

See discussions, stats, and author profiles for this publication at: <http://www.researchgate.net/publication/262641496>

Topographic and spectral data resolve land cover misclassification to distinguish and monitor wetlands in western Uganda

ARTICLE *in* ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING · AUGUST 2014

Impact Factor: 3.13 · DOI: 10.1016/j.isprsjprs.2014.05.001

READS

51

4 AUTHORS, INCLUDING:



[Aerin L. Jacob](#)

University of Victoria

17 PUBLICATIONS 99 CITATIONS

[SEE PROFILE](#)



[Tyler R. Bonnell](#)

University of Lethbridge

11 PUBLICATIONS 75 CITATIONS

[SEE PROFILE](#)



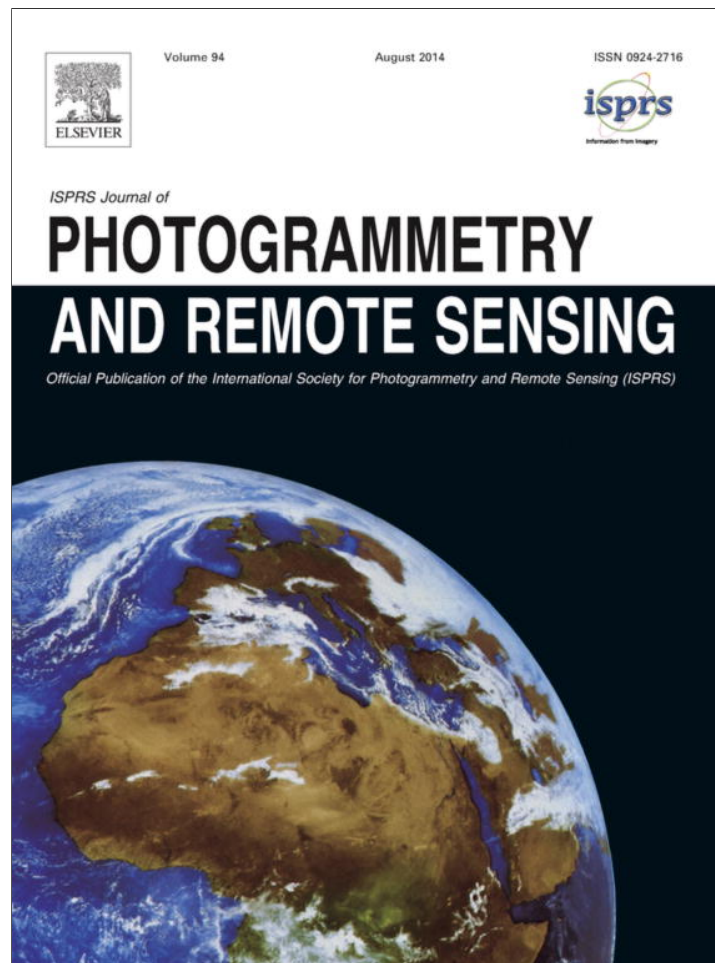
[Nicholas Dowhaniuk](#)

University of New Hampshire

4 PUBLICATIONS 4 CITATIONS

[SEE PROFILE](#)

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

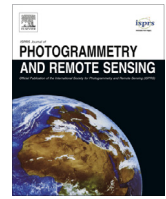
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/authorsrights>



Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Topographic and spectral data resolve land cover misclassification to distinguish and monitor wetlands in western Uganda

Aerin L. Jacob^{a,b,*}, Tyler R. Bonnell^c, Nicholas Dowhaniuk^d, Joel Hartter^e^a Department of Biology, McGill University, 1205 Dr. Penfield Avenue, Montreal, QC H3A 1B1, Canada^b Department of Geography, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada^c Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 0B9, Canada^d Department of Natural Resources and the Environment, University of New Hampshire, 114 James Hall, 56 College Road, Durham, NH 03824, USA^e Environmental Studies Program, UCB 397, University of Colorado, Boulder, CO 80309-0397, USA

ARTICLE INFO

Article history:

Received 10 September 2013

Received in revised form 28 April 2014

Accepted 1 May 2014

Available online 27 May 2014

Keywords:

Classification

Kibale National Park

Landsat

Mixed pixel

Papyrus

Uganda

ABSTRACT

Wetlands provide vital wildlife habitat and ecosystem services, but changes in human land use has made them one of the world's most threatened ecosystems. Although wetlands are generally protected by law, growing human populations increasingly drain and clear them to provide agricultural land, especially in tropical Africa. Managing and conserving wetlands requires accurately monitoring their spatial and temporal extent, often using remote sensing, but distinguishing wetlands from other land covers can be difficult. Here, we report on a method to separate wetlands dominated by papyrus (*Cyperus papyrus* L.) from spectrally similar grasslands dominated by elephant grass (*Pennisetum purpureum* Schumach.). We tested whether topographic, spectral, and temperature data improved land cover classification within and around Kibale National Park, a priority conservation area in densely populated western Uganda. Slope and reflectance in the mid-IR range best separated the combined papyrus/elephant grass pixels (average accuracy: 86%). Using a time series of satellite images, we quantified changes in six land covers across the landscape from 1984 to 2008 (papyrus, elephant grass, forest, mixed agriculture/bare soil/short grass, mixed tea/shrub, and water). We found stark differences in how land cover changed inside versus outside the park, with particularly sharp changes next to the park boundary. Inside the park, changes in land cover varied with location and management history: elephant grass areas decreased by 52% through forest regeneration but there was no net difference in papyrus areas. Outside the park, elephant grass and papyrus areas decreased by 61% and 39%, mostly converted to agriculture. Our method and findings are particularly relevant in light of social, biotic, and abiotic changes in western Uganda, as interactions between climate change, infectious disease, and changing human population demographics and distribution are predicted to intensify existing agricultural pressure on natural areas.

© 2014 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS). Published by Elsevier B.V. All rights reserved.

1. Introduction

Wetlands cover roughly 8.5% of the Earth's land surface and include a wide variety of habitats such as permanent and seasonal marshes, fens, peatlands, floodplains, and coastal areas. They are among the world's most productive ecosystems, providing habitat for many animal species and up to 40% of the world's annual renewable ecosystem services (Zedler and Kercher, 2005).

However, wetlands are also degraded and lost more rapidly than any other ecosystem in the world (Millennium Assessment, 2005). Sustainable use of wetland is particularly challenging in tropical environments where areas of dense human settlement have disproportionately high species extinctions and habitat loss (Balmford and Bond, 2005). Although local livelihoods depend on wetlands for food and resources (Morrison et al., 2013; van Dam et al., 2011; WRI, 2009), wetlands also represent areas of undeveloped land and are frequently converted to agriculture or housing settlements (Kaggwa et al., 2009; Maclean et al., 2013; Owino and Ryan, 2007). Conserving wetlands depends on implementing sustainable management on the ground (Mafabi, 2000), but first and foremost it depends on managers' ability to detect and

* Corresponding author at: Department of Biology, McGill University, 1205 Dr. Penfield Avenue, Montreal, QC H3A 1B1, Canada. Tel.: +1 514 570 6623.

E-mail addresses: aerin.jacob@mail.mcgill.ca (A.L. Jacob), tyler.bonnell@mail.mcgill.ca (T.R. Bonnell), nick.dowhaniuk@unh.edu (N. Dowhaniuk), joel.hartter@colorado.edu (J. Hartter).

quantify how wetlands change over space and time (Adam and Mutanga, 2009; Fuller et al., 1998).

Accurately mapping vegetation at large scales requires environmental managers to precisely estimate the size and extent of land cover types, increasingly through satellite remote sensing (Zedler and Kercher, 2005). In general, land cover types are identified in satellite images by their spectral signature, the distinctive combination of reflected and absorbed electromagnetic radiance (Turner et al., 2003; Xie et al., 2008). However, if two or more plant species have similar biochemical composition, their light absorption and reflectance features might overlap (Schmidt and Skidmore, 2003), rendering them indistinguishable in remote sensing classification. This phenomenon occurs within habitat types, e.g., among wetlands (Schmidt and Skidmore, 2003), grasslands (Adjorlolo et al., 2012), or forests (Wolter et al., 1995), and between habitat types, e.g., confusing wetlands with uplands (Ozesmi and Bauer, 2002), degraded pastures and coffee plantations with successional forests (Lu et al., 2003), and impervious urban surfaces with dry soils (Lu and Weng, 2006). Such misclassifications can lead to management errors (Ozesmi and Bauer, 2002), which is particularly grave for small, biodiverse habitats that people depend on.

The challenges policy makers, land managers, and conservation scientists face in detecting changes in small habitats is exemplified in Ugandan wetland management. The total extent of wetlands in Uganda decreased by over 30% (11,268 km²) in the last 20 years (Kaggwa et al., 2009; NEMA, 2010); today, wetlands constitute approximately 11% (26,308 km²) of Uganda's total area (WRI, 2009). Similar to elsewhere in sub-Saharan Africa, many wetlands are dominated by emergent papyrus sedge (*Cyperus papyrus* L.) (Hughes and Hughes, 1992). Papyrus wetlands are found in low-lying, flat areas, are linear or dendritic in shape (i.e., following the shape of a stream and tributaries), and can be large (tens of kilometers in length) or quite small (<1 ha) (Southworth et al., 2010). As in other parts of East Africa, papyrus wetlands in Uganda provide many ecosystem goods and services for local communities (Maclean et al., 2011; Morrison et al., 2013; Namaalwa et al., 2013; van Dam et al., 2011). Although the human benefits of maintaining existing papyrus wetlands greatly outweigh converting them to agriculture (Maclean et al., 2011; Schuyt, 2005), they are under increasing threat (Mafabi, 2000; Owino and Ryan, 2007).

In addition to anthropogenic pressures, managing papyrus wetlands is challenging because their size and shape makes it difficult to discriminate them from other land covers (Adam and Mutanga, 2009; Adam et al., 2012; Mwita et al., 2013). Papyrus is spectrally very similar to elephant grass (*Pennisetum purpureum* Schumacher), a very tall grass commonly found on hillsides, hilltops, or abandoned fields throughout East Africa. Like papyrus wetlands, grasslands dominated by elephant grass provide specific ecosystem services (e.g., erosion control, thatching and fuel, livestock grazing) and wildlife habitat (e.g., for bulk grazing ungulates, grassland-specialist butterflies and birds). As a result of their spectral similarity, these very different habitats have hitherto been inseparable in remote sensing (Hartter and Southworth, 2009; Southworth et al., 2010). This misclassification makes it difficult for local land managers to accurately monitor land cover; indeed, the need for accurate spatial data has been highlighted as a major challenge for policymakers in western Uganda (NEMA, 2004). Classification methods using secondary data (other landscape attributes associated with land cover types, e.g. topography, temperature) in a rule-based approach have successfully distinguished wetlands in other tropical areas (Davranche et al., 2010; Lambin and Ehrlich, 1995) and may be especially important to distinguish land cover types at small spatial scales, such as separating small, interstitial wetlands (<500 ha) from grasslands in western Uganda (Mwita et al., 2013).

In this paper, we resolved the outstanding remote sensing problem of distinguishing between papyrus and elephant grass. We

tested approaches using temperature, topographic and spectral data to separate papyrus-dominated wetlands and elephant grass-dominated grasslands within and around Kibale National Park in western Uganda. This landscape exemplifies the need to accurately map and monitor tropical wetlands, as intense anthropogenic pressures around Kibale juxtapose meeting conservation objectives with using park resources and land to sustain local livelihoods. We developed a new land cover classification to quantify land cover change inside and outside the park between 1984 and 2008, and identify possible drivers of change and priority conservation areas in this landscape.

2. Study area

2.1. Kibale region

Western Uganda's Kibale National Park (hereafter Kibale; 0°13'–0°41'N and 30°19'–30°32'E; Fig. 1) is in the Albertine Rift, a global biodiversity hotspot and one of the most densely human-populated areas in sub-Saharan Africa (Cordeiro et al., 2007; United Nations, 2011). Kibale is approximately 795 km², with elevation between 1110 and 1590 m and average annual rainfall 1543–1700 mm, with two wet seasons March–May and September–November. The park ranks fifth in terms of species richness and sixth in terms of overall biodiversity importance among all Ugandan forests (Howard et al., 1997). Kibale has a complicated management history (Chapman and Lambert, 2000). The central and northern parts of Kibale were originally designated a Forest Reserve in 1932, with parts of the northern area logged in the 1960s. Conversely, what is now southwestern Kibale was designated a Game Corridor in 1926 for hunting and to promote movement of large animals between Kibale and Queen Elizabeth National Park (Ryan and Hartter, 2012). Over a third of the game corridor was encroached and settled by agriculturalists in the 1970s and 1980s until their eviction in 1992 (Chapman and Lambert, 2000; Van Orsdol, 1986). The Forest Reserve and Game Corridor were joined and upgraded to National Park status in 1993.

In the 1960s, land cover inside the forest reserve was broadly described as 60% forest and 40% grassland, woodland-thicket, and colonizing forest (Wing and Buss, 1970); forest succession over the last half century shows a progressive loss of grassland and increase in native forest cover, primarily from preventing fire (Chapman and Lambert, 2000) and intensive reforestation (Omeja et al., 2011). In the most recent classification (2003), land cover inside the former forest reserve was composed of unlogged and regenerating forest (90%), papyrus/elephant grass (7%), short grasses (2%), and shrubs (1%) (Hartter and Southworth, 2009; Southworth et al., 2010). In 2003, land cover outside Kibale was composed of short grasses and agriculture (37%), forest (29%), papyrus/elephant grass (29%), tea and shrub (5%), and water (<1%) (Hartter and Southworth, 2009). However, these assessments failed to separate papyrus from elephant grass. To compare our results to previous research on land cover change in the Kibale region (e.g., Hartter and Southworth, 2009; Southworth et al., 2010) and to make our results for the widest range of local research, we defined three separate study areas: (a) *the former forest reserve*, (b) *the former game corridor*, and (c) *outside the park* as within a five km buffer from the Kibale park boundary (Fig. 1). In addition, we summed land covers in the former forest reserve and former game corridors to quantify land cover for the entire national park.

Our results differ from Southworth et al. (2010) in two key ways. First, the five km buffer in this paper surrounds the entire park, while the five km buffer defined by Southworth et al. (2010) only covered the area surrounding the former forest reserve

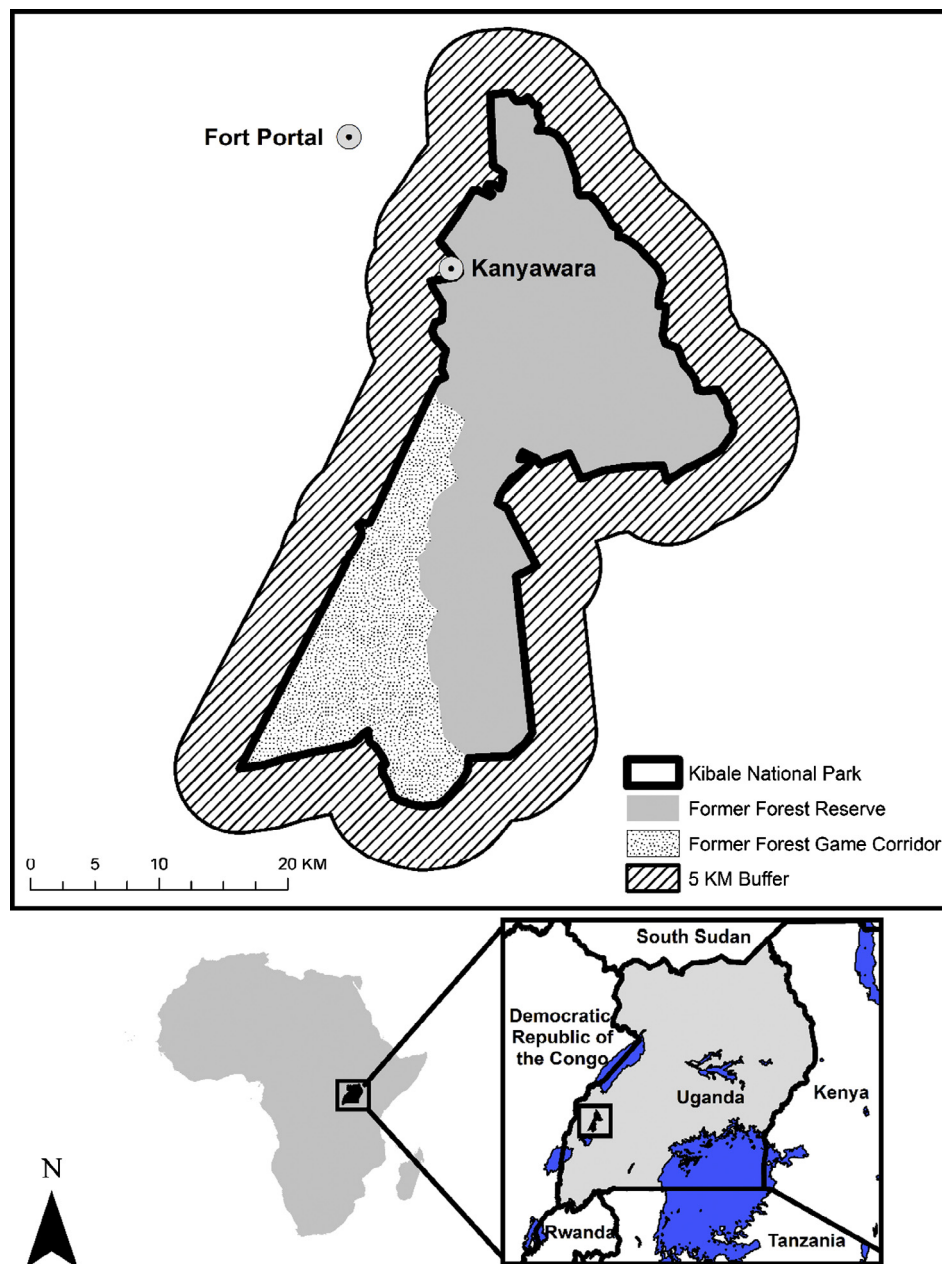


Fig. 1. Location of Kibale National Park within Uganda, and the differentiation of four areas of interest in this study: Kibale National Park, the former game corridor, the former forest reserve, and the five km buffer area outside of the park boundary.

(meaning that part of their five km buffer is actually inside the former game corridor). Second, we report findings inside the park separated by management history: the former game corridor and the former forest reserve, summed for Kibale National Park in its entirety. These differences are critical for other scientists and land managers studying environmental and socio-ecological changes in the landscape.

2.2. Papyrus and elephant grass habitats

Both papyrus and elephant grass are robust, rhizomatous, perennial, C4, nitrogen-fixing plants native to Africa (Fig. 2). Living papyrus is often more than five meters tall, overlying several meters of water and living rhizome and root mats. Submerged detritus and peat accumulate in the oxygen-depleted water over hundreds or thousands of years, creating an important carbon sink. The dense papyrus canopy intercepts over 90% of incoming

radiation, resulting in a cool microclimate and high rates of biomass accumulation (up to 6.28 kg/m²/yr; Jones and Muthuri, 1997). Papyrus wetlands are used by local people to collect water, papyrus, and poles for thatching and construction, or cleared and drained for agriculture, pasture, and woodlots (Hartter, 2010). In Kibale, papyrus wetlands provide specialized habitat for sitatunga antelope (*Tragelaphus spekii*), harvested fish including mudfish (*Clarias mossambicus*) and lungfish (*Protopterus aethiopicus*), and numerous birds including the near-threatened papyrus gonolek (*Laniarius mufumbiri*), and the restricted-range African marsh harrier (*Circus ranivorus*), black coucal (*Centropus grillii*), little rush warbler (*Bradypterus baboecala*), and white-winged scrub warbler (*Bradypterus carpalis*) (Howard et al., 1996; Maclean et al., 2003a).

Swaths of elephant grass are generally found on hillsides, often following relatively regular-shapes of abandoned cultivated areas (Fig. 2b; Buss, 1961; Southworth et al., 2010). Elephant grass frequently reaches heights of three meters, has a vigorous root

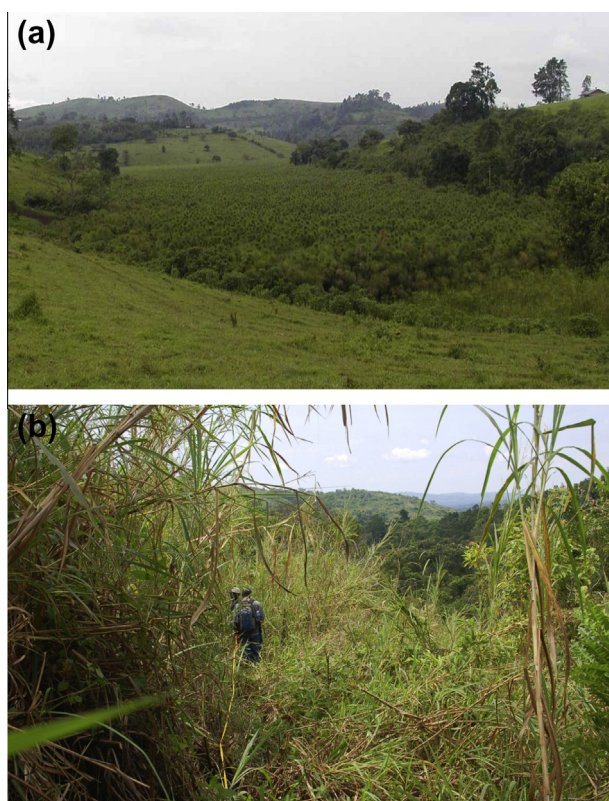


Fig. 2. Photographs of (a) wetland dominated by papyrus (*Cyperus papyrus* L.) in agricultural area outside Kibale National Park, Uganda (photo by J. Hartter), and (b) grassland inside Kibale dominated by elephant grass (*Pennisetum purpureum* Schumacher) (photo by A. Jacob).

system, and low water and nutrient requirements. It is commonly used by local people for grazing livestock, thatching, fuel, or planted as wind breaks and to improve soil fertility or prevent erosion. Like papyrus, elephant grass accumulates biomass quickly ($3.62 \text{ kg/m}^2/\text{yr}$) (Strezov et al., 2008). In Kibale, these grasslands provide habitat for large mammals, including African buffalo (*Syncerus caffer*), African elephant (*Loxodonta africana*), Uganda kob (*Kobus kob*) and olive baboon (*Papio anubis*) (Wanyama et al., 2010; Jacob and Chapman, unpublished data), as well as grassland-specialist species, e.g., at-risk birds: grey crowned-crane (*Balearica regulorum*, EN) and martial eagle (*Polemaetus bellicosus*, NT); restricted-range birds: button quail (*Turnix sylvaticus*) and Verreaux's eagle owl (*Bubo lacteus*); and restricted-range butterflies: deprived grizzled skipper (*Spialia depauperata*) and grizzled bush brown (*Bicyclus ena*) (Howard et al., 1996). With consistent fire prevention inside the park, elephant grass is replaced by forest through natural forest regeneration and active replanting programs (Lwanga, 2003; Omeja et al., 2011). Previously, some communities around southern Kibale had permits to graze livestock on grasslands inside the park. These permits were discontinued in recent years, although livestock (mostly cattle) are still illegally grazed in the area (MacKenzie et al., 2012). Outside the park, grasslands are frequently, and usually permanently, converted to agriculture.

3. Methods

3.1. Land cover

We collected three land cover maps of our study area that identified five land cover types (forest, water, tea, agriculture/bare soil/short grass, and the mixed papyrus/elephant grass category). We used two land cover maps, from 1984 (Landsat TM: May 26) and

2003 (Landsat ETM+: January 17) from Hartter and Southworth (2009) and added a third land cover map from 2008 (SPOT-5: November 21). We used a SPOT-5 image for 2008 because recent cloud-free Landsat images were unavailable. We created the 2008 land cover map using the same five land cover classes and following the same methods that were used in the 1984 and 2003 classifications (supervised maximum likelihood classification) (Hartter and Southworth, 2009).

The 2008 image was geometrically registered to Google Earth images, using roads and other permanent features, with a root mean-square error (RMS) of $<2 \text{ m}$. The image was then radiometrically corrected using the SPOT calibration tool in ENVI version 4.8 (Exelis Visual Information Solutions, Boulder, Colorado); no atmospheric correction was done. In 2009, 289 reference points were collected in the field from agriculture (maize/short grass/tea) and forest plots. We supplemented these points with an additional 197 reference points for papyrus/elephant grass, bare soil, and water using Google Earth images (Geoeye-1: 2010, World-View-1: December 2007; 0.5 m spatial resolution). We randomly split the total ($n = 486$) into two halves: a reference set to create the 2008 classification, and a validation set to test classification accuracy.

We classified the 2008 image using 18 stacked layers: panchromatic, green, red, NIR, SWIR, green/red, red/NIR, NIR/SWIR, EVI, NDVI, PCA 1,2,3, and texture bands (3×3 windows calculating mean pixel value) for panchromatic, green, red, NIR, and SWIR. The initial classification was done using seven land cover classes: forest, mixed papyrus/elephant grass, maize, tea, short grass, bare soil, and water. We then combined the maize, short grass, and bare soil classes to a mixed "agriculture/bare soil/short grass" class to match the 1984 and 2003 classifications (Hartter and Southworth, 2009).

3.2. Separating papyrus and elephant grass

To attempt to divide the mixed elephant grass/papyrus land cover type, we first tested their separability by examining both land cover temperature and reflectance in each land cover. On the ground, a noticeable physical difference between the two land covers is the difference in daytime temperatures of the microclimate: papyrus-dominated wetlands tend to be cool while elephant grass-dominated grasslands tend to be warm. We sought to test whether these differences in daytime surface temperatures, combined with Landsat's thermal band ($10.40\text{--}12.50 \mu\text{m}$, sensitive to changes in emitted thermal radiation as a result of temperature differences), could help divide the mixed elephant grass/papyrus land cover type (Coll et al., 2010; Southworth, 2004). To examine temperature differences of each land cover type, we used temperatures recorded in each land cover class with Hobo Tidbit v2 temperature data loggers (utbi-001, Onset Computer Corporation, Bourne, Maine) every 20 min between July 2008 and August 2011. Temperature was measured at the umbels of the papyrus and the canopy of the elephant grass by mounting the data logger on a wooden pole and permanently securing it in the substrate. The data loggers were enclosed and operated as per manufacturer and temperature data collection standards. Since Landsat is in a sun-synchronous orbit and passes over Kibale around 11h00 EAT (UTC/GMT +3), we used a daily time window of 10h30–11h30 and a t -test to compare mean temperature between wetland and grassland. We tested whether Landsat's thermal band could help distinguish between the land covers (Coll et al., 2010; Southworth, 2004).

Next, to identify the largest spectral differences between the spectrally similar papyrus and elephant grass land covers we used reference points (28 for papyrus and seven elephant grass) taken from inside and around Kibale using Google Earth (June 2002 QuickBird-2). Reflectance values were extracted from a georeferenced,

radiometrically calibrated, and atmospherically corrected Landsat image taken on 31 January 2003. We tested for spectral differences between land cover types in each of the eight spectral bands (blue, green, red, NIR, Mid-IR, Therm, SWIR, and Pan) using both parametric (*t*-test) and non-parametric (Wilcoxon-test) approaches.

The results of these two tests (spectral and temperature) helped to identify potential differences between papyrus and elephant grass land covers. We then used a regression tree approach to separate papyrus and elephant grass in each of the three classified images (1984, 2003, and 2008), incorporating reflectance and topographic information. To test the accuracy of this separation, we collected a second set of reference points ($n = 437$), separate from the reference points used to classify the 2008 Spot-5 image. This second set of reference points focused on areas classified as papyrus/elephant grass only, identifying points in these regions as either papyrus or elephant grass. Previous studies have illustrated Google Earth can be used as an adequate substitute for field collection of accuracy assessment points (Biswal et al., 2013; Cha and Park, 2007). To ensure greatest accuracy of using this method, it is important that researchers have on-the-ground experience working in the habitats and study area in question; otherwise, it would be difficult to accurately distinguish land covers remotely using aerial views from Google Earth imagery. Although Google provides limited accuracy information for their imagery, horizontal positional accuracy of Google Earth imagery has been tested in previous studies (Benker et al., 2011; Potere, 2008; Yousefzadeh and Mojaradi, 2012). These studies reported the average Root Mean Squared Error (RMSE) for the imagery used within their respective study areas was sufficient for reference point selection to be used with medium and low resolution imagery. However, caution should be exercised while using Google Earth as a reference for high resolution imagery, especially imagery with a spatial resolution of greater than six meters, as the RMSE will often be larger than the imagery's spatial resolution (Yousefzadeh and Mojaradi 2012). For the 2008 image classification, we visually collected 100 papyrus and 100 elephant grass points from a Google Earth image (December 2007, World-View-1); for the 2003 classification, we visually collected 65 papyrus and 62 elephant grass points from another Google Earth image (June 2002, Quickbird-2); and for the 1984 classification we visually collected 51 papyrus and 59 elephant grass points from 1:31,000 aerial photographs (December 1988).

We made the simplifying assumption that the two main land cover classes within the mixed pixels were either (i) wetlands dominated by papyrus, or (ii) grasslands dominated by elephant grass. This assumption follows field observations from Kibale (Chapman et al., 2001; Chapman et al., 2001; Jacob and Hartter, unpublished data). Due to the limited ability to distinguish imaged-derived reference points, further separating this mixed class into types of swamps or grasslands would require additional collection of reference data from in-field surveys. To assess the accuracy of the separation, we divided the total set of reference points ($n = 437$) into approximately half: (1) "training points" to train a regression tree for each image, using these trees to separate pixels into papyrus or elephant grass, and (2) "validation points" to assess the accuracy of the separation.

We derived reflectance and topographic information at each training point. We extracted reflectance values (panchromatic, green, red, NIR, SWIR, principle component 1-2-3, Tassel cap 1-3, mid-IR index, NDVI, LSWI, and MSI) targeting bands identified in Section 3.2. We did not include emittance values from the thermal band for the Landsat images (1984, 2003) as a variable in the final regression tree since they were not significantly different between land cover types (see Section 4.2). Furthermore, when we included the thermal band in the conditional regression tree in a separate analysis, it was not selected for as a significant variable. We

calculated slope at each training point using a 90 m digital elevation model (DEM) from the NASA Shuttle Radar Topography Mission (SRTM), resampled from 90 m to 30 m spatial resolution using bi-cubic convolution (Keeratikasikorn and Trisirisatayawong, 2008).

We next built a regression tree for each year (1984, 2003, and 2008) using the 'ctree' function in the 'PartyKit' package in R (Hothorn and Zeileis, 2012). The 'ctree' function uses statistical inference in a recursive way to build classification trees by determining (1) which parameter(s) to split the data, and (2) what parameter values to perform the split on. Using these trees, we then separated papyrus and elephant grass pixels in each classification, using the Knowledge Engineer and Knowledge Classifier in ERDAS Imagine version 10.1.2 (Intergraph, Norcross, GA, USA) to implement the selected regression tree. We calculated confusion matrices for each separation using the aforementioned validation points.

3.3. Assessing land cover change

Once we successfully separated the mixed papyrus/elephant grass pixels, we calculated the total area for each of the six land cover types (forest, papyrus, elephant grass, agriculture/bare soil/short grass, tea, water) in our three study areas (inside the former game corridor and former forest reserve, and within the five km buffer surrounding the entire park) (Fig. 1). To assess land cover changes between 1984–2003 and 2003–2008, we calculated the change for each land cover between the two time periods. We identified areas of the landscape with particularly marked changes in land cover and identified anthropogenic and natural factors that may have contributed to these changes.

4. Results

4.1. Land cover

Combining reference points collected in the field with those collected from Google Earth, we achieved an overall accuracy of 85.6% for the 2008 land cover classification (Table 1). This accuracy was comparable to 89.1% achieved for the 2003 classification (Hartter and Southworth, 2009). Within our total study area, 14,953 ha were classified as mixed papyrus/elephant grass in 2008 (Table 3).

4.2. Separating papyrus and elephant grass

Sub-sampling temperature measurements from the HOBO recorder within the 10h30–11h30 time window resulted in 4219 temperature readings from papyrus and 3168 from elephant grass. Elephant grass areas were on average 4.3 °C warmer than papyrus areas ($t = 45.6$, $p < 0.001$). We found significant differences in reflectance distributions for the mid-IR ($W = 178$, $p < 0.001$) and Panchromatic bands ($W = 172$, $p = 0.002$) between papyrus and elephant grass. A *t*-test showed significant differences in means ($p < 0.05$) in the mid-IR and Panchromatic bands of 15.1 and 7.4 (Table 4). However, we did not find differences between the land cover types for the thermal band.

We created one regression tree per image with overall separation accuracies of 92.0%, 93.1%, and 76.8% for 2008, 2003 and 1984 respectively (Table 2). To distinguish between papyrus and elephant grass, the Tassel cap brightness index, slope, and the Mid-IR band were selected for the 2008 image, and the Mid-IR index (Mid-IR/SWIR) and slope for the 2003 image ($p < 0.05$) (Fig. 3). Only slope was selected in the 1984 image ($p < 0.15$) (Fig. 3). By including topographic information in the regression trees, we were able to improve our classifications: slope was the

Table 1

Confusion matrix for the classification of the 2008 SPOT-5 image. EG stands for elephant grass, SG stands for short grass.

Classification	Ground reference classes					Row total	User's accuracy (%)
	Forest	Papyrus/EG	Agr/bare/SG	Tea	Water		
Forest	38	3	2	2	0	45	84
Papyrus/EG	2	35	0	0	0	37	95
Agr/bare/SG	9	9	73	4	0	95	77
Tea	0	1	0	19	0	20	95
Water	0	0	0	0	25	25	100
Column total	49	48	75	25	25	222	–
Producer's accuracy (%)	78	73	97	76	100	–	86

Table 2

Confusion matrix for separation of elephant grass and papyrus pixels in 1984, 2003, and 2008.

Classification	Ground reference classes		
	Elephant grass	Papyrus	User's accuracy (%)
2008			
Elephant grass	43	1	97.7
Papyrus	7	49	87.5
Producer's accuracy	86.0%	98.0%	–
Overall accuracy	–	–	92.0
2003			
Elephant grass	34	5	87.18
Papyrus	0	33	100.0
Producer's accuracy	100.0%	86.8%	–
Overall accuracy	–	–	93.05
1984			
Elephant grass	26	10	72.2
Papyrus	2	18	90.0
Producer's accuracy	92.9%	64.3%	–
Overall accuracy	–	–	78.6

only distinguishing variable in the 1984 image, and slope also increased the overall accuracy in the 2003 image from 88.9% to 93.1% in the 2003 image. In the 2008 image the inclusion of slope did not increase the overall accuracy, but was able to better define uncertainty in classification of papyrus pixels (e.g., Fig 3a, more uncertainty in papyrus pixels with >2° slope) (see Fig. 4).

4.3. Assessing land cover change

Patterns in land cover change were markedly different inside and outside the park. Outside the park, all natural land cover (i.e., forest, papyrus, and elephant grass) declined between 1984

Table 4

Total area (in hectares) of patches classified as papyrus and elephant grass in the 2008 SPOT 5 image that are smaller than the spatial resolution of a Landsat pixel (0.09 ha): outside the park (within five km of park boundary), inside the former game corridor, inside the former forest reserve, and inside Kibale National Park as a whole (the sum of former game corridor and former forest reserve). Percentages in parentheses indicate the proportion of total land cover for papyrus or elephant grass in 2008.

	Papyrus (%)	Elephant grass (%)
Outside park	222 (10)	1831 (36)
Former game corridor	146 (9)	454 (12)
Former forest reserve	571 (40)	149 (19)
Kibale National Park (total)	717 (24)	603 (13)

and 2008. Inside the park, land cover change varied with habitat type and management history (Fig. 5, Table 3).

Outside the park, the area of papyrus, elephant grass, and forest decreased by 56 ha (–2%), 907 ha (–7%), and 6884 ha (–32%) from 1984 to 2003. Each habitat decreased by a further 1415 ha (–39%), 7856 ha (–61%), and 3322 ha (–22%) from 2003 to 2008. Conversely, the area of agriculture increased by 5739 ha (+21%) from 1984 to 2003 and by 13,957 ha (+30%) from 2003 to 2008.

Inside the park, the area of elephant grass increased by 66 ha (+5%) by and 113 ha (+<1%) from 1984 to 2003 for both the former game corridor and former forest reserve, but decreased by 2730 ha (–12%) and 2205 ha (–4%) from 2003 to 2008. However, trends in the extent of papyrus, varied between the former game corridor and former forest reserve for each time period. In the former game corridor, papyrus increased by 1547 ha (+59%) from 1984 to 2003 and then decreased by 2600 ha (–62%) from 2003 to 2008. In the forest reserve, it increased by 243 ha (+58%) from 1984 to 2003

Table 3

Total area (in hectares) classified for each land cover type in each year: outside the park (i.e., within the five km buffer around the park boundary), inside the former game corridor, inside the former forest reserve, and for Kibale National Park as a whole (the sum of former game corridor and former forest reserve). Percentages in parentheses indicate the proportion of total land cover for each year.

	Water (%)	Papyrus (%)	Elephant grass (%)	Tea (%)	Agr/bare/short grass (%)	Forest (%)
Outside park						
1984	295 (0)	3727 (5)	13,853 (20)	1613 (2)	27,324 (40)	21,792 (32)
2003	446 (1)	3671 (5)	12,946 (19)	3569 (5)	33,063 (48)	14,908 (22)
2008	287 (0)	2256 (5)	5090 (7)	2102 (3)	47,021 (69)	11,586 (17)
Former game corridor						
1984	171 (1)	2628 (11)	6464 (27)	84 (0)	5625 (24)	8536 (36)
2003	354 (2)	4175 (18)	6530 (28)	172 (1)	3500 (15)	8776 (37)
2008	184 (1)	1576 (7)	3800 (16)	439 (2)	8971 (38)	8470 (36)
Former forest reserve						
1984	0 (0)	422 (1)	2881 (5)	269 (0)	3999 (7)	48,854 (87)
2003	31 (0)	665 (1)	2994 (5)	514 (1)	1095 (2)	51,125 (91)
2008	0 (0)	1443 (3)	789 (1)	436 (1)	2773 (5)	50,862 (90)
Kibale National Park (total)						
1984	171 (0)	3050 (4)	9345 (12)	353 (0)	9624 (12)	57,390 (72)
2003	386 (0)	4840 (6)	9524 (12)	686 (1)	4595 (6)	59,901 (75)
2008	184 (0)	3018 (4)	4589 (6)	875 (1)	11,744 (15)	59,332 (74)

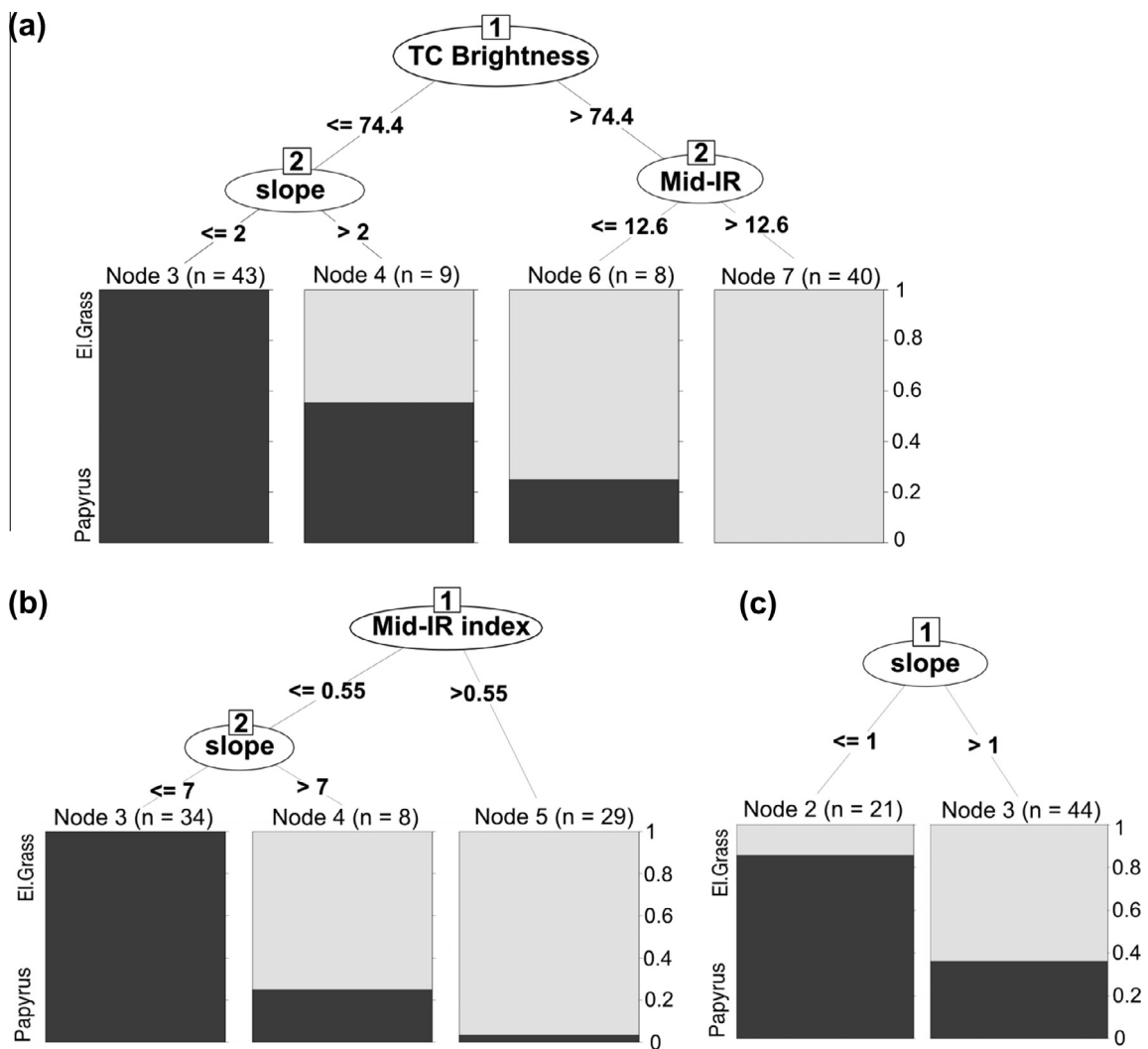


Fig. 3. Classification trees for the (a) 2008, (b) 2003, and (c) 1984 images, selected to distinguish between papyrus and elephant grass pixels.

and increased again by 778 ha (+117%) from 2003 to 2008. Forest increased by 240 ha (+1%) in the game corridor and by 2271 ha (+4%) in the forest reserve from 1984 to 2003, and decreased by 306 ha (−1%) in the game corridor and by 263 ha (−1%) in the forest reserve from 2003 to 2008.

5. Discussion

Using topographic and spectral data proved effective in distinguishing between papyrus and elephant grass in and around Kibale National Park. Using a regression tree approach, we found consistent decreases in papyrus (and forest) and increases in agriculture outside the park in 1984–2003 and 2003–2008. This suggests a continuation of the 1984–2003 trend identified by Hartter and Southworth (2009) of decreasing natural land covers outside the park.

5.1. Important factors differentiating land covers

We found that reflectance in the mid-IR range and slope were the most effective at separating the mixed papyrus/elephant grass pixels. Reflectance in the mid-IR band is thought to be sensitive to water and moisture levels, and is used in other wetland

studies (Ozesmi and Bauer, 2002). Therefore, information from the mid-IR band would likely be best to distinguish between papyrus and elephant grass during the dry season. This is one possibility of the lower success of mixed pixel separation in the 1984 image, as it was acquired at the end of the wet season (May), limiting the distinction in moisture content.

We also found slope to be a significant variable in all regression trees, where pixels with lower slope values were more likely papyrus (i.e., in valley bottoms as opposed to hillsides). We found that the spatial resolution of our slope estimates was a limiting factor. Resampling the 90 m STRM data to 30 m created some sharp transition zones, resulting in some papyrus pixels at a wet-land edges receiving high slope values, which could in turn lead to misclassification. This suggests that increased resolution of topographic information, as well as consistently using image data taken during the dry season, would increase the accuracy of identifying papyrus.

Although the temperature in elephant grass was an average of 4.3 °C warmer than papyrus, the conditional inference regression trees did not select reflectance from the Landsat thermal band (10.40–12.50 μm) as an important parameter. Additionally, we found no spectrally significant difference in the Landsat’s thermal bands between the two land cover types using a *t*-test or Wilcoxon test. This suggests that the difference in temperature is too

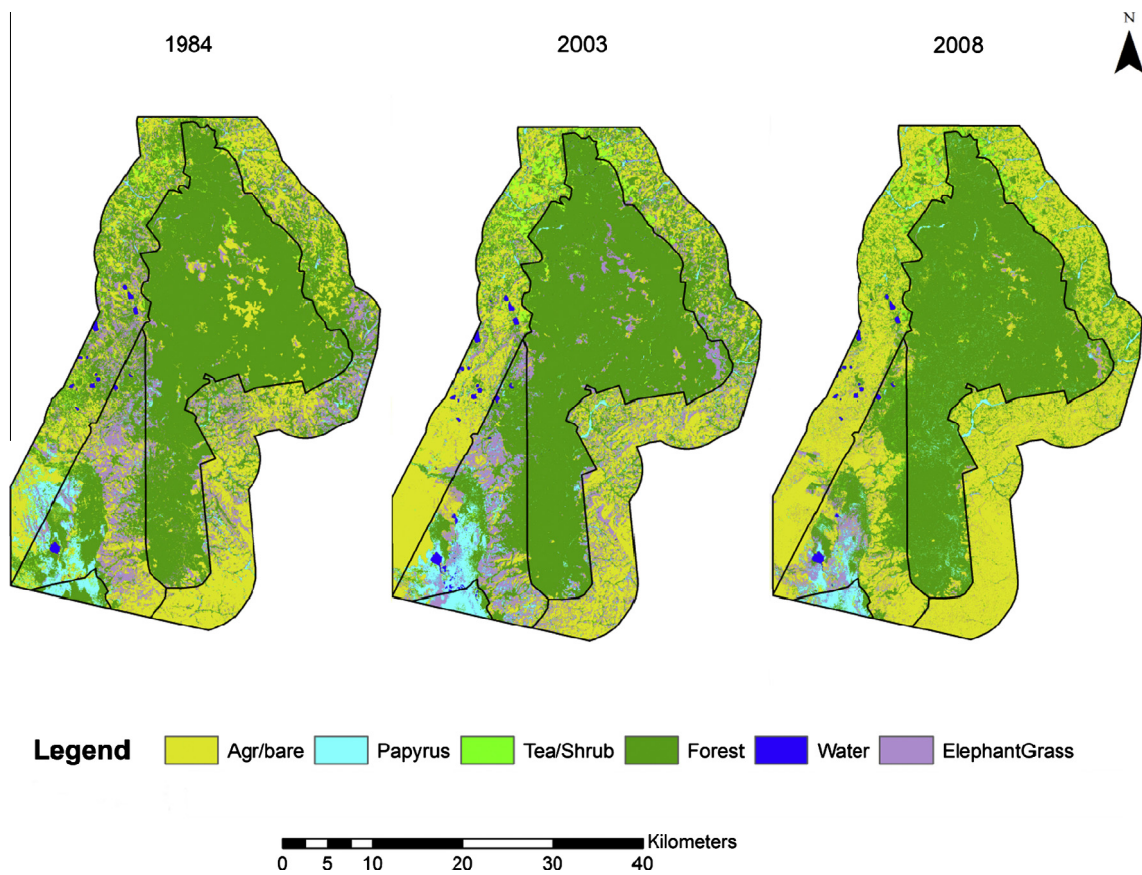


Fig. 4. Classifications of 1984, 2003, and 2008 with papyrus and elephant grass separated.

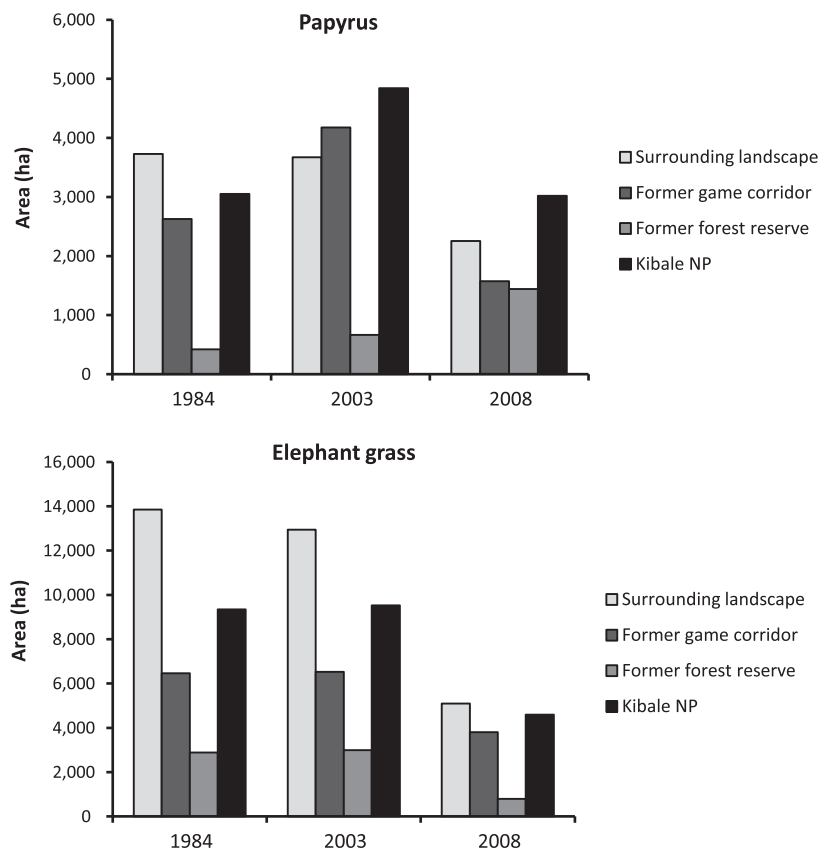


Fig. 5. Total area classified as papyrus or elephant grass for each year in the three study areas: the surrounding landscape within five km of the park boundary, the former game corridor, and the former forest reserve, as well as Kibale National Park (NP) as a whole (sum of the former game corridor and forest reserve).

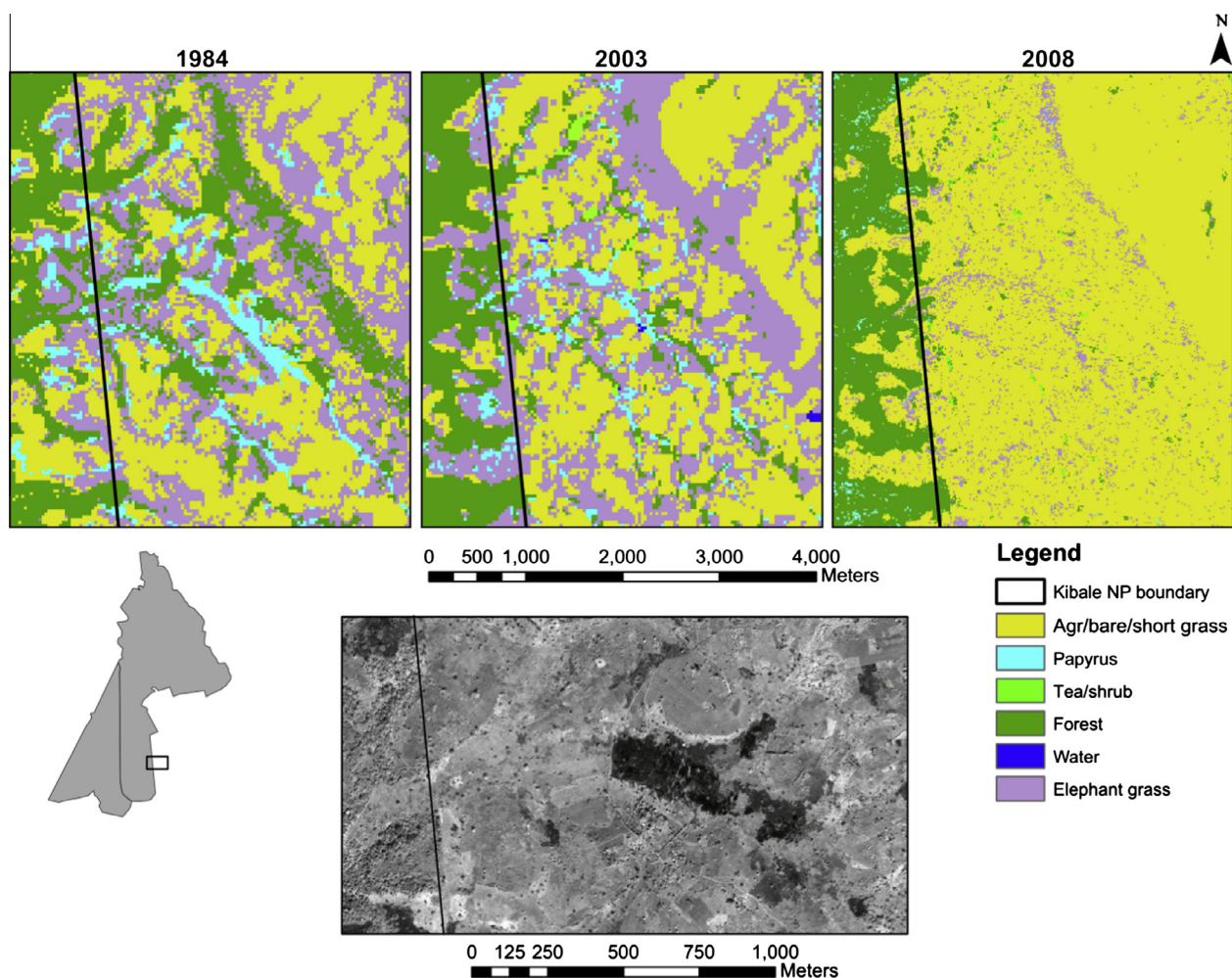


Fig. 6. Fine scale examination of one area outside the park, near Kamwenge village in the southeast: (a) land cover classifications from 1984, 2003 and 2008, (b) Google Earth image (January 2009, World-View-1) taken adjacent to the park boundary along the principal area classified as papyrus in 1984 and 2003 classifications (the black area of the image is burnt vegetation). Note the drastic reduction in forest, papyrus, and elephant grass outside the park.

small to be captured with the Landsat thermal band (however, see Coll et al., 2010), or alternatively that the spatial resolution (120 m^2 TM and 60 m^2 ETM) was too large to detect temperature variations due to the small size of wetlands in this study area. Since Landsat 8 data is collected at 100 m spatial resolution, and resampled to 30 m for delivery in two thermal bands of differing spectral resolution ($10.6\text{--}11.19 \mu\text{m}$ and $11.50\text{--}12.51 \mu\text{m}$) (Irons et al., 2012), it is possible that this increase in spectral resolution might capture thermal differences between papyrus and elephant grass. However, such spatial resolution is still low and likely only applicable to large wetland areas.

Conditional inference methods to build regression trees were useful in removing bias when choosing parameters and the parameter values upon which to split the data. The results of this method also provided a measure of classification certainty for each pixel, as some pixels with particular attributes (reflectance, topographic values) ended up in terminal nodes with higher certainty than others: e.g. terminal nodes 3 (0% error) and 7 (0% error) as opposed to 4 (44% error) and 6 (25% error) (Fig. 3a).

Using different sensors within one project can be problematic; in this study we have differences in spectral range and spatial resolution from Landsat TM, ETM+, and SPOT-5. However, these differences lead to useful comparisons between sensors in terms of classifying wetlands. The mid-IR index, which uses two bands in the mid-IR region, was selected as the most significant factor

in distinguishing between elephant grass and papyrus in the 2003 image; this suggests that extra bands within the mid-IR region for the Landsat series were advantageous. In terms of spatial resolution, wetlands within our study area are generally small and thin, suggesting the increased spatial resolution of the SPOT-5 sensor would be advantageous. Image classification in general can be highly affected by the spatial resolution of the imagery used (Chen et al., 2004), where larger pixel sizes generally increases the chances of a pixel containing more than one land cover (Li et al., 2011). This increases the proportion of mixed pixels within Landsat images compared to imagery with a smaller spatial resolution. However, given that separation within the 2003 Landsat image was slightly more successful than in the 2008 SPOT image, it suggests that in our case the extra band in the mid-IR band was equally useful as the increase in spatial resolution. To quantify the effects of spatial resolution on our results, we calculated the area of pixels classified as papyrus and elephant grass in the 2008 classification which were smaller than the Landsat spatial resolution (0.09 ha). The results suggest that a significant amount of papyrus in the former forest reserve, and elephant grass in the 5 km buffer outside the park, consists of patches smaller than the spatial resolution of Landsat sensor systems ($<0.09 \text{ ha}$). However, the trends remain the same in our study areas when we remove these pixels (e.g., increasing papyrus inside the forest reserve and decreasing outside the park).

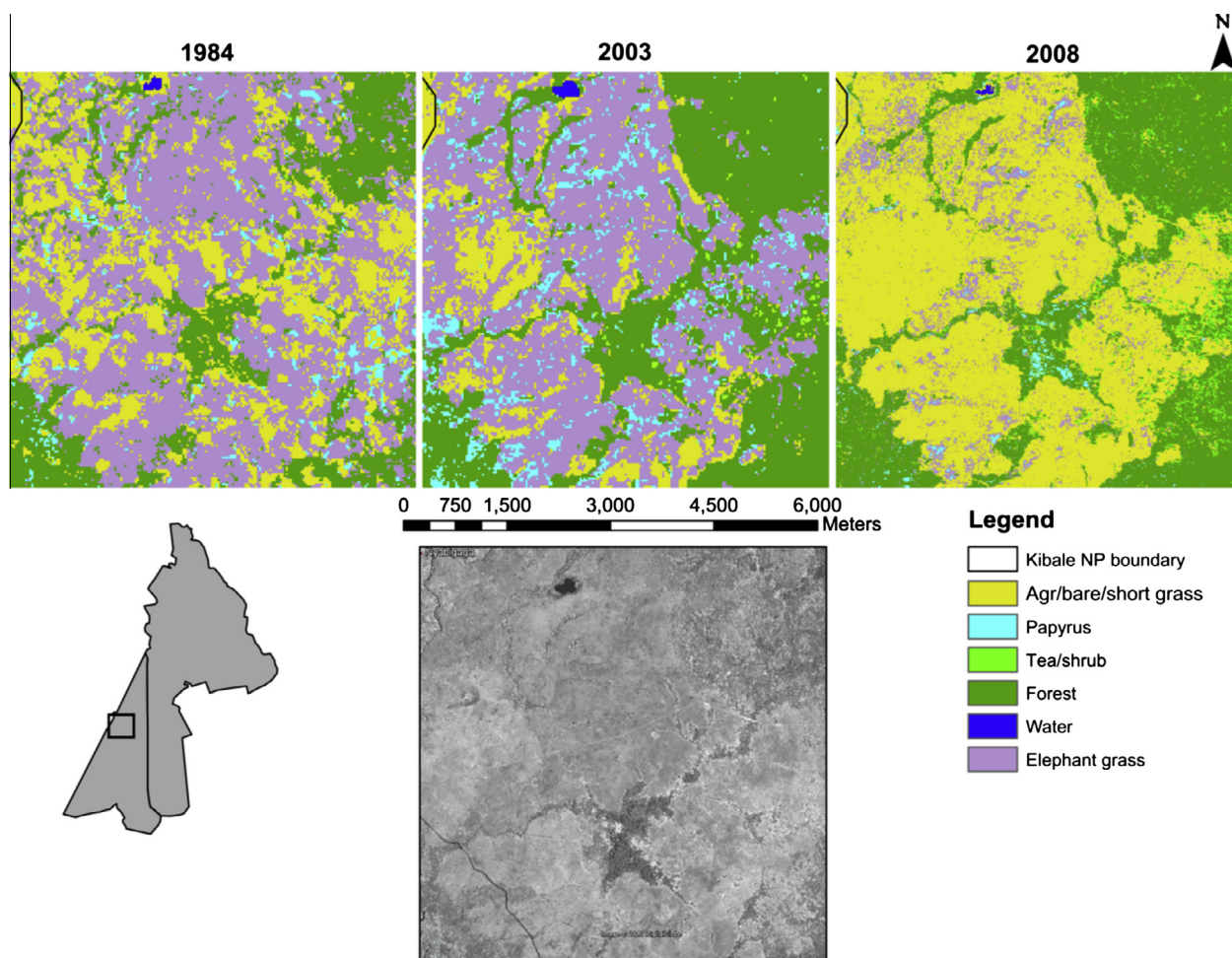


Fig. 7. Fine scale examination of one area inside Kibale (specifically inside the former game reserve): (a) land cover classification from 1984, 2003 and 2008, (b) Google Earth image (December 2007, World-View-1) taken in the same region as the classifications. Note increased connection between the central forest patch and the larger contiguous forest through the growth of thin forest corridors, and expansion of the contiguous forest in the bottom left and right.

5.2. Land cover change within and around Kibale

5.2.1. Papyrus wetlands

Inside Kibale National Park as a whole, the extent of papyrus first increased and then decreased by nearly the same amount, resulting in almost no net change between 1984 and 2008 (Fig. 5). However, we recorded a relatively small but steady increase in papyrus from 1984 to 2008 exclusively within the former forest reserve. Within the former game corridor, the patterns are more difficult to interpret: the amount of papyrus increased by 150% between 1984 and 2003, but by 2008 it declined to less than half the initial 1984 estimate (Table 3). These changes occurred mostly in the southwestern part of the former game corridor in the large seasonal wetland around Lake Kabaleka, the largest body of water in this area and part of the Lake George Ramsar Site.

Several ecological and hydrological mechanisms could account for fluctuations in wetland size within Kibale. Anecdotal evidence indicates that elephant activity can maintain or increase the size of wetlands, at least at small scales; this phenomenon has been noted in the northern part of the former forest reserve (Lauren Chapman, pers. comm.). More importantly, although warming of the Indian Ocean over the last 30 years has likely made the region drier overall, the fluctuations in wetland size we identified are likely due to inter-seasonal changes in rainfall controlled by the Intertropical Convergence Zone, which is in turn affected by the El Niño Southern Oscillation (in East Africa, El Niño years are

wetter while La Niña years are drier) (Marchant et al., 2007; Wolff et al., 2011). Since the timing and specific weather history before a satellite image was acquired could influence phenology, thereby influencing spectral reflectance and the amount of area classified as papyrus (and to some extent the other classifications as well). The 1984 and 2008 images were acquired at the end of the wet seasons (May and November) while the 2003 image was acquired during the middle of the dry season (January). However, rainfall records for northern and central Kibale show that early 1984 was particularly dry, especially in May, while the months preceding the 2003 image were particularly wet (El Niño); although 2008 was considered a La Niña year, the rainfall in Kibale was within the normal range (Jeremy Diem, pers. comm.). This pattern of low–high–normal rainfall would explain the 1984–2003 increase and 2003–2008 decrease in papyrus extent we identified inside the park, particularly in the former game corridor. Nevertheless, we caution that rainfall patterns in this region are very complex (Diem et al., 2013; Marchant et al., 2007; Stampone et al., 2011) with unpredictable onset and cessation dates (Hartter et al., 2012), limiting the degree of certainty we can put on the mechanism behind this change in extent of papyrus.

Outside the park, we identified a clear decrease in papyrus, with a total reduction of 39% between 1984 and 2008, which almost entirely occurred between 2003 and 2008. In general, loss of papyrus was evenly distributed throughout this study area and replaced by agriculture; however, there are some regions of particular interest because of demonstrably higher rates of change. For example,

an area on the southeastern edge of Kibale (0°17'24"N, 30°24'23"E), about 13 km northwest of Kamwenge town, showed a clear papyrus area in 1984 that is not present in the 2008 classification (Fig. 6); instead, this area was entirely classified as agriculture/bare/short grass. Long-term wetland ecologists working in the area confirm that pressure on wetlands has increased over the last twenty years (Lauren Chapman, pers. comm.), thought to be largely caused by burning and draining the wetland to create land for subsistence cultivation or grazing livestock. This can be seen in images from Google Earth, in which it is typically possible to identify burnt or cleared areas with the naked eye: the 2009 Google Earth image shows a large burnt area in this location. Our results show that although some wetland was converted to agriculture in the 19 years between 1984 and 2003, the vast majority of the conversion likely occurred between 2003 and 2008.

5.2.2. Elephant grass grasslands

Areas classified as elephant grass decreased by nearly 60% throughout the entire study area from 1984 to 2008. This is in part due to fewer areas being confused with papyrus in the 2008 image, and instead being classified directly in the agriculture/bare soil/short grass class. The reduced confusion likely represents fewer areas of long, moist grass confused with papyrus, and points towards an opening up of the landscape. There are additional interesting trends in elephant grass-dominated grasslands both inside and outside the park.

Inside the park, human disturbance in grasslands has historically focused on maintaining grasslands for grazing and hunting (e.g., fire) or clearing them for agriculture (Chapman and Lambert, 2000; Van Orsdol, 1986). Since 1992, human activities inside the park have focused on converting grasslands to forest by preventing fire (Lwanga, 2003) or replanting trees. Most of the reduction in grassland extent occurred between 2003 and 2008. Inside the former forest reserve, this is attributed to passive forest regeneration from continued prevention of fire (Lwanga, 2003); in the former game corridor, it is attributed to active forest regeneration from planting native trees to sequester carbon (in addition to preventing fire) (Omeja et al., 2011; Fig. 7). This latter area also shows a large change in classification from elephant grass to agriculture/bare soil/short grass, largely a result of less area being originally classified into the combined class elephant grass/papyrus. Converting grasslands to forest within the park has particular conservation importance. Connecting formerly isolated forest patches to the larger contiguous forest through the growth of thin forest corridors will facilitate the movement of forest specialist animals (e.g., primates), which will in turn facilitate further, natural forest regeneration by attracting seed dispersers. However, forest regeneration also reduces habitat and forage for grassland specialist species (e.g., butterflies, birds; Howard et al., 1996) and bulk grazers (African buffalo, and to less extent bulk grazer/browsers like African elephant). Whether this is a desirable or undesirable trend depends on management goals: the vegetation and fire management objectives for Kibale include restoring natural forest cover to previously encroached areas but also limiting the transition of natural grassland to scrubland (UWA, 2003).

6. Conclusion

Our analysis successfully resolved two outstanding issues in remotely sensing land cover in our study region: (1) separating papyrus-dominated wetlands from elephant grass-dominated grasslands and (2) quantifying their spatial and temporal changes over 24 years. Maximizing the benefits of wetlands and grasslands to both conserve biodiversity and provide ecosystem services requires accurate monitoring to develop, implement, and adapt

effective interdisciplinary management policies and practices. There may be local and global trade-offs between individual ecosystem service and/or biodiversity conservation priorities at the expense of another (Palm et al., 2010; Rodríguez et al., 2006; Thomas et al., 2013), for instance, conserving wetlands to store carbon and attract nature tourism versus harvesting them for crafts or fuel (Maclean et al., 2011). Sound strategies to conserve and sustainably use Uganda's wetlands are urgently needed because of changes in, and interactions between, population distribution and growth, cultivation and grazing, climate change, and infectious disease. Climate change will affect local and regional patterns of rainfall and temperature and reduce the amount of carbon stored in papyrus wetlands (possibly changing them from a carbon sink to a source) (Jones and Humphries, 2002). Although many aquatic environments can provide habitat for disease, researchers are divided about whether climate change and ecological restoration will increase or decrease disease transmission from wetlands (Cromie et al., 2012; Lindblade et al., 2000; Malan et al., 2009; Patz et al., 2004; Zedler and Kercher, 2005).

Although lack of stakeholder awareness of the environmental importance of wetlands is often cited as a key driver of wetland degradation in East Africa (Amaniga Ruhanga and Iyango, 2010; Mirona, 2005; Sekitoleko, 1993), other studies show that local people are acutely aware of the ecosystem goods and services wetlands provide (Maclean et al., 2003b,c; Morrison et al., 2013; Nalukenge et al., 2009). The ultimate drivers for wetland degradation are poverty/inequity, wetland privatization, and the breakdown of traditional management structures (Hartter and Ryan, 2010; Iyango et al., 2012; Kaggwa et al., 2009; Maclean et al., 2011); therefore, sustainable wetland management requires a coordinated, interdisciplinary, and participatory approach to regulate, monitor, and conserve these important ecosystems. Accurately identifying and measuring spatial and temporal change in wetlands is a fundamental step in this process.

Acknowledgments

We thank the Uganda National Council for Science and Technology, Uganda Wildlife Authority, and local leaders of the communities for permission to conduct this research. ALJ was supported by the Natural Sciences and Engineering Research Council and the Canadian Federation of University Women. TRB was supported by the Fonds québécois de la recherche sur la nature et les technologies. JH and ND were supported by a National Science Foundation Coupled Natural-Human Systems grant (CNH-EX 1114977). Funding sources had no involvement in study design, analysis or writing. We thank Catrina Mackenzie for sharing her reference dataset for Kibale. We are grateful to Lauren Chapman, Jeremy Diem, Martin Lechowicz, Catrina MacKenzie, and Pete Parker for helpful comments and discussion which improved the manuscript.

References

- Adam, E., Mutanga, O., 2009. Spectral discrimination of papyrus vegetation (*Cyperus papyrus* L.) in swamp wetlands using field spectrometry. *ISPRS J. Photogramm. Rem. Sens.* 64, 612–620.
- Adam, E.M., Mutanga, O., Rugege, D., Ismail, R., 2012. Discriminating the papyrus vegetation (*Cyperus papyrus* L.) and its co-existent species using random forest and hyperspectral data resampled to HYMAP. *Int. J. Rem. Sens.* 33, 552–569.
- Adjorlolo, C., Cho, M.A., Mutanga, O., Ismail, R., 2012. Optimizing spectral resolutions for the classification of C3 and C4 grass species, using wavelengths of known absorption features. *J. Appl. Rem. Sens.* 6, 063560-063561–063560-063515.
- Amaniga Ruhanga, I., Iyango, L., 2010. A socio-economic baseline survey of communities adjacent to Lake Bisina/Opeta and Lake Mburo/Nakivali wetland systems. In: *Providing Baseline Information for the Implementation of the COBWEB Project in Western and Eastern/North-Eastern Uganda*. Nature Uganda, Kampala, Uganda, p. 65.
- Balmford, A., Bond, W., 2005. Trends in the state of nature and their implications for human well-being. *Ecol. Lett.* 8, 1218–1234.

- Benker, C.S., Langford, R.P., Pavlis, T.L., 2011. Positional accuracy of the Google Earth terrain model derived from stratigraphic unconformities in the Big Bend region, Texas, USA. *Geocart Int.* 26, 291–303.
- Biswal, S., Ghosh, A., Sharma, R., Joshi, P., 2013. Satellite data classification using open source support. *J. Indian Soc. Rem. Sens.* 41, 1–8.
- Buss, I.O., 1961. Some observations on food habits and behavior of the African elephant. *J. Wildlife Manage.* 25, 131–148.
- Cha, S.-Y., Park, C.-H., 2007. The utilization of Google Earth images as reference data for the multitemporal land cover classification with MODIS data of North Korea. *Korean J. Rem. Sens.* 23, 483–491.
- Chapman, L.J., Balirwa, J., Bugenyi, F.W.B., Chapman, C.A., Crisman, T.L., 2001. Wetlands of East Africa: Biodiversity, exploitation, and policy perspectives. In: Gopal, B., Junk, W.J., Davis, J.A. (Eds.), *Biodiversity in wetlands: Assessment, function and conservation*, Backhuys Publishers, vol. 2. Leiden, Netherlands, pp. 101–131.
- Chapman, L., Chapman, C., Crisman, T., Prenger, J., 2001. Predictors of seasonal oxygen levels in an Ugandan swamp/river system: a 3-year profile. In: *Verh. Int. Ver. Theor. Angew. Limnol./Proc. Int. Assoc. Theor. Appl. Limnol./Trav. Assoc. Int. Limnol. Theor. Appl.*, pp. 3048–3053.
- Chapman, C.A., Lambert, J.E., 2000. Habitat alteration and the conservation of African primates: case study of Kibale National Park, Uganda. *Am. J. Primatol.* 50, 169–185.
- Chen, D., Stow, D.A., Gong, P., 2004. Examining the effect of spatial resolution and texture window size on classification accuracy: an urban environment case. *Int. J. Rem. Sens.* 25, 2177–2192.
- Coll, C., Galve, J.M., Sanchez, J.M., Caselles, V., 2010. Validation of Landsat-7/ETM+ thermal-band calibration and atmospheric correction with ground-based measurements. *IEEE Trans. Geosci. Rem. Sens.* 48, 547–555.
- Cordeiro, N.J., Burgess, N.D., Dovie, D.B., Kaplin, B.A., Plumpton, A.J., Marrs, R., 2007. Conservation in areas of high population density in sub-Saharan Africa. *Biol. Conserv.* 134, 155–163.
- Cromie, R.L., Lee, R., Delahay, R.J., Newth, J.L., O'Brien, M.F., Fairlamb, H.A., Reeves, J.P., Stroud, D.A., 2012. Ramsar wetland disease manual: Guidelines for assessment, monitoring and management of animal disease in wetlands. In: *Ramsar Technical Report No. 7. Ramsar Convention Secretariat*, Gland, Switzerland, p. 353.
- Davranche, A., Lefebvre, G., Poulin, B., 2010. Wetland monitoring using classification trees and SPOT-5 seasonal time series. *Rem. Sens. Environ.* 114, 552–562.
- Diem, J.E., Hartter, J., Palace, M.W., and S.J. Ryan. 2013. Validation of satellite-based rainfall products for Western Uganda. Association of American Geographers Annual Meeting, April 9–13, 2013, Los Angeles, CA.
- Fuller, R.M., Groom, G.B., Mugisha, S., Ipulet, P., Pomeroy, D., Katende, A., Bailey, R., Ogutu-Ohwayo, R., 1998. The integration of field survey and remote sensing for biodiversity assessment: A case study in the tropical forests and wetlands of Sango Bay, Uganda. *Biol. Conserv.* 86, 379–391.
- Hartter, J., 2010. Resource use and ecosystem services in a forest park landscape. *Soc. Nat. Resour.* 23, 207–223.
- Hartter, J., Ryan, S.J., 2010. Top-down or bottom-up?: Decentralization, natural resource management, and usufruct rights in the forests and wetlands of western Uganda. *Land Use Policy* 27, 815–826.
- Hartter, J., Southworth, J., 2009. Dwindling resources and fragmentation of landscapes around parks: Wetlands and forest patches around Kibale National Park, Uganda. *Landscape Ecol.* 24.
- Hartter, J., Stampone, M.D., Ryan, S.J., Kirner, K., Chapman, C.A., Goldman, A., 2012. Patterns and perceptions of climate change in a biodiversity conservation hotspot. *PLoS One* 7, e32408.
- Hothorn, T., Zeileis, A., 2012. Partykit: A toolkit for recursive partytioning. In: *R Package Version 0.1-4*.
- Howard, P., Davenport, T., Matthews, R. (Eds.), 1996. Kibale National Park biodiversity report. Forest Department, Kampala, Uganda.
- Howard, P., Davenport, T., Kigenyi, F., 1997. Planning conservation areas in Uganda's natural forests. *Oryx* 31, 253–264.
- Hughes, R.H., and Hughes, J.S., 1992. A directory of African wetlands. IUCN. Gland, Switzerland and Cambridge, UK, 820p.
- Irons, J.R., Dwyer, J.L., Barsi, J.A., 2012. The next Landsat satellite: The Landsat data continuity mission. *Rem. Sens. Environ.* 122, 11–21.
- Iyango, L., Kiwazi, F., Tindamanyire, T., Kaganzi, E., Busulwa, H., Mafabi, P., 2012. Traditional wetland practices in rural communities in Uganda. In: Lake Victoria Environmental Management Project I. Kampala, Uganda: Wetlands Inspection Division, Ministry of Water Lands and Environment.
- Jones, M., Humphries, S., 2002. Impacts of the C4 sedge *Cyperus papyrus* L. on carbon and water fluxes in an African wetland. *Hydrobiologia* 488, 107–113.
- Jones, M.B., Muthuri, F.M., 1997. Standing biomass and carbon distribution in a papyrus (*Cyperus papyrus* L.) swamp on Lake Naivasha, Kenya. *J. Trop. Ecol.* 13, 347–356.
- Kaggwa, R., Hogan, R., Hall, B., 2009. Enhancing wetlands' contribution to growth, employment and prosperity. UNDP/NEMA/UNEP Poverty Environment Initiative, Uganda, Kampala, p. 59.
- Keeratikasikorn, C., Trisirisatayawong, I., 2008. Reconstruction of 30 m DEM from 90 m SRTM DEM with bicubic polynomial interpolation method. *Int. Arch. Photogramm. Rem. Sens. Spatial Inform. Sci.* B1, 791–794.
- Lambin, E.F., Ehrlich, D., 1995. Combining vegetation indexes and surface-temperature for land-cover mapping at broad spatial scales. *Int. J. Rem. Sens.* 16, 573–579.
- Li, X., Du, Y., Ling, F., Wu, S., Feng, Q., 2011. Using a sub-pixel mapping model to improve the accuracy of landscape pattern indices. *Ecol. Ind.* 11, 1160–1170.
- Lindblade, K.A., Walker, E.D., Onapa, A.W., Katungu, J., Wilson, M.L., 2000. Land use change alters malaria transmission parameters by modifying temperature in a highland area of Uganda. *Trop. Med. Int. Health* 5, 263–274.
- Lu, D., Weng, Q., 2006. Use of impervious surface in urban land-use classification. *Rem. Sens. Environ.* 102, 146–160.
- Lu, D., Moran, E., Batistella, M., 2003. Linear mixture model applied to Amazonian vegetation classification. *Rem. Sens. Environ.* 87, 456–469.
- Lwanga, J.S., 2003. Forest succession in Kibale National Park, Uganda: Implications for forest restoration and management. *Afr. J. Ecol.* 41, 9–22.
- MacKenzie, C.A., Chapman, C.A., Sengupta, R., 2012. Spatial patterns of illegal resource extraction in Kibale National Park, Uganda. *Environ. Conserv.* 39, 38–50.
- Maclean, I.M., Hassall, M., Boar, R., Nasirwa, O., 2003a. Effects of habitat degradation on avian guilds in East African papyrus *Cyperus papyrus* swamps. *Bird Conserv. Int.* 13, 283–297.
- Maclean, I.M., Tinch, R., Hassall, M., Boar, R., 2003b. Social and economic use of wetland resources: A case study from Lake Bunyonyi, Uganda. In: *Environmental Change and Management Working Paper*. Centre for Social and Economic Research on the Global Environment, p. 9.
- Maclean, I.M., Tinch, R., Hassall, M., Boar, R., 2003c. Towards optimal use of tropical wetlands: An economic valuation of goods derived from papyrus swamps in southwest Uganda. *Environmental Change and Management Working Paper*, 2003, p. 10.
- Maclean, I.M., Boar, R.R., Lugo, C., 2011. A review of the relative merits of conserving, using, or draining papyrus swamps. *Environ. Manage.* 47, 218–229.
- Maclean, I.M., Bird, J.P., Hassall, M., 2013. Papyrus swamp drainage and the conservation status of their avifauna. *Wetlands Ecol. Manage.*, 1–13.
- Mafabi, P., 2000. The role of wetland policies in the conservation of waterbirds: The case of Uganda. *Ostrich* 71, 96–98.
- Malan, H., Appleton, C., Day, J., Dini, J., 2009. Wetlands and invertebrate disease hosts: Are we asking for trouble? *Water SA* 35, 753–768.
- Marchant, R., Mumbi, C., Behera, S., Yamagata, T., 2007. The Indian Ocean dipole – the unsung driver of climatic variability in East Africa. *Afr. J. Ecol.* 45, 4–16.
- Millennium Assessment, 2005. *Ecosystems and Human Well-being: Wetlands and water synthesis*. World Resources Institute, Washington, DC, p. 68.
- Mironga, J., 2005. Effect of farming practices on wetlands of Kisii District, Kenya. *Appl. Ecol. Environ. Res.* 3, 81–91.
- Morrison, E.H., Upton, C., Pacini, N., Odhiambo-K'oyoo, K., Harper, D.M., 2013. Public perceptions of papyrus: Community appraisal of wetland ecosystem services at Lake Naivasha, Kenya. *Ecohydrol. Hydrobiol.*
- Mwita, E., Menz, G., Misana, S., Becker, M., Kisanga, D., Boehme, B., 2013. Mapping small wetlands of Kenya and Tanzania using remote sensing techniques. *Int. J. Appl. Earth Obs. Geoinf.* 21, 173–183.
- Nalukenge, I., Antle, J., Stoorvogel, J., 2009. Assessing the feasibility of wetlands conservation: Using payments for ecosystem services in Pallisa, Uganda. *Payment for Environmental Services in Agricultural Landscapes*. Springer, pp. 239–253.
- Namaalwa, S., van Dam, A.A., Funk, A., Ajie, G.S., Kaggwa, R.C., 2013. A characterization of the drivers, pressures, ecosystem functions and services of Namatala wetland, Uganda. *Environ. Sci. Policy*.
- NEMA, 2004. District State of Environment Report for Kamwenge. National Environment Management Authority, Kampala, p. 58.
- NEMA, 2010. State of Environment Report for Uganda. National Environment Management Authority, Kampala, p. 177.
- Omeja, P.A., Chapman, C.A., Obua, J., Lwanga, J.S., Jacob, A.L., Wanyama, F., Mugenyi, R., 2011. Intensive tree planting facilitates tropical forest biodiversity and biomass accumulation in Kibale National Park, Uganda. *For. Ecol. Manage.* 261, 703–709.
- Owino, A.O., Ryan, P.G., 2007. Recent papyrus swamp habitat loss and conservation implications in western Kenya. *Wetlands Ecol. Manage.* 15, 1–12.
- Ozesmi, S.L., Bauer, M.E., 2002. Satellite remote sensing of wetlands. *Wetlands Ecol. Manage.* 10, 381–402.
- Palm, C.A., Smukler, S.M., Sullivan, C.C., Mutuo, P.K., Nyadzi, G.I., Walsh, M.G., 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. *Proc. Natl. Acad. Sci.* 107, 19661–19666.
- Patz, J.A., Daszak, P., Tabor, G.M., Aguirre, A.A., Pearl, M., Epstein, J., Wolfe, N.D., Kilpatrick, A.M., Foutopoulos, J., Molyneux, D., 2004. Unhealthy landscapes: Policy recommendations on land use change and infectious disease emergence. *Environ. Health Perspect.* 112, 1092.
- Potere, D., 2008. Horizontal positional accuracy of Google Earth's High-Resolution Imagery Archive. *Sensors* 8, 7973–7981.
- Rodríguez, J.P., Beard, T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time, and ecosystem services. *Ecol. Soc.* 11, 28.
- Ryan, S.J., Hartter, J., 2012. Beyond ecological success of corridors: Integrating land use history and demographic change to provide a whole landscape perspective. *Ecol. Restor.* 30, 320–328.
- Schmidt, K., Skidmore, A., 2003. Spectral discrimination of vegetation types in a coastal wetland. *Rem. Sens. Environ.* 85, 92–108.
- Schuyt, K.D., 2005. Economic consequences of wetland degradation for local populations in Africa. *Ecol. Econ.* 53, 177–190.
- Sekitoleko, V., 1993. Resolution of conflicts between agriculture and environment protection in Uganda. *Nord. J. Afr. Stud.* 2, 103–108.
- Southworth, J., 2004. An assessment of Landsat TM band 6 thermal data for analyzing land cover in tropical dry forests. *Int. J. Rem. Sens.* 25, 689–706.

- Southworth, J., Hartter, J., Binford, M.W., Goldman, A., Chapman, C.A., Chapman, L.J., Omeja, P., Binford, E., 2010. Parks, people and pixels: Evaluating landscape effects of an East African national park on its surroundings. *Trop. Conserv. Sci.* 3, 122–142.
- Stampone, M.D., Hartter, J., Chapman, C.A., Ryan, S.J., 2011. Trends and variability in localized precipitation around Kibale National Park, Uganda, Africa. *Res. J. Environ. Earth Sci.* 3, 13–23.
- Strezov, V., Evans, T.J., Hayman, C., 2008. Thermal conversion of elephant grass *Pennisetum purpureum* Schum to bio-gas, bio-oil and charcoal. *Bioresour. Technol.* 99, 8394–8399.
- Thomas, C.D., Anderson, B.J., Moilanen, A., Eigenbrod, F., Heinemeyer, A., Quafe, T., Roy, D.B., Gillings, S., Armsworth, P.R., Gaston, K.J., 2013. Reconciling biodiversity and carbon conservation. *Ecol. Lett.* 16, 39–47.
- Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., Steininger, M., 2003. Remote sensing for biodiversity science and conservation. *Trends Ecol. Evol.* 18, 306–314.
- United Nations, 2011. *World Population Prospects: The 2010 Revision*. United Nations Department of Economic and Social Affairs Population Division, New York.
- UWA, 2003. *Kibale National Park General Management Plan 2003–2013*. Uganda Wildlife Authority, Kampala, Uganda, p. 79.
- van Dam, A., Kipkemboi, J., Zaal, F., Okeyo-Owuor, J., 2011. The ecology of livelihoods in East African papyrus wetlands (ECOLIVE). *Rev. Environ. Sci. Biotechnol.* 10, 291–300.
- Van Orsdol, K.G., 1986. Agricultural encroachment in Uganda's Kibale Forest. *Oryx* 20, 115–117.
- Wanyama, F., Muhabwe, R., Plumptre, A.J., Chapman, C.A., Rothman, J.M., 2010. Censusing large mammals in Kibale National Park: Evaluation of the intensity of sampling required to determine change. *Afr. J. Ecol.* 48, 953–961.
- Wing, L.D., Buss, I.O., 1970. Elephants and forests. *Wildlife Monogr.* 19, 3–92.
- Wolff, C., Haug, G.H., Timmermann, A., Damsté, J.S.S., Brauer, A., Sigman, D.M., Cane, M.A., Verschuren, D., 2011. Reduced interannual rainfall variability in East Africa during the last ice age. *Science* 333, 743–747.
- Wolter, P.T., Mladenoff, D.J., Host, G.E., Crow, T.R., 1995. Improved forest classification in the Northern Lake States using multi-temporal Landsat imagery. *Photogramm. Eng. Rem. Sens.* 61, 1129–1144.
- WRI, 2009. *Mapping a better future: How spatial analysis can benefit wetlands and reduce poverty in Uganda*. Uganda Ministry of Water and Environment, Uganda Bureau of Statistics, International Livestock Research Institute, World Resources Institute, Washington, DC and Kampala.
- Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. *J. Plant Ecol.* 1, 9–23.
- Yousefzadeh, M., Mojaradi, B., 2012. Combined rigorous-generic direct orthorectification procedure for IRS-p6 sensors. *ISPRS J. Photogramm.* 74, 122–132.
- Zedler, J.B., Kercher, S., 2005. Wetland resources: Status, trends, ecosystem services, and restorability. *Annu. Rev. Environ. Resour.* 30, 39–74.