | Attributes | Parameter of interest | Data source |
|---|---|---|---|---|---|---|---|
| Landsat 5 TM | 171/057 | 30 m | 1987-01-13 | USGS/GLCF | Orthorectified, GLS 1990 | Forest cover | GLCF |
| Landsat 7 ETM+ | 171/057 | 30 m | 2001-01-27 | USGS/GLCF | Orthorectified, GLS 2000 | Forest cover | GLCF |
| Landsat 5 TM | 172/057 | 30 m | 1986-01-17 | USGS/GLCF | Orthorectified, GLS 1990 | Forest cover | GLCF |
| Landsat 7 ETM+ | 172/057 | 30 m | 2001-01-02 | USGS/LP DAAC | L1T LPGS | Forest cover | GLOVIS |
| Landsat 7 ETM+ | 171/057 | 30 m | 2003-01-17 | USGS/LP DAAC | L1T LPGS | Forest cover | GLOVIS |
| Landsat 5 TM | 171/057 | 30 m | 2010-12-14 | USGS/LP DAAC | L1T LPGS | Forest cover | GLOVIS |
| Landsat 7 ETM+ | 172/057 | 30 m | 2003-02-09 | USGS/LP DAAC | L1T LPGS | Forest cover | GLOVIS |
| Landsat 5 TM | 172/057 | 30 m | 2010-12-21 | USGS/LP DAAC | L1T LPGS | Forest cover | GLOVIS |
| MODIS (MOD13Q1) | H21v08 | 250 m | 2000–2010 dry season months | USGS/LP DAAC | 16 day NIR reflectance | NDVI | WIST |
| Aerial photographs | Within 171/057 and 172/057 | varies | 2009-01-30 and 2009-01-31 | WCS | 500–700 ft above ground | Land cover and land use | WCS |
| South Sudan Settlements | N/A | 1: 1,000,000 | Updated on January 2007 | DEPHA | Reliability of Data = Primary Source | Human Settlements | SIM |
| Administrative boundaries for South Sudan | N/A | 1: 1,000,000 | 1996 | USAID/FEWS/ARD | Unknown attribute reliability | South Sudan/ Uganda border | DEPHA |
| Northern Uganda IDP camps and villages | N/A | 1: 1,000,000 | 2009 | OCHA | Unknown attribute reliability | IDP camps and villages in Kitgum District | GEO — IM Working Group www.ugandaclusters.ug |
| Imatong Central Forest Reserve and Agoro-Agu Forest Reserve | N/A | 1: 1,000,000 | 2009 | WCS South Sudan and Uganda Programs | Unknown attribute reliability | Forest Reserve Outlines | WCS South Sudan and Uganda Programs |

ARD = Associates in Rural Development
FAO = Food and Agriculture Organization
FEWS = Famine Early Warning System
GLCF = Global Land Cover Facility
GLOVIS = Global Visualization Viewer
JLC = Joint Logistics Commission
LP DAAC = Land Processes Distributed Active Archive Center
MODIS = Moderate Resolution Imaging Spectroradiometer
SIM = Sudan Interagency Mapping (includes contributions from OCHA, FAO, JLC, and UNMIS — see below)
OCHA = Office for the Coordination of Humanitarian Affairs
UNMIS = United Nations
USAID = United States Agency for International Development
USGS = United States Geological Survey
WCS = Wildlife Conservation Society
WIST = Warehouse Inventory Search Tool

2007). Therefore, all scenes acquired for this study were pre-processed by their producer (U.S. Geological Survey or the Global Land Cover Facility) as part of the Global Land Survey (GLS) collection, which improves upon the previous GeoCover product by using more accurate elevation data (SRTM) for terrain correction. The GLS dataset is compatible with the L1T scenes acquired directly from USGS, which is similarly precision- and terrain-corrected. Both TM and ETM+images were resampled to 30 m pixel size using the Cubic Convolution (CC) method. All scenes used the Level 1 Product Generation System (LPGS), further minimizing any potential geometric, radiometric, and data format differences between scenes. An extensive visual inspection and comparison of all eight images indicated that no further geometric adjustments were necessary. Each of the eight Landsat TM and ETM+images was then converted to at-satellite reflectance prior to analysis (Chander & Markham, 2003).

The stacked images were then transformed to 'greenness' 'brightness' and 'wetness' using coefficients for the derived Tasseled Cap Transformation based on at-satellite reflectance (Huang et al., 2002). Next, for each Landsat image, a 'mature forest' unsupervised classification was performed using the Iterative Self-Organizing Data Analysis (ISODATA) classifier, with masks for clouds and shadows applied where necessary. A separate mask was then created for each 'mature forest' year and used to normalize the Tasseled Cap brightness, greenness, and wetness components to that of the mature forests using the following equations (Healey et al., 2005):

$$B_r = (B - B_\mu)/B_\sigma$$
$$G_r = (G - G_\mu)/G_\sigma$$
$$W_r = \left(W - W_\mu\right)/W_\sigma$$

where $B_r$, $G_r$, $W_r$ is rescaled Brightness, Greenness and Wetness. $B_\mu$, $G_\mu$, and $W_\mu$ is mean Brightness, Greenness and Wetness of 'mature forest' and $B_\sigma$, $G_\sigma$, and $W_\sigma$ is the standard deviation of Brightness, Greenness and Wetness. Once the images were rescaled, the disturbance index (DI) was calculated following:

$$DI = B_r - (G_r + W_r)$$

Forest cover change was then assessed for each multi-temporal stack for each side of the study area (Landsat scene p172r057: 1986–2001 and 2003–2010 and Landsat scene p171r057: 1987–2001 and 2003–2010) by creating a differenced image for each period of interest (war = 1986/87 to 2001 and peace = 2003 to

2010) so that positive numbers would indicate forest recovery and negative numbers would indicate forest disturbance.

The mean and standard deviation values were calculated for each differenced image, with a cloud and shadow masks applied where appropriate. Using a threshold value of mean +/− two standard deviations, pixels of forest loss and forest gain were identified and isolated for import to ArcGIS. Isolated classified pixels were removed by applying a post-classification filter. Finally, to ensure that observed reductions in forest cover between periods were in fact occurring in areas that had previously been vegetated, the Normalized Difference Vegetation Index (NDVI) – a commonly used surrogate measure representing the density of green vegetation on land – was calculated for the earlier image for both periods using the equation

$$\mathbf{NDVI} = (\mathbf{NIR}\text{–}\mathbf{Red})/(\mathbf{NIR} + \mathbf{Red}),$$

and a mask applied to the initial results using a threshold value of 0.3 that was selected by comparing the computer-generated threshold ranges using the density slice function of ENVI 4.8 with the original Landsat image (bands R = 4, G = 3, B = 2).

When using an image differencing approach like the one described here, the selection of a threshold to separate real and spurious change can be somewhat subjective and results are improved when the analyst has first-hand knowledge of the region (Hayes & Sader, 2001). In this case, the threshold was based on our knowledge of the landscape from a 2009 field visit, combined with examination of publically available imagery visible on Google Earth which used 2.5 m resolution SPOT (Satellite pour l'Observation de la Terre) Image dated 2011. During the 2009 visit, the use of a global positioning system (GPS) during aerial reconnaissance flights provided the locations of forested and deforested areas within the ICFR. Therefore, the forest loss and gain thresholds for each differenced image were selected by first using the initial automated results generated by the ENVI remote sensing software and by then examining these against the original composite images to visually corroborate where forest cover had been lost or gained for each side and for each period, and modifying the threshold accordingly. 'Forest loss' and 'forest gain' pixels were then masked and merged to create 'forest loss' and 'forest gain' masks for the entire study area.

The accuracy assessment was conducted using a 'nested approach' and followed standard validation protocol (Congalton & Green, 1999; Thomas et al., 2011). First, we selected 100 points for each of the three classes – unchanged, forest gain, and forest loss – based on a stratified random sample technique. High resolution imagery over a significant portion of the study area is not available; therefore, we used the existing Landsat 2003 and 2010 moderate resolution images to visually compare each sample site and label it accordingly based on a careful comparison of the image pairs. This visual analysis approach has been successfully used by researchers to validate the accuracy of disturbance in other areas (Huang et al., 2009; Thomas et al., 2011). Overall accuracy using this method was 81.67% with a Kappa Coefficient of 0.722 (Table 3a).

Next, we related specific areas to field observations obtained during a January 2009 aerial survey, conducted using a small high wing aircraft (Cessna 206). This one-year discrepancy between the aerial photos (January 2009) and the most recent Landsat imagery (December 2010) was the best possible temporal matching given the general lack of data available for the area. At this time, a log of the flight track was recorded using a handheld GPS on a one-second time setting. Observations were recorded on both sides of the airplane along the flight path; however, for the validation only photos from the front-seat observer (FSO) were used as these photos were specifically taken vertically out of the open front window at pre-selected points as well as at frequent intervals along the flight path. The survey zone centered on the main massif and within 10 km of the massif and was restricted to South Sudan only. To achieve representative coverage, surveys were conducted along altitude bands and each quarter of a degree cell was visited. The reconnaissance flights were flown at various speeds and altitude due to the mountainous terrain with average speeds at approximately 145 km/h. and at a height of 500–700 ft above ground. The aerial flight took place over a two-day time period for a total of 10 h. All photographs were then geo-referenced using the GPS track log.

We overlaid our 2009 aerial flight plan and points depicting where photos had been taken over the change map to identify two major areas where a) significant change had occurred during the 2003–2010 time period and b) aerial photos were available. These were the Laboni IDP camp (recovery/gain) and the Dongotana Hills (disturbance/loss) (see Figs. 3 and 5). The number of aerial photos was extremely limited, therefore, we manually selected a point roughly centered within each of these two geographical areas, and included it, along with nearly all of the remaining sample points on either side of the centered point, amounting to a total of 36 sample points for both areas. We then visually compared the photos with the change map results. Overall accuracy using this approach was 91.67% with a Kappa Coefficient of 0.762 (Table 3b).

## 4. Results

Fig. 4 presents the results for each of the three areas. For the ICFR, the rate of forest recovery was significantly higher than the rate of disturbance both during and after wartime and the net rate of forest cover change remained largely unchanged for the two time periods. In contrast, the nearby Dongotana Hills experienced high rates of disturbance during both periods; however, post war period losses were largely offset by some gains in forest cover. For the AFR in Uganda,

**Table 3a**
Accuracy assessment using original Landsat imagery.

| Predicted Class | | Observed class | | | | |
|---|---|---|---|---|---|---|
| | | No change | Forest loss | Forest gain | Total | Commission (percent) |
| | No change | 102 | 31 | 17 | 150 | 32.00 |
| | Forest loss | 2 | 72 | 1 | 75 | 4.00 |
| | Forest gain | 4 | 0 | 71 | 75 | 5.33 |
| | Total | 108 | 103 | 89 | 300 | |
| | Omission (percent) | 5.56 | 30.1 | 20.22 | | |

Overall Accuracy = 81.67%
Kappa Coefficient = 0.722

**Table 3b**
Accuracy assessment using aerial photographs.

| | | Observed class | | | | |
|---|---|---|---|---|---|---|
| | | No change | Forest loss | Forest gain | Total | Commission (percent) |
| Predicted Class | No change | 27 | 3 | 0 | 30 | 10.00 |
| | Forest loss | 0 | 4 | 0 | 4 | 0.00 |
| | Forest gain | 0 | 0 | 2 | 2 | 0.00 |
| | Total | 27 | 7 | 2 | 36 | |
| | Omission (percent) | 0.00 | 42.86 | 0.00 | | |
| | Overall Accuracy = 91.67% | | | | | |
| | Kappa Coefficient = 0.762 | | | | | |

the rate of forest disturbance was only slightly higher during the first period while the rate of forest recovery increased markedly during the second period (Fig. 4).

The location of forest cover loss and gain for both periods is shown in Fig. 5a and b. For the ICFR and its buffer, most of the forest gain during the war period occurred in the forest interior, and within the Lotti Lowland Forest. The pronounced circular patch of renewed forest cover in Fig. 5a is likely due to secondary growth in and around the former Talanga tea estate. Forest loss during this time occurred mainly near the Laboni IDP camp, which saw a large influx of Bor Dinka peoples in the early 1990s. This same area shows a minor increase in forest cover during the post-war years, following the return of IDPs from Labone to their former villages further north (Fig. 5b). In the AFR and its buffer, forest cover loss occurred in the southwest portion of the 5 km buffer area, near the village of Aweno Olwiyo village and Potika A IDP camp, and increases in forest cover for the second period occurred near this same area (Fig. 5a and b). In the Dongotana Hills, forest cover loss was pronounced around the perimeter of the montane forest during the conflict years, particularly on the southern side; post-conflict forest cover loss in the Hills was concentrated on the northern tier (Figs. 5a, b and 6).

## 5. Discussion

One possible explanation for the high rates of forest recovery within the ICFR interior is a reduction in human-induced fire activity leading to the spread of vegetation in previously open areas. The presence of the LRA and other factions in the ICFR seems to have had a negligible impact on forest cover during the earlier time period. This may be due to the fact that trees were used to ensure secrecy of troop whereabouts, and/or because villagers who under normal circumstances would promote conversion of forests to cropland, were forced to abandon their homes during this tumultuous time. However, if this is the case, one would expect an increase in the rate of disturbance during the second time period, but in fact the rate of forest cover loss actually declines slightly suggesting that precise, fine-scale demographic data are needed to fully understand where returnees are resettling and how their land use practices are affecting forest cover.

As expected in the AFR, forest cover rebounded slightly during the second period — likely due to the abandonment of IDP camps beginning in 2006 resulting in regrowth of previously destroyed and degraded forests. Interestingly, very little forest cover loss or gain occurs in the heavily forested area near the border with South Sudan — perhaps because this area was restricted and/or inaccessible to locals and if so, it is possible that this tract of forest is still largely intact. The location of forest recovery is concentrated approximately 5 km from the Aweno Olwiyo IDP camp. While in general this is a reasonable distance to expect to see changes in forest cover resulting from demographic change near an IDP camp (USAID, 2003), the lack of observed change in other areas indicates that additional fine-scale imagery combined with socio-economic surveys is necessary to fully understand the land cover and land use dynamics occurring here.

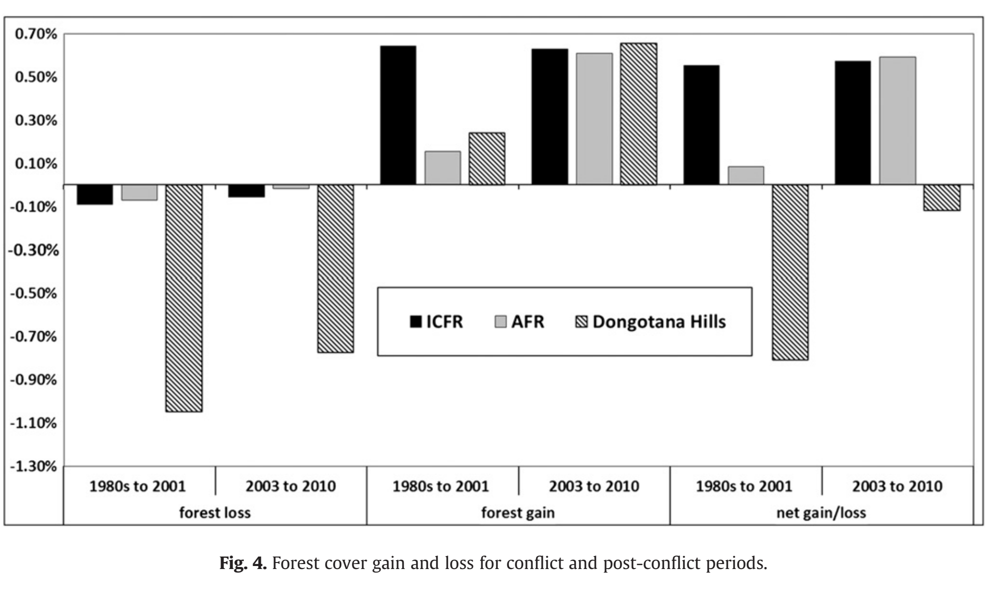


**Fig. 4.** Forest cover gain and loss for conflict and post-conflict periods.

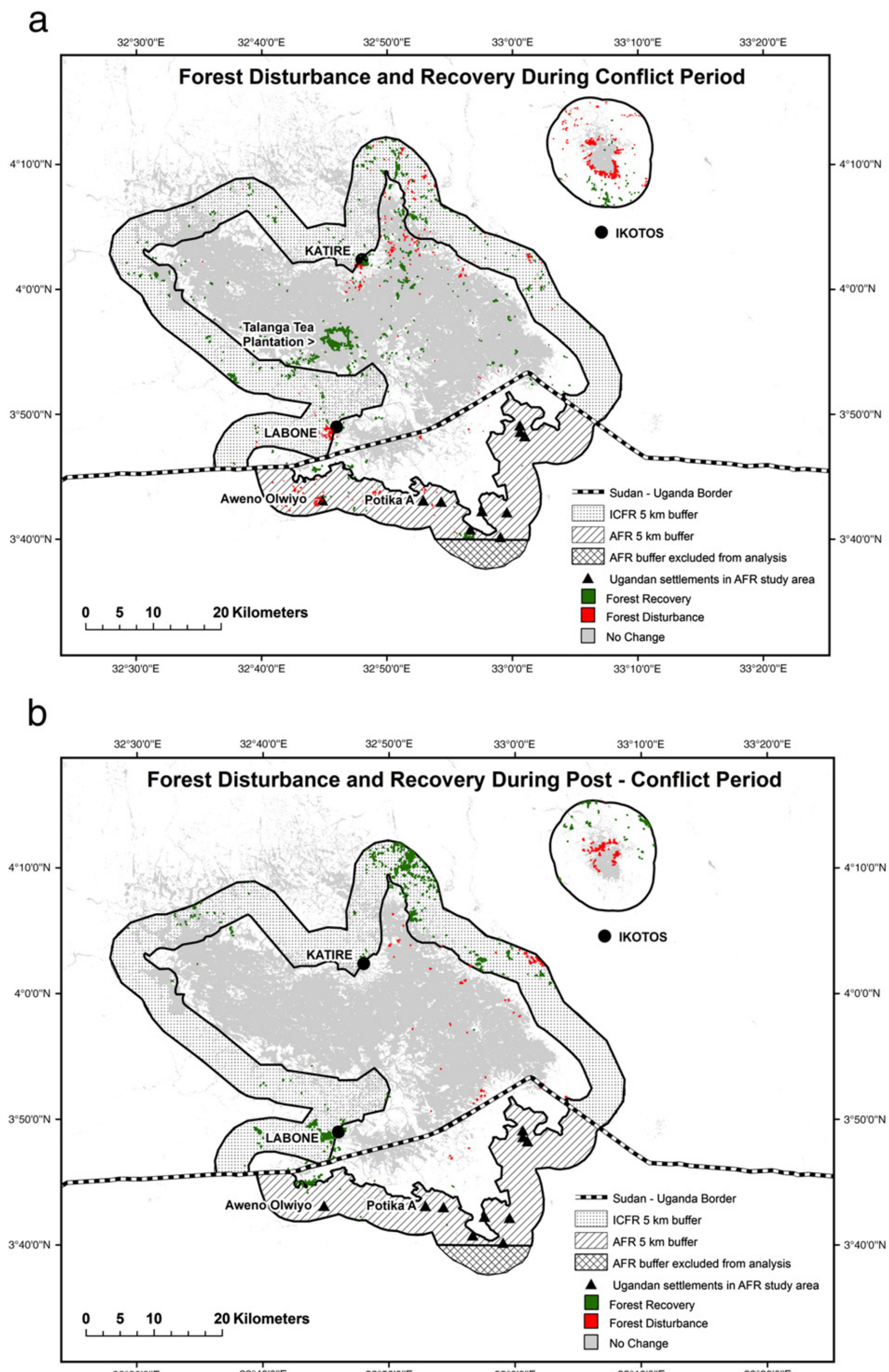


**Fig. 5.** a. Location of forest cover gain and loss during conflict period (mid-1980s to 2001). b. Location of forest cover gain and loss during post-conflict period (2003 to 2010).

In the Dongotana Hills, forest cover loss during both periods is pronounced and is corroborated by aerial photos taken of the area in 2009 (Fig. 6). One explanation is that unlike the ICFR, the montane forest ecosystem has never been under formal protection as a National Park or Reserve. More likely is the fact that as a relatively small patch of forest with numerous villages in the immediate vicinity, this area is easily accessible to people who depended on the forest and forest product during the war to survive and continue to use the forest to rebuild their communities. This 'ease of access' notion is supported by the fact that most of the clearing of forest in this area is for agriculture so that early forest removal occurred in the south where the slope is less pronounced than in the north.

The relatively long time interval for the 'war period' of nearly fifteen years was unavoidable due to the lack of available, cloud-free Landsat imagery in intervening years. As a result it is likely that all of the disturbance occurring during this period was not adequately captured (Masek et al., 2008).

## 6. Conclusion

Results from this study indicate that changes in forest cover are generally consistent with what one would expect as a result of population and land use changes associated with civil war. In contrast to other forested regions of the world that have experienced extensive

**Fig. 6.** Photograph of northern side of the Dongotana Hills taken during 2009 overflight.

losses such as the Amazon Basin at roughly 0.45% per annum from 1990 to 2000 (Rojas-Briales & Ze Meka, 2011), losses in the most heavily disturbed of the three study areas – the Dongotana Hills – are by comparison quite minimal. However, given the recent rise in population for all of South Sudan and the heavy dependence of people on the forests for food, fuel and construction materials, future planned development should consider how additional human pressure could impact long-term sustainability of the region. At the same time, the fact that the ICFR was largely left intact during and immediately following the war in Sudan is encouraging and these findings should be used to encourage the creation of a National Park to protect key vegetation types and their associated biodiversity. Finally, results for the Agoro-Agu Forest Reserve offer a hopeful sign that a reduction in population pressure is allowing for recovery of forests in this area, potentially paving the way for a trans-boundary park with South Sudan, as has been proposed by the Wildlife Conservation Society (Grossmann et al., 2009).

A major challenge highlighted by this paper is interpreting results in the absence of fine-scale population data or other information that could help validate results and/or provide in-depth explanation of observed changes. Yet it is precisely because of the conflict that this information is unavailable. The end of hostilities in both Southern Sudan and in Northern Uganda provides an opportunity to corroborate findings and further investigate underlying causes of land use change and to use this newfound understanding as the basis for conservation and land use planning efforts for the region.

Rapid changes in human population migration due to conflict can leave a lasting impact on the natural landscape. As this study shows, whether the effects lead to an increase or decrease in forest cover depends on numerous underlying factors that cannot be explained through remote sensing technologies alone. Yet despite limitations stemming from an imprecise matching of spatial and temporal scales, remotely sensed satellite imagery is a useful tool for monitoring the longer-term impact of human activity on the landscape — particularly where precise, time-series population data are difficult to obtain or non-existent.

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