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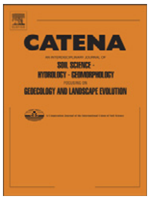

Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides

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ABSTRACT

A reconstruction of land use changes and the implications thereof for landslide occurrence on critical slopes of Mount Elgon in Eastern Uganda were undertaken. Aerial photographs taken in 1960 formed the benchmark for the analysis of respective land use changes between 1995 and 2006, using 30 m Landsat TM and 20 m SPOT MS images. Landslide sites were mapped using a MobileMapper, and terrain parameters were derived using a 15 m Digital Elevation Model. A supervised classification approach was employed to generate land-cover maps, from which the areas of three land-cover classes (agricultural fields, woodlands and forests) were calculated. A post-classification comparison change-detection technique revealed different trends in land-cover change between the periods 1960–1995 and 1995–2006. Whereas there were minimal land use changes between 1960 and 1995, the period 1995–2006 marked a considerable loss of woodlands and forest cover, particularly on steep concave slopes (36°–58°) of the National Park. The encroachment onto the critical slopes was noted to have induced a series of shallow and deep landslides in the area. All the mapped landslides were noted to lie on steep concave slopes of a northerly orientation, which had been opened up for cultivation. Deforestation and cultivation alter the soil hydrological conditions on steep concave slopes, rendering them susceptible to saturation. This may trigger debris flows during rainfall events. There is a need to restore forest cover on the fragile steep slopes and restrain local communities from opening up new areas for cultivation on critical slopes, particularly within the protected area.

1. Introduction

Mountain ecosystems are continuously experiencing extensive land use changes, due to natural and anthropogenic processes (Agarwal et al., 2002; Klein, 2001; Liu et al., 2003). These changes have not only led to modifications, but also to the conversion of land cover, with serious environmental implications (Hansen et al., 2001; Lung and Schaab, 2010). Studies on Mt Kilimanjaro (see Gamassa, 1991; Maro, 1974; 1998; Soini, 2005; William, 2002; Yanda and Shishira, 2001) provide evidence of replacement of forests by agriculture and settlements, leading to severe erosion, disruption of water sources and the drying up of rivers. Mountain forest ecosystems are particularly important from an ecological perspective, as they provide goods and services that are essential to maintain the life-support system on a local and global scale. Greenhouse gas regulation, water supply, nutrient cycling, genetic and species diversity, as well as recreation, are some of the services that mountain forests provide (Beniston, 2003; Nagendra et al., 2004; Sivrikaya et al., 2007). Mountains also represent unique areas for the detection of climatic change and the assessment of climate-related impacts, because when the climate changes rapidly with height, over relatively short horizontal distances, so does vegetation and hydrology (Whiteman, 2000).

There has been growing concern over the human destruction of forests, especially in the tropical and subtropical countries' mountain environments and the associated consequences on soil and water quality, biodiversity, global climatic and livelihood systems (Armentaras et al., 2003; Laurence, 1999; Noss, 2001; Turner et al., 1995). East Africa's highlands have a large potential for agricultural production and, until the mid-20th century, they were resilient to exploitation (McCall, 1985). The favourable climate with abundant rainfall and fertile soils attracted farmers to the region many centuries ago. The productivity of the land also supported chiefdoms and kingdoms with a stratified social structure. The land adequately supported both subsistence and surplus food production. However, today, land degradation is threatening the very basis of the farming communities. The expansion of cultivation on the marginal slopes of Mt. Kilimanjaro, for example, has threatened the existence of its montane forests with considerable climatic impacts, ranging from vanishing glaciers, increased frequency and intensity of fires, decreasing water supplies, and an overall change in the people's livelihoods (Beniston, 2003;

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Hemp, 2009; Soini, 2005). According to the East African scenarios, the expansion of cropland and grazing land will continue to replace natural forests by a further 38% of its 1995 areal extent until 2032 (UNEP, 2004).

Mass movements are recognised and well-documented global geomorphic hazards, owing to their major role in slope evolution in mountainous areas and the considerable economic, social and geomorphological impacts. However, literature on landslides in East Africa's highlands is still rather restricted (Claessens et al., 2007; Knapen et al., 2006; Ngecu and Mathu, 1999). Examples of some of the landslide studies in East Africa include those of Ngecu and Ichangi, 1999; Davies, 1996; Westerberg and Christianson, 1998; Ngecu and Mathu, 1999; Westerberg, 1999; Inganga et al., 2001, in Kenya; Muwanga et al., 2001; Knapen et al., 2006; Claessens et al., 2007; Kitutu et al., 2004; 2009, in Uganda; Rapp et al., 1972; Christianson and Westerberg, 1999 in Tanzania; Moeyersons, 1989, 2003, in Rwanda. These studies all point to anthropogenic factors, especially population pressure coupled with slope disturbance, inconsiderate irrigation and deforestation, as being major trigger factors of landslides in the East African highlands.

The coupling between intense rainfall and landslide initiation has been examined by many scholars (Bacchini and Zannoni, 2003; Crosta and Frattini, 2003; Iverson, 2000), and triggering thresholds have been determined. However, theoretical frameworks have not been developed for anticipating how landslides respond to land use change. Triggering thresholds are considerably lowered when rainfall and anthropogenic triggering factors combine. It is this combination that could explain the triggering of the majority of the landslides surveyed in the present study.

The Ugandan side of Mt. Elgon National Park (MENP) was formerly gazetted as a natural forest reserve in 1938, with a variety of wild animals. In October 1993, the Government of Uganda declared the area a National Park — in an effort to strengthen the conservation status of the ecosystem. Encroachment for cultivation into the National Park is a major threat to the Mt. Elgon ecosystem, due to the amount of degradation caused by the removal of natural vegetation. Encroachment has resulted in the destruction of approximately 25,000 ha within the past generation, or about one fifth of Elgon's forest. Virtually all of the forest cover below an elevation of 2000 m has been removed, as a result of encroachment. The breakdown of civil order in the 1970s and 1980s provided a social and economic climate within which encroachment was rife (Malpas, 1980; UWA, 2000).

Despite efforts to protect the Park boundaries, and to regenerate previously encroached-on lands, encroachment continues to be a management problem. Incidences of infringement have continued to occur for a variety of reasons, including a strong community desire for more agricultural land, declining land productivity in some areas, high population pressure, political interference and connivance with National Park Staff. In addition, problems with identifying and marking the correct Park boundaries have occurred in a number of areas, with different boundary surveys over the years producing different outcomes — either as a result of lack of information, or because of manipulation of the true boundaries by the surveyors because of community pressure. The most recent boundary survey carried out between 1993 and 1996 has, in many areas, found that land already used for cultivation is, in fact, within the gazetted park boundaries; thereby, creating conflict with the community, who consider the land to be theirs (UWA, 2000).

Against the above background, this paper investigates the relationship between land use changes and landslide occurrence on the slopes of Mount Elgon. The specific objectives of the study are:

1. To examine the temporal and spatial trends in land use change for the period between 1960 and 2006.
2. To establish the relationship between land use, topographic parameters and the occurrence of landslides.

2. Study area

The study was conducted in the Manafwa and Bududa districts located on the slopes of Mount Elgon, Eastern Uganda (Fig. 1). It extends from 0° 59′ N, 34° 17′ E to 1° 04′ N, 34° 25′ E. In the Manafwa district, a specific area that typifies land use and cover change in the region was chosen. The availability of imagery, particularly the 1960 aerial photography of the area was also a basis for the selection. Sites that have experienced frequent landslides in the recent past were chosen for field surveys in both districts. The study area is located on the mid slopes (1800–2600 m), which receive more rainfall than either the lower slopes or the summit (UWA, 2000).

According to Scott (1994), Mt. Elgon, a solitary volcano, is one of the oldest in East Africa. It was built up from lava debris blown out from a greatly enlarged volcanic vent during the Pliocene epoch (Knapen et al., 2006) and rises to a height of about 4320 m above sea level. The geology of the area is dominated by basaltic parent materials and strongly weathered granites of the Basement Complex (Claessens et al., 2007). Carbonatite intrusions on the lower slopes are reported by Knapen et al. (2006) and Claessens et al. (2007) as having caused fenitization of the granites, rendering them sensitive to slope instability. Identified as inorganic clays of high plasticity, the soils of the study area were classified by Mugagga et al. (2011) as vertisols characterised by a clay content exceeding 41%. Such properties qualify the soils as ‘problem soils’ that are susceptible to landslides.

The area receives a bimodal pattern of rainfall, generally, with the wettest period occurring from April to October. The mean annual rainfall ranges from 1500 mm on the eastern and northern slopes, to 2000 mm in the southern and the western slopes. The mean maximum and minimum temperatures are 23° and 15 °C respectively. Mid-slopes oriented towards the east and north, at elevations between 2000 and 3000 m tend to be wetter than either the lower slopes or the summit.

The vegetation of Mt. Elgon reflects the altitudinally controlled zonal belts commonly associated with large mountain massifs. Four broad vegetation communities are recognised, namely: mixed montane forest up to an elevation of 2500 m, bamboo and low canopy montane forest from 2400 to 3000 m, and moorland above 3500 m (Scott, 1994).

Land in the study area is divided between the National Park and farmland. Land use in the latter area is itself divided between two topographic zones: an upland zone, characterised by intensive coffee and maize farming, and a lowland zone, where beans, yams and onions are grown. Arabica coffee is traditionally the major cash crop of the area, and bananas are the staple food. Much of the cultivation takes place on steep slopes ranging between 36° and 58°.

Despite cultivating on steep slopes, there is inadequate use of soil conservation measures in the area, a significant factor that leads to soil erosion, declining levels of soil fertility and decreasing crop yields. The use of soil conservation methods varies with distance from the National Park. Farmers living far from the Park boundary use far better soil conservation methods than their counterparts in and around the Park. This is explained by the insecure land tenure and the constant fear of eviction by the Park authorities (Mugagga et al., 2010).

3. Methods

3.1. Aerial photography and multi-temporal imagery

Remote sensing has shown great potential in land-cover mapping and monitoring, due to its advantages over traditional procedures in terms of cost effectiveness and timeliness in the availability of information over larger areas (Armentaras et al., 2003; Franklin, 2001; Murthy et al., 1998). In the present study, aerial photographs of

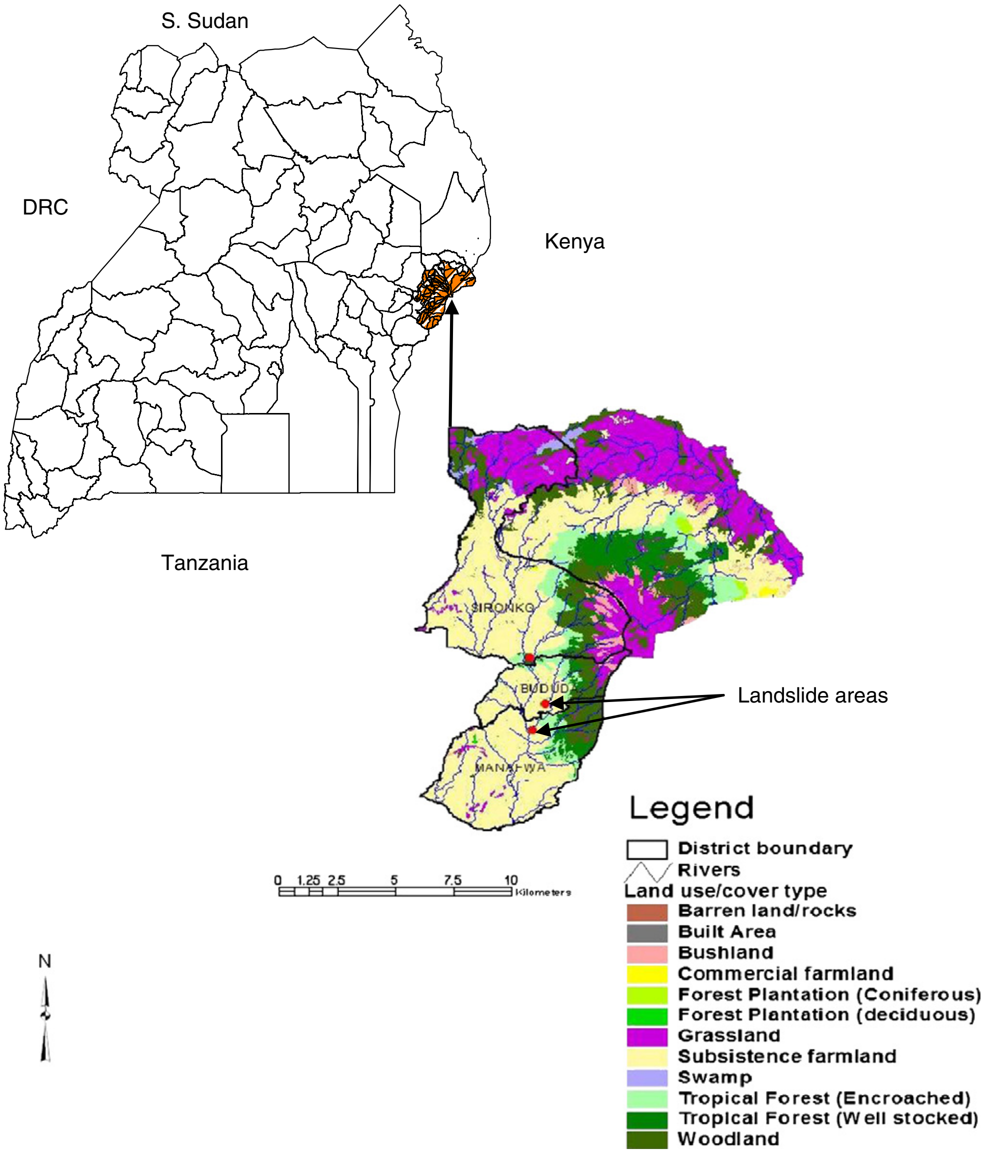

Fig. 1. The study area. Inset map shows the districts where landslide sites surveyed in this study are located.

1:24,000 scale taken on 7 February 1960, acquired from the Uganda Department of Mapping and Surveys, provided a benchmark for the analysis of land use and vegetation cover changes in the study area. Land use/cover categories ranging from agricultural fields, woodlands to forest cover were mapped from the aerial photographs using a mirror stereoscope.

In order to overcome scale distortions inherent in aerial photographs, the mapped details were transposed to transparencies overlaid on to orthophoto maps of 1:10,000 scale, prepared in 1959. The land use and cover maps were captured onto a GIS, using Arc GIS 9 Software. Owing to the unavailability of anniversary images of the area, Landsat MS and SPOT imagery taken on 2 September 1995 and 17 February 2006, respectively, were used to assess subsequent land use and land cover changes. The months of February and September are planting and post-harvesting periods in the study area, thus providing a good comparative ground, as far as cultivation changes are concerned.

3.2. Land-use classes

On the basis of *a priori* knowledge of the study area and the need to consistently discriminate land use/cover classes using images with a different spatial resolution, three broad land-use classes were adopted, namely: forest cover, woodlands and agriculture. Forest cover consists of a main stratum of continuous and closed canopy broad-leaved evergreen trees spread over the area without intervals or breaks. Riparian vegetation, shrubs and bushes were categorised as woodlands. All cultivated and fallow land was designated as agricultural fields, whose identification was aided by the coinciding planting and post-harvesting seasons in the respective images.

3.3. Image processing and classification

Despite image pre-processing by Spotimage (suppliers of both Landsat MS and SPOT imagery) that included geo-referencing and ortho-rectification, geo-rectification accuracy was further improved by using 15 ground control points (GCPs) obtained during field visits by means of a Magellan Professional MobileMapper ^{TM} CX. Both the Landsat and SPOT imagery were resampled in IDRISI Andes GIS environment, using the nearest-neighbour technique; and the residual values ranged from 0.0001 to 0.001 pixels. Using the 'CALIBRATE' module in IDRISI, radiometric correction of the imagery was carried out. Atmospheric correction was not performed, because the post-classification comparison technique adopted for land use/cover analysis, also compensates for variations in atmospheric conditions and vegetation phenology between the dates, since each land use/cover classification is independently mapped (Coppin et al., 2004; Yuan et al., 2005). The Landsat and SPOT imagery were visually enhanced by processing 8-bit composites with original values and stretched saturation points.

On the basis of *a priori* field surveys and aerial photographic analysis, a supervised classification using a maximum likelihood algorithm was used to categorise the imagery into the three broad classes (forest cover, woodlands and agriculture). Since the two images were acquired by different sensors, the post-classification comparison method was used, so that the supervised classification of the 1996 and 2006 land cover was independently undertaken. This approach has the advantage of compensating for the differences in sensors.

The classification-accuracy assessment of the remotely sensed data, particularly in developing countries, is greatly compromised by the unavailability of reference ground data or aerial photographs at or near the time of satellite overpass (Kamusoko and Aniya, 2009; Skirvin et al., 2004). In this study, the accuracy assessment for the 1995 and 2006 Landsat and SPOT classifications was carried out by using GPS-verified land use/cover features identified during fieldwork in 2008 as comparison benchmarks. These were discerned as common to both imagery sets by means of on-screen visual interpretation. The accuracy of the classification generated from the imagery was assessed by comparing it with the reference data using an error matrix (Congalton and Green, 2009). High classification accuracies were achieved, as illustrated by the summary of classification measures derived from the error matrices for the two imagery sets (Table 1).

The National Park boundary distinctly marked by thick forest cover was identified, using the Normalized Difference Vegetation Indices (NDVI) for both sets of imagery. Among other uses, the NDVI is reliable in monitoring vegetation change (Lillesand and Keifer, 2004; Michael and Graham, 2003). The upper-slope limit of the cultivated area was distinctive on both sets of imagery. Hence, change detection in terms of upper-slope expansion of cultivated land into the protected forest cover, was done by way of overlaying a vector layer marking the 1995 boundary of the protected area on the 2006 imagery. A change-detection polygon was delineated, and its area was calculated in IDRISI Andes database query facility, thereby, giving an indication of the extent of encroachment into the National Park forest between 1995 and 2006.

3.4. Landslide surveying and mapping

Field surveying and mapping of landslide sites were undertaken, in order to gain an understanding of the spatial and site-specific characteristics of the recent landslides in the study area. Thirteen of the 14 landslides surveyed occurred during a spell of torrential rainfall events that occurred in February 2010. The surveys were conducted on the midslopes within and outside the montane forest of the Mount Elgon National Park at an altitude ranging between 1800 m and 2400 m above sea level. The Nametsi killer and Buwabwala landslides were the largest and most destructive among the surveyed sites. Owing to the freshness and highly fragile nature of the moist material, surveying at all the sites, except Buwabwala was limited to capturing co-ordinates using a Magellan Professional MobileMapper™ CX. The Buwabwala landslide, which occurred in June 2006 and had stabilised, was surveyed in detail.

Table 1
Summary of classification accuracies (%) for 1995 and 2006.

Land use/cover category	1995			2006		
	Producer's%	User's%	KIA	Producer's%	User's%	KIA
Forest	96	84	0.83	100	91	0.89
Agriculture	97	89	0.87	97	90	0.88
Woodland	100	95	0.91	82	97	0.83
Overall kappa statistic	0.88		0.86			
Overall accuracy (%)	90		92			

3.5. Terrain parameters

The versatility of Digital Elevation Models (DEMs) in terms of deriving macro- and micro-terrain attributes has been proven in many studies (Band, 1986; Claessens et al., 2007; Demirkesen, 2008: Jayaprasad et al., 2009; Kakembo et al., 2007; Knapen et al., 2006; Moore et al., 1991; Sivrikaya et al., 2007). Local topographic features, such as slope, aspect, convexities and concavities all play a crucial role in the number of morphological, ecological, and hydrological processes and are thus conditioning factors for landslide occurrence.

In order to establish the relationship between land use, selected topographic parameters and landslide occurrence, a 15 m Digital Elevation Model (DEM), based on Aster imagery, was acquired from TTH Earth Observation Consulting Services, France. Slope, aspect, hillshade and curvature surfaces were calculated from the DEM in IDRISI Andes environment. The hill-shade surfaces served to visually enhance topographic variations, particularly general slope curvature. By overlaying the mapped landslide sites onto the hill-shade, curvature, aspect and slope surfaces, the relationship between landslide occurrence, land use and topography was established.

Boolean images for cultivated land and slope angle classes (0–9°, 10–19°, 20–29° and 30°+) were generated using the RECLASS module in IDRISI Andes and overlaid on a slope surface to highlight the extent to which cultivation had expanded on to critically steep slopes, some of which form part of the protected area. The slope surfaces calculated from the 15 m DEM were resampled to the 20 m SPOT and 30 m Landsat MS, for overlay purposes, using the nearest neighbour resampling technique (Kamusoko and Aniya, 2009; Yang and Lo, 2000).

4. Results

4.1. Land use/cover changes between the periods 1960–1995 and 1995–2006

The major land use and cover changes between 1960 and 2006 in the specific area chosen in Manafwa district are illustrated by Figs. 2 and 3.

Woodlands and forest cover were the dominant land use/cover classes between 1960 and 1995. Computed percentages for land-use classes show that in 1960, woodlands, forests and agricultural fields occupied 53%, 29% and 17% of the area, respectively. There were minimal changes in the land-use cover between 1960 and 1995. Woodlands decreased by 1.1% from 5845 to 5779 ha, while agricultural fields and forest cover increased slightly by 3.4% (from 1957 to 2024 ha) and 1.7% (3185 to 3241 ha) respectively. Spatial changes are also discernible, as cultivation assumed more of a linear pattern in 1960, mainly along rivers compared to 1995 where it appeared more spread out (see Fig. 2). Conversely, considerable spatial expansion in agriculture and a rapid decrease in woodlands and forests were observed during the period 1995 to 2006. The area under woodlands and forest cover was substantially reduced by 58% and 34% respectively, while agricultural fields increased by 241% — from 2024 ha in 1995 to 6895 ha in 2006.

4.2. Encroachment of cultivation onto critical slopes of the National Park

An overlay of the vector layers marking the 1995 and 2006 Park boundaries onto the 2006 SPOT NDVI image revealed marked changes

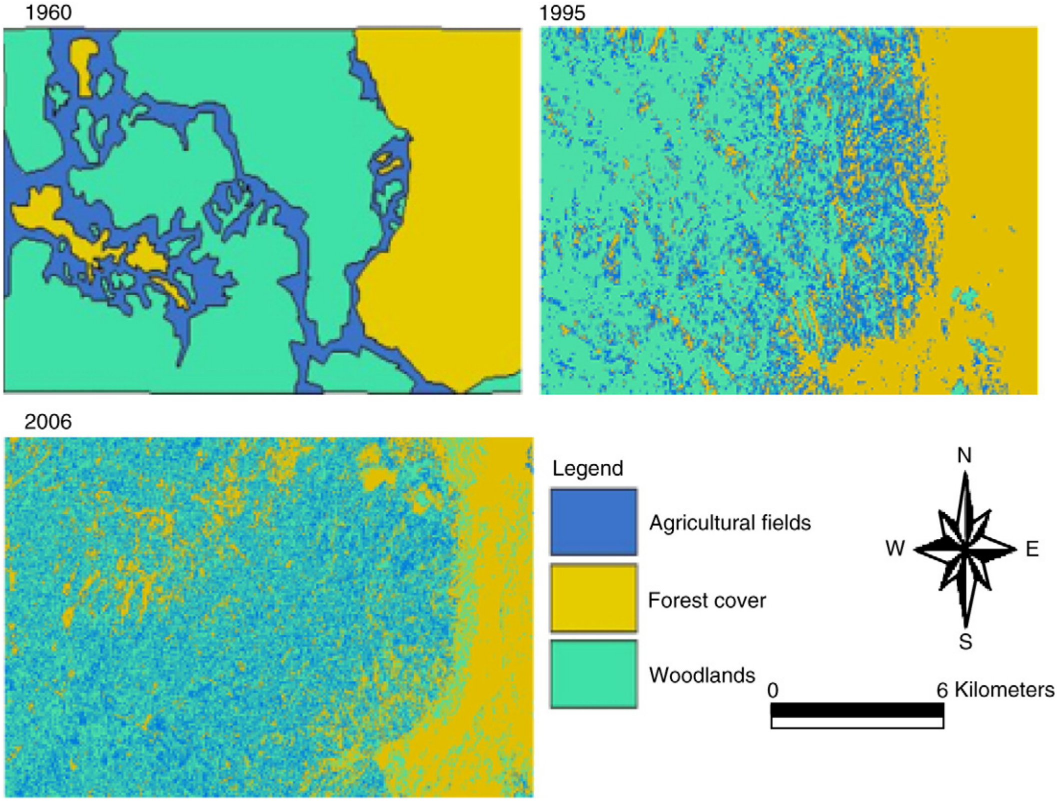

Fig. 2. Details mapped from aerial photography and classified images illustrating land use/cover changes in Manafwa district between 1960 and 2006.

in the extent of agricultural encroachment into the National Park forest (Fig. 4). It is also discernible from the figure that most the landslide sites lie on the encroached cultivated slopes straddling the Park boundary. Between 1995 and 2006, 2093 ha of National Park forest was lost to illegal expansion of agricultural fields onto critically steep slopes, a phenomenon which is ongoing.

Changes in the extent of agricultural fields in relation to slope angle are illustrated in Fig. 5. The most significant overall trend is the shift from lower and gentle slopes (0–9°) to critically steep ones (10–19°, 20–29° and 30°+) during the study period. Cultivation on gentle slopes decreased by 19%, from 1517 ha to 1231 ha, but increased by 12%, 31% and 61% on the 10–19°, 20–29° and 30°+ slopes, respectively. Similar observations were made in the same area by Buyinza and Nabalegwa (2008), who noted that much of the cultivation took place on slopes ranging between 36° and 58°. As illustrated in the NDVI image (Fig. 4), all the mapped landslides lie on cultivated land, particularly on steep slopes (see Table 2), which were opened up for cultivation during the post-1995 period.

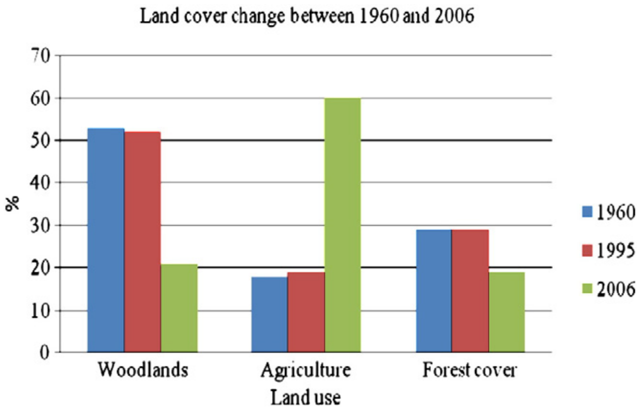

Fig. 3. Trends in land use change in Manafwa district between 1960 and 2006.

The Buwabwala and Nametsi killer landslides were identified as a rotational debris slide and flow respectively. The former, which was surveyed in detail, had a scarp depth of 8.4 m, a maximum length of 180 m and a width of 110 m. The accumulation and debris slide zones had an average length and width of 125 and 55 m, and 270 and 27 m respectively. The depth of the latter landslide, estimated by comparing the MobileMapper and DEM readings was ≥8 m. The rest of the landslides, which were smaller in extent, were classified as surficial rotational slides.

An overlay of the mapped landslides on the slope surface revealed that they occurred on slope gradients ranging between 32° and 60° (Table 2). Most of them happened at the bottom of a 2200 m altitude scarp, discernible from the hillshade surface (Fig. 6) on slopes which had been deforested for cultivation. Regarding aspect, most of the landslide sites are oriented north (see Table 2). Coupled with crop cultivation, the susceptibility of these slopes to landsliding was exacerbated.

The visual enhancement of the slope configuration by the hillshade surface (Fig. 6) vividly illustrates that the mapped landslides occurred on concave elements of slope. The Nametsi killer landslide (see inset, Fig. 6) is particularly noticeable and occupies an elongated concave depression which defined the trajectory of the massive debris flow that buried three villages and killed more than 300 people.

The role of slope curvature in landslide occurrence has been highlighted by Knapen et al. (2006) and Claessens et al. (2007). In order to quantify the relationship between slope curvature and landslide occurrence, a curvature surface was derived from the DEM and the mapped landslide sites were overlaid on it. Average curvature values extracted from points digitised on the draped slope units were calculated for each landslide site. As depicted by the positive eigenvalues (Table 2), all the surveyed landslide sites are located on concave slope elements, which were noted earlier as either under

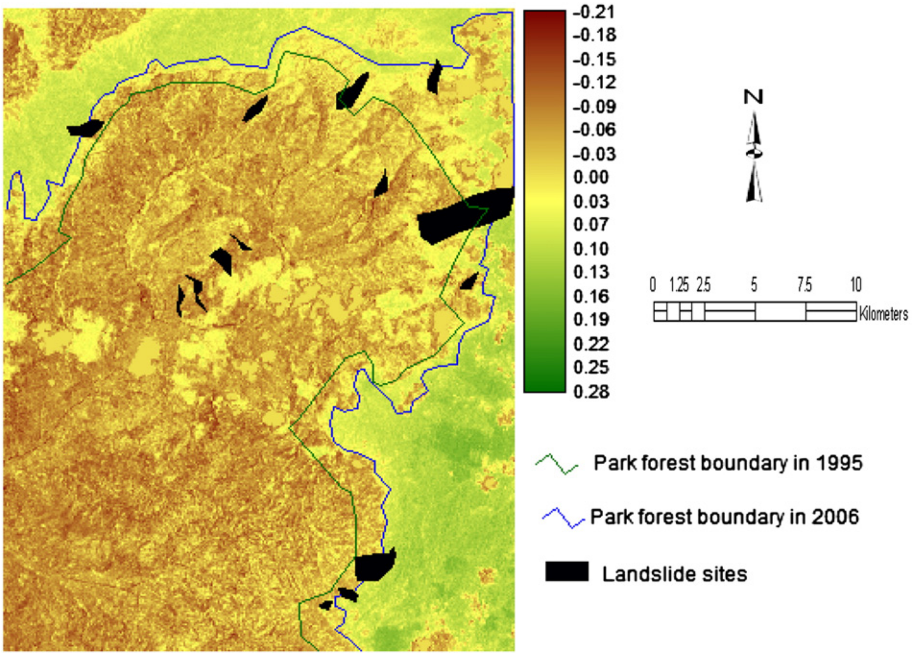

Fig. 4. NDVI image depicting the extent of encroachment of the National Park forest steep slopes between 1995 and 2006 in Manafwa and Bududa districts.

intensive cultivation, or were being opened up for the same activity (see Fig. 4).

Land use changes as a triggering factor in the form of encroachment of cultivation onto protected steep slopes and topographic attributes, as inherent factors — particularly slope steepness, aspect and concavity — combined to create a higher susceptibility to landsliding. As noted earlier, a coupling of these factors with rainfall will lower triggering thresholds considerably. These interactions are discussed in the subsequent section.

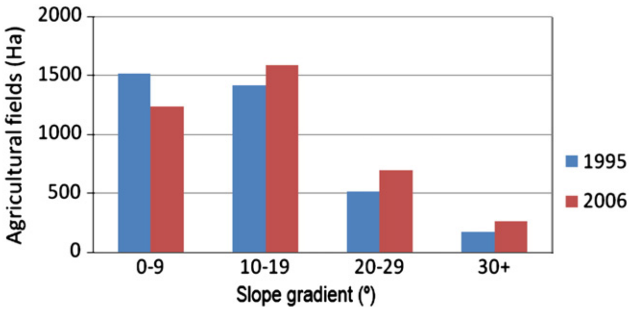

Fig. 5. Expansion of agricultural fields onto critically steep slopes.

Table 2
Topographic attributes of the surveyed landslide sites.

Landslide no	Slope gradient (°)	Aspect	Curvature (eigenvalues)
1	54	351	7158
2	45	348	3788
3	60	332	9325
4	37	354	6015
5	38	360	8380
6	39	352	2222
7	39	331	9389
8	39	344	9121
9	50	322	5765
10	49	347	5912
11	52	344	2223
12	48	215	8253
13	32	329	4224
14	36	348	6436

5. Discussion

5.1. Implications of land-use cover change trends

The land-use/cover change trends identified above reveal a drastic decimation of forest and woodland cover, due to agricultural encroachment, particularly into the National Park. This can be attributed to acute land shortages, resulting from the exponential population growth in the Mount Elgon region. Similar trends in land use and cover change have been observed on the slopes of Mt. Kilimanjaro where bush-lands are progressively being replaced by agricultural fields (Soini, 2005; William, 2002; Yanda and Shishira, 2001). Lung and Schaab (2010) also identified positive relationships between population pressure and forest clearance in the mid-altitude tropical forests of Kakamega and Budongo in Kenya and Uganda, respectively. As noted by Knapen et al. (2006), population pressure forces people to cultivate unsuitable steep slopes, thus contributing to slope instability.

An increase in landslide occurrence with land use changes is a phenomenon that has been identified by several studies (Glade, 2003; Gorsevski et al., 2006; Meusburger and Alewell, 2009; Wasowski et al., 2010). The new ploughing on steeper slopes for EU-sponsored wheat cultivation has been invoked by Wasowski et al. (2010) as the cause for the higher frequency of and susceptibility to landsliding in south-eastern Italy. Notwithstanding the hitherto ongoing occurrence of landslides on cultivated land in the present study area, the frequency and enormity of landslides have increased with the encroachment of steep slopes for cultivation within the protected area. This is demonstrated by the fact that most landslides surveyed in this study occurred on the recently deforested steep cultivated slopes straddling the Park boundary. It is noteworthy however, that landslides can occur even without human intervention. Mugagga et al. (2011) reported a major landslide in pristine densely forested slopes of the gazetted Mount Elgon National Park. On the basis of the soil analyses done, they concluded that the inherently 'problem nature' of the soils on Mount Elgon slopes is ubiquitous. Conservation-related forms of land use are recommended on these critical slopes.

Mountain regions are particularly sensitive to anthropogenic impacts. A broad overview of both Landsat 1996 and SPOT 2005 satellite

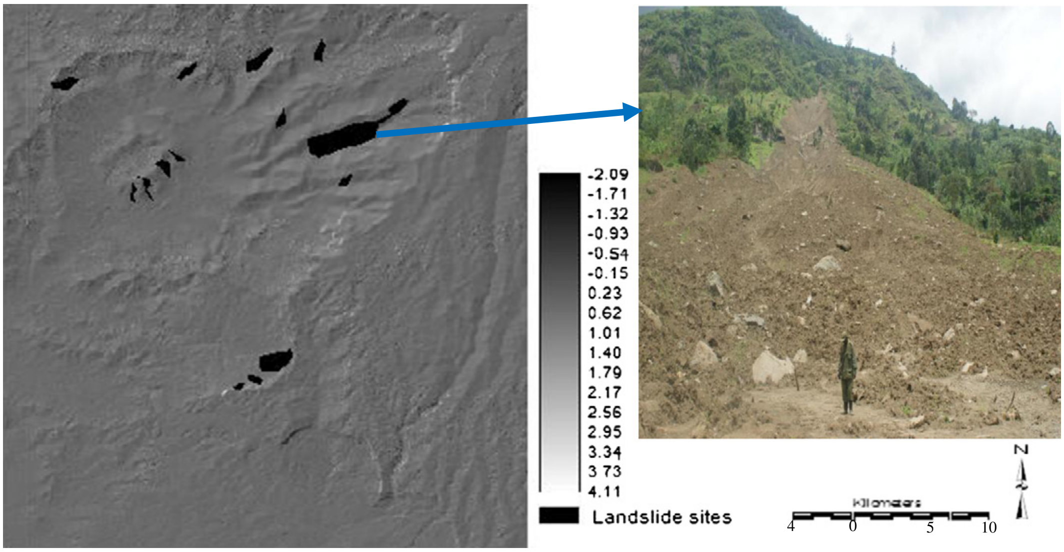

Fig. 6. Hillshade with mapped landslides overlaid. Note the concave hillslope nature of the landslide sites. Inset: photograph of Nametsi killer landslide which occurred on 1st of March 2010. Over 300 people, homes and a community health centre were buried by the debris.

imagery, clearly indicates that forest cover for the entire region stretching from the Northern slopes of Kapchorwa to the south-eastern slopes, on the Ugandan side of Mt. Elgon, has been decimated. The loss of vegetation cover inevitably alters mountain hydrology, and has implications for local and regional climate variability (Beniston, 2003; IPCC, 2007a,b). Such variability is not confined to mountain ecosystems, as populated lowlands depend on mountain water resources. Vegetation change and associated shifts in intra-annual precipitation patterns could give rise to drought episodes (Barnett et al., 2005). The impacts of climate variability have already been reported by NEMA (2008) in the low-lying areas of Butaleja, Soroti and Pallisa Districts that surround Mt. Elgon. These impacts include drought, heat waves, and flash floods, economic dislocation, decline, conflict, crop failure, and associated malnutrition and hunger.

5.2. Slope factors and landslide occurrence

An expansion of agricultural fields from lower and gentle slopes to critically steep ones has been identified above as the most significant land-use change trend. The landslide sites surveyed were found to occur on steep concave slopes, most of which are oriented north. This is in keeping with the findings of Knapen et al., (2006), who identified steep concave slope segments oriented to the north to north-east dominant rainfall direction, as the most favourable precondition for mass movement.

The soil hydrological conditions on concave slopes are greatly altered through deforestation and intensive cultivation. This not only enhances saturation, but also triggers a series of debris flows under extreme rainfall events (Inganga et al., 2001; NEMA, 2007; Nyssen et al., 2002). The vertic nature of the soils at the landslide sites, which renders them susceptible to landslides, was identified by Mugagga et al. (2011). In a nutshell, deforestation and cultivation drastically lower the threshold of slope stability on the densely populated steep concave slopes of Mt. Elgon.

6. Conclusion

The decimation of forest cover by agricultural encroachment — particularly between 1995 and 2006 — has been identified as the main land-use change trend in the study area. A spatial relationship between the surveyed landslide sites and steep slopes recently deforested for cultivation has been identified. The vulnerability to landsliding of steep concave slopes with a northerly orientation, which was noted by studies conducted earlier on the lower slopes of Mount Elgon, has been further confirmed by this study. Deforestation and cultivation of steep concave slopes lower the threshold of slope stability, as they alter soil hydrological conditions within the slope elements by way of enhancing saturation, hence triggering debris flows. It is recommended that forest cover be restored, and the local communities restrained from opening up new areas for cultivation on critical slopes, particularly within the protected area.

Acknowledgements

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